Generic models of technical systems sustainability

by

Laura Hay

A thesis submitted to the University of Strathclyde
for the degree of
Doctor of Philosophy

Department of Design, Manufacture and Engineering Management
University of Strathclyde
Glasgow, UK

June 2015

Signed: Date: *1st June 2015*

To my friend, Arthur Yip.

“The essential step is to recognise that nobody, least of all the chief designer, has, at the start, the knowledge to say how the design will turn out, or even what the problem really is – how it will seem when, eventually, everyone’s intuitions become informed by the experience of having designed it. At the start one’s intuition is likely to be wrong, informed by what IS, but not by what is to be conjured into existence.”

John Chris Jones

Acknowledgement

I have long looked forward to writing this acknowledgement. Throughout the process of writing up, when the going was tough, I assured myself that this would be the easiest and most enjoyable part. Well, enjoyable it most certainly is – however, it is certainly not an easy task. I apologise to anyone that I may have missed.

First and foremost, I thank my supervisor, Professor Alex Duffy. "Supervisor," however, does not do justice to the role he has played in my journey up the mountain. In the beginning he was my climbing instructor, and has become the most motivational of climbing partners over the years. Throughout, he has been a wise sherpa, an excellent role model, and a trusted adviser. Under his supervision, not only have I gained confidence in my abilities as a researcher, but I have overcome my anxieties and fears to develop confidence in my capabilities as a human being. Thank you for helping me to conquer myself as well as the mountain. What I have learned from you goes far beyond the bounds of my PhD, and will stay with me all my life.

I am grateful to all of those in industry who so kindly provided me with their time and expertise during the evaluation phase of my research. In particular, thank you to Malcolm Robb and Caroline Voong at BAE Systems – I could not have completed this work without your assistance. Thanks also to Willi Galloway, Peter Worthington, Jim Strachan, and Ross Gallacher for their time, guidance, and patience during my time at the company. Thank you to all of those who participated in various interviews and workshops, who are too numerous to name but most greatly appreciated. I am also most grateful to the two Masters students who evaluated my work as part of their own research in industry. Lastly, thanks to Andrew Daw for several fruitful discussions. I must specifically thank you for your input regarding the notion of contaminants.

I thank the University of Strathclyde and EPSRC for providing the studentship that supported me financially throughout my PhD. I would also like to thank David Cunningham, Barrie Hunter, and my second supervisor Dr Ian Whitfield, for helping to keep me afloat in the final months with paid work. A huge thank you also goes to my parents – completing this journey would have been so difficult without your help.

Thanks to all the residents of the Leonardo suite, past and present, who have made my PhD more fun than it probably should have been! I cannot possibly begin to name you all, but I hope that you know who you are. I must also thank my partner Ben, who has endured many frustrated tantrums and lonely evenings and weekends over the course of the past three and a half years.

Finally, I would like to thank Dr Kepa Mendibil, who first suggested that I apply for a PhD studentship during a very confused period of my life. I would never have embarked upon this journey if it were not for your suggestion. Thank you for helping me to find my place in the world.

Abstract

Technical systems are critical drivers of economic consumption and production, and are generally accepted to be dependent on natural systems and processes throughout their life cycle. Accordingly, their sustainability is under increasing scrutiny. However, the basic constitution of sustainability of technical systems is unclear, and views on how sustainability can be assessed and improved are inconsistent. To address these issues, the research reported in this thesis developed two generic models of technical system sustainability: the Sustainability Cycle (S-Cycle), and the Sustainability Loop (S-Loop).

The general elements and relationships involved in sustainability were identified through an inductive literature investigation spanning nine sectors. Sustainability was found to constitute an ability, which is in turn an emergent property of a system and manifested to humans as behaviour that maintains something. Activities were identified as the means by which materials and energy are transformed in a system. From a sustainability perspective, the behaviour of system activities was observed to involve the production of intended output, waste, and intended resources from inputs of renewable and non-renewable resources. This behaviour is formalised in the S-Cycle model. Humans seeking improved sustainability were found to interpret the behaviour of system activities to produce knowledge, and take action on the basis of this knowledge to produce effects that alter activity behaviour. This process is formalised in the S-Loop model, which positions the S-Cycle model within the context of human knowledge and interpretations.

The validity, utility, and applicability of the S-Cycle model were evaluated through: two independent worked examples; three independent industrial case studies; two expert appraisal workshops with 27 practicing engineering designers; and an analytical study of 324 sustainability performance indicators (SPIs). Through these methods, the model was applied to ten distinct technical systems and expert opinions were elicited. All model elements and relationships were supported. One additional element/relationship was identified, leading to a refined model. The model was found to be artefact independent, supporting the identification of SPIs for different technical systems, and providing a consistent view on the behaviour of different sub-systems at various levels within a technical system. The S-Loop model received a degree of support through peer review and publication in the Journal of Environmental Management.

Lastly, the research and findings were critiqued, leading to the identification of advantages, disadvantages, and recommendations, and areas for future research.

Contents

List of appended papers

This thesis is partially based on three journal articles and one technical report, described below. These are referred to as Papers A – D throughout the thesis.

Paper A (Appendix 1)

Hay, L., Duffy, A., Whitfield, R. I., 2014. The Design Sustainability Matrix. Under revision for re-submission to the Journal of Engineering Design.

Paper B (Appendix 2)

Hay, L., Duffy, A., Whitfield, R. I., 2014. The S-Cycle Performance Matrix: A rational basis for selecting comprehensive sustainability performance indicators for technical systems. Under revision for submission to an engineering journal.

Paper C (Appendix 3)

Hay, L., Duffy, A., Whitfield, R. I., 2014. The Sustainability Cycle and Loop: Models for a more unified understanding of sustainability. Journal of Environmental Management. 133, 232-257.

Paper D (Appendix 4)

Hay, L., 2014. A model of the chilled water system and its sustainability. Technical report for BAE Systems Maritime, documenting an industrial study carried out with the company.

The work reported in each paper was conducted by the author of this thesis as an individual PhD student. In each case, co-authors provided the same level of general and editorial guidance as they provided for the PhD thesis as a whole.

Signed: Date: *1st June 2015*

List of figures

List of tables

Nomenclature

Abbreviation	Meaning
η	Efficiency
ε	Effectiveness
AHG method	Avoided Heat Generator method
AI	Accounting indicator
A-IR	Active intended resource
AR	Active resource
C	Contaminant input
CAD	Computer-aided design
CHP	Combined heat and power plant
CO	Carbon monoxide
CO2	Carbon dioxide
CS	Case study
CW	Chilled water
CWP	Chilled water plant
DfE	Design for environment
DfS	Design for sustainability
DSM	Design Sustainability Matrix
E	Model element
E^2	E^2 performance model
ECD	Environmentally conscious design
ED	Ecodesign
EEA	Embodied energy analysis
EI	Ecological indicator
ELCC	Environmental life cycle costing
ELECTRE	ELimination and Choice Expressing REality
EmA	Emergy analysis/accounting
EnA	Energy analysis
EPFI	Energetic and physical flow indicator
EROI	Energy return on investment
ExA	Exergy analysis
FMEA	Failure mode and effects analysis
G	Global scale
GER	Gross Energy Requirement
GHG	Greenhouse gas
HCFC	Hydrochlorofluorocarbon
hkW	Kilowatts of heat
HP	High pressure
HVAC	Heating, ventilation, and air conditioning
I	Issue
IA	Impact assessment
IDEF0	Integration Definition for Function Modelling
Im	Impact indicator
IO	Intended output
IR	Intended resource
ISO	International Organisation for Standardisation
IY	Intended yield
K	Knowledge contribution
kW	Kilowatt
L	Local scale
LCA	Life cycle assessment
LCC	Life cycle costing
LP	Low pressure

M	Design method
MCHP	Micro combined heat and power plant
Mechs.	IDEF0 mechanisms
MFA	Material flow analysis
MJ	Mega joules
NOx	Nitrous oxide
NR-AR	Non-renewable active resource
NR-PR	Non-renewable passive resource
NRR	Non-renewable resource
O	Objective
PILOT	Product Investigation , Learning, and Optimisation Tool
P-IR	Passive intended resource
PLC	Programmable logic centre
PM	Particulate matter
PMS	Platform Management System
PO	Phosphorous oxide
PR	Passive resource
PROMETHEE	Preference Ranking Organization METHod for Enrichment of Evaluations
PS	Pilot study participant
PW	Workshop participant
Q	Question
QFD	Quality function deployment
R	Regional scale
RS	Model relationship
RAILS	Readiness Assessment for Implementing DfE Strategies
R-AR	Renewable active resource
R-PR	Renewable passive resource
RR	Renewable resource
SCALES	Special skills, Creating change agents, Awareness, Learning together, Ethical responsibilities, Synergy and co-creating
SCAMPER	Substitute, Combine, Adapt, Modify, Put to another use, Eliminate, Reverse
S-CPIP	S-Cycle Performance Improvement Process
S-Cycle	Sustainability Cycle model
SD	Sustainable design
SDI	Sustainable development indicator
SI	Sustainability indicator
SLCA	Social life cycle assessment
S-Loop	Sustainability Loop model
SO	Sulphur oxide
SoI	System of interest
S-philosophy	Sustainability-oriented design philosophy
SPI	Sustainability performance indicator
SR	Sustainability reporting
SW	Sea water
T	Design tool
t	Time
TEx valve	Thermostatic expansion valve
TRIZ	Theory of Inventive Problem Solving
UNEP	United Nations Environment Programme
V	Conceptual viewpoint
WS	Workshop
W	Waste
WCED	World Commission on Environment and Development
WE	Worked example
WSD	Whole system design

1 Introduction

It is generally accepted that much of human activity within the Earth system is dependent upon the Earth's natural resource base (UNEP, 2012). The increasing scale of this activity has led to the emergence of sustainability as a significant area of research, driven by a growing consensus that societal consumption and production may be compromising the natural systems and processes that support it (Rockström et al., 2009; Chapman, 2011; UNEP, 2012). From an anthropocentric perspective, sustainability broadly refers to the ability of human activity to continue within the Earth system (Kajikawa et al., 2007; Voinov, 2007). The concept has been applied to a diverse range of activities and systems in different sectors, including: agricultural activities and farming systems (Tilman et al., 2002; Darnhofer et al., 2010); the harvest of biological entities such as fish and trees (Hahn and Knoke, 2010; Standal and Utne, 2011); business processes and organisations (Dyllick and Hockerts, 2002; Hahn and Figge, 2011); cities, regions, and nations (Campbell and Garmestani, 2012; Mori and Christodoulou, 2012; Eurostat, 2013); and the overarching process of socio-economic development (WCED, 1987; UNDP, 2011).

A key concept in sustainability research is that of *natural capital* (Costanza and Daly, 1992; Ekins, 2011). Natural capital refers to the natural systems and processes "from which the human economy takes its materials and energy (sources) and to which we throw those materials and energy when we are done with them (sinks)" (Meadows, 1998, p.x). Flows of materials and energy from natural capital stocks are transformed into goods and services by *manufactured capital*. According to Meadows (1998, p.43), examples of manufactured capital include "tools, machines, factories, smelters, electric generators, pumps, [and] trucks." In other words, what Hubka and Eder (1988) term *technical systems*: artificial systems designed and built by humans to meet the needs of society. Ubiquitous in different sectors, technical systems are critical drivers of economic consumption and production across society. However, there has been a growing realisation that throughout their life cycle, these systems may have a significant impact upon the natural systems and processes that support them (Stasinopoulos et al., 2009). Consequently, organisations are under increasing consumer and regulatory pressure to improve the sustainability of their technical systems and products (Park et al., 2005; Chapman, 2011).

In sustainability research, the technical system life cycle is typically considered to include the extraction/processing of raw materials, manufacturing, system operation, and disposal/recycling (Stasinopoulos et al., 2009; Ulgiati et al., 2011). Manufacturing may be considered to cover system design and development, as well as physical construction and distribution (Stasinopoulos et al., 2009). Engineering design has been positioned as a crucial activity with respect to achieving improvements in technical system sustainability (Park et al., 2005; Stasinopoulos et al., 2009; Spangenberg et al., 2010). For instance, Unger et al. (2008, p.14) remark that "[it] is assumed that about 80% of all environmental effects associated with a product are determined in the design phase of development." Accordingly, considerable research has been conducted on sustainability in an engineering design context. Significant effort has been spent on the development of new methods and tools, or the reorientation of existing ones, to support a range of design activities from a sustainability perspective (Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010). A plethora of design methods, tools, and metrics are now presented as conducive to sustainable engineering design, demonstrated by reviews of the literature presented by e.g. Bovea and Pérez-Belis (2012), Gagnon et al. (2012), and Pigosso et al. (2014). Overarching design methodologies and the structure of the design process *per se* have also been investigated from a sustainability perspective (e.g. Park et al., 2005; Waage, 2007; Gagnon et al., 2012).

Widespread investigation of sustainability by researchers working independently in different areas has resulted in a plethora of different sustainability definitions and interpretations, as well as multifarious objectives, goals, and indicators intended to facilitate the improvement and management of sustainability in practice (Kajikawa, 2008; Waage, 2007; Lindsey, 2011). From this perspective, improving the sustainability of human activities and systems has been framed as a "wicked problem"[1] by authors (Wahl and Baxter, 2008; Metcalf and Widener, 2011). It has been suggested that "the transition towards a sustainable human presence in the world is *the* wicked problem for design in the twenty-first century" (Wahl and Baxter, 2008, p.75). Buchanan (1992, p.16) highlights that for "every wicked problem there is always more than one possible explanation, with explanations depending on the *Weltanschauung* [worldview] of the designer." Worldviews may differ greatly between people, depending on aspects such as their personal background, culture, values, and expertise (Wiersum, 1995; Lele and Norgaard, 1996; Meadows, 1998). Differences in worldviews mean that people may have different interpretations of sustainability, which can make it difficult to work collectively towards sustainability goals (Meadows, 1998; Kajikawa, 2008).

[1] Wicked problems are defined by Churchman (1967, p.141) as "a class of social system problems which are ill-formulated, where the information is confusing, where there are many clients and decision makers with conflicting values, and where the ramifications of the whole system are thoroughly confusing."

For example, the engineering design process[2] is typically undertaken by a design team consisting of several designers (Pugh, 1991; Ulrich and Eppinger, 2008). Each designer may have different views of sustainability and its implications for the structure and behaviour of the technical artefact. Similarly, a manufacturing organisation typically has numerous stakeholders e.g. employees/managers, shareholders, customers, and suppliers. All of these groups and individuals may have different views regarding the sustainability of a manufacturing system, and how it can be assessed/improved.

To effectively manage and improve technical system sustainability, a common basis for interpreting and discussing the system is needed (Lindsey, 2011). This can aid in reconciling potentially conflicting or misaligned perceptions of sustainability held by different decision makers (Meadows, 1998). As shown above, considerable research has been conducted on technical system sustainability in an engineering design context. However, this has largely focused on the design process and methods/tools to support sustainable engineering design. Research focusing specifically on the sustainability of the design artefact, i.e. the technical system, is limited. In the literature, authors refer to complex sustainable systems and sustainability in engineered systems (Alfaris et al., 2010), sustainable design concepts (Chiu and Chu, 2012), sustainable design solutions (Charter and Tischner, 2001), and sustainable products (Mayyas et al., 2012a, b), without providing any clear exposition regarding their nature and constitution. Azkarate et al. (2011, p.165) conclude that "it is not clear in an operational way what sustainability means applied to different industries and products." A generic formalism describing the basic constitution of sustainability of technical systems could provide insights in this respect, as well as a common basis among decision makers attempting to manage and improve technical system sustainability.

1.1 Scope of the work

The research presented in this thesis focused on the sustainability of technical systems. Two generic models, describing the fundamental elements and relationships involved in sustainability in this context, are presented: the Sustainability Cycle (S-Cycle), and the Sustainability Loop (S-Loop). The models were developed through inductive literature research, and evaluated using several research methods to study their application to different technical systems (the

[2] The term "design" may be used to refer to both the *design artefact*, i.e. what is being designed, and the *design process*, i.e. the series of activities carried out by designers to design the artefact. In this thesis, "design" is used to refer to the design process, whilst the design artefact may be referred to as a technical artefact, a technical product, or a technical system.

research approach is elaborated in Chapter 2). The scope of the work is outlined below.

1.1.1 Technical system activities

Hubka and Eder (1988, p.28) describe society as a socio-technical transformation system. That is, a system comprised of both social and technical components, where inputs are transformed to outputs via activities. The system has relationships with ecosystems in terms of inputs of resources from natural stocks, and outputs of waste to natural sinks. Additionally, the environment within which a particular activity immediately operates exerts effects on the transformation (e.g. meteorological and geological effects). The key system components are considered to be “individual human beings, groups of humans recognized by common occupation or purpose, and artifacts and organizations within and around which these humans act.” Relationships in the system include “culture, economics and financing, politics, etc.” As such, any sub-transformation system within society may include “manufacturers, suppliers, distributors, planners, foremen, users, reporters for communications media, spectators, innocent victims, etc., as well as those systems that are primarily technical, such as cars, machine tools, printing presses, distribution equipment, etc.”

The scope of the research reported in this thesis focused on the sustainability of technical systems. That is, sustainability of the technical aspects of socio-technical transformation systems. As discussed previously, sustainability research is fundamentally concerned with society’s dependence on the Earth’s natural capital stocks, and the transformation of materials and energy from these stocks into goods and services for the economy. In the context of a socio-technical transformation system, these physical transformations are primarily achieved through activities carried out by technical systems (Blanchard and Fabrycky, 1981; Hubka and Eder, 1988; Stasinopoulos et al., 2009). Basic physical transformations are necessary for other transformations driving societal progress, e.g. the transformation of goods and services into higher ends such as living standards, wealth, wellbeing, and happiness through socio-economic and human development activities (Daly, 1992; Meadows, 1998; UNDP, 2011; UNEP, 2012). The sustainability of these kinds of transformations and activities did not form the focus of the modelling work reported herein. Nonetheless, to develop generic models, definitions and interpretations of sustainability in nine sectors were initially considered, namely: agriculture; business; design; economics; fisheries; forestry; socio-economic development; sustainability science; and urban studies. These sectors were selected for consideration on the basis of a citation analysis and an integrative review conducted by Kajikawa et al. (2007) and Kajikawa

(2008), respectively, in which they were identified as significant contributors to sustainability science and the general body of knowledge on sustainability in the Earth system.

As stated above, technical system activities transform materials and energy. In addition, they also transform information (Blanchard and Fabrycky, 1981; Hubka and Eder, 1988). Hubka and Eder (1988, p.30) state that typically, materials, energy, and information "occur in combination, and it is almost impossible to separate them, but one or other may be regarded as the principal operand [entity being transformed], and the others can usually be neglected." As discussed above, from a sustainability perspective, it is the transformation of materials and energy from resource stocks that is of fundamental concern. Thus, the scope of the research focused primarily on the material and energetic aspects of technical system behaviour. As elaborated in Chapter 3, considerable research has been conducted on the sustainability of socio-economic development in the Earth system, with technical systems constituting key drivers of the development process. Research in this area focuses primarily upon a triad of environmental, economic, and social objectives known as the three pillars (Dalal-Clayton and Bass, 2002; Kemp and Martens, 2007). Given the focus on materials and energy as stated above, the scope of the work covers the environmental pillar. That is, economic and social aspects of technical system behaviour are not considered.

1.1.2 Sustainability performance

Human beings, supported by information and management systems, direct the behaviour of technical systems towards desired outcomes through processes of "goal-setting and goal-realizing" (Hubka and Eder, 1988, p.28). In a sustainability context, the activity of sustainability performance evaluation provides a means for humans to interpret and reflect upon a technical system's behaviour from a sustainability perspective (Ulgiati et al., 2011). Owing to the scope of the work as discussed above, material and energetic aspects of technical system sustainability performance were considered during the research. Sustainability performance indicators (SPIs) applied to a range of technical systems by authors were analysed, and the behaviour and sustainability performance of technical systems in industry was modelled and assessed.

As discussed in the introduction to this chapter, technical systems are ubiquitous throughout society. Examples include:

- agricultural systems, e.g. tractors and combines (Hubka and Eder, 1988);

- energy conversion systems, e.g. wind turbines (Uddin and Kumar, 2014), heat pumps (Balta et al., 2010), and combined heat and power plants (Buonocore et al., 2012);
- fuel production systems, e.g. biorefineries (Ofori-Boateng and Lee, 2014) and oil refineries (Waheed et al., 2014);
- heating and cooling systems, e.g. air conditioning systems (Abdel-Salam and Simonson, 2014), boilers, and solar heaters (Balta et al., 2010);
- medical devices, e.g. X-ray apparatus and prostheses (Hubka and Eder, 1988); and
- transportation systems, e.g. railways, ships (Hubka and Eder, 1988), and aircraft (Aydin et al., 2013).

Owing to the time and resource constraints of PhD research, industrial work on technical system behaviour and sustainability performance focused on systems in two sectors: the energy sector, including a wind turbine and a transformer; and the marine (defence) sector, including various sub-systems of a warship. Both of these sectors are generally viewed as having significant challenges in terms of material and energetic sustainability performance. For example, the issue of fossil fuel dependence and associated CO2 emissions in the energy sector receives considerable attention in the literature (Evans et al., 2009). In the marine sector, legislation prohibiting the discharge of certain types of waste (e.g. waste water, residues from cargo, and cleaning chemicals) by ships at sea has recently come into force in response to ecological concerns (Holan Fenwick Willan, 2013). As such, these sectors were considered to provide an appropriate context for the research.

1.1.3 Technical system life cycle

Finally, as stated previously, the system life cycle is typically considered to include the extraction/processing of raw materials, manufacturing, system operation, and disposal/recycling. It is generally accepted that technical systems are dependent upon natural capital throughout their life cycle. Therefore, to obtain a complete view from a sustainability perspective, the behaviour and performance of technical systems should be considered throughout the life cycle (Ulgiati et al., 2011). Different portions of the life cycle were considered during different parts of the research reported in this thesis, as briefly discussed below.

To gain a comprehensive view on the behaviour and performance of technical systems from a sustainability perspective, a range of SPIs covering all life cycle phases were reviewed and analysed during the research. These were identified from the literature. The behaviour and performance of the energy and marine systems studied in industry (mentioned above) was modelled and assessed over timescales not exceeding the operation phase of the life cycle. This was due to both the time constraints of PhD research, and data limitations, as discussed in Chapter 9 (Section 9.1.1.3).

As highlighted previously, with respect to improving the sustainability of technical systems, design is considered to be a critical part of the manufacturing phase of the life cycle. Specifically, technical systems are developed through engineering design (Hubka, 1982; Eder, 2003), with sustainability-oriented engineering design focusing on the design of sustainable technical artefacts (discussed in Chapter 4). Engineering design involves defining and refining a technical system structure that will exhibit the behaviour required to fulfil a desired function (Tully, 1993; Gero and Kannengiesser, 2004; Wang et al., 2008). Accordingly, to gain insight into the function, behaviour, and structure of technical systems from a sustainability perspective, sustainability-oriented engineering design was examined during the review. Other types of design may be involved in the life cycle of a technical system, e.g. industrial design, focusing on aesthetics and form (Bhamra and Lofthouse, 2007), and graphic design, focusing on product packaging and branding (Lopes et al., 2012). Limited sources from an industrial design context were considered during the research, given that this design domain may be viewed as occupying a position "between art and engineering" (Bhamra and Lofthouse, 2007, p.3). However, these branches of design are not chiefly concerned with the function, behaviour, and structure of technical systems. As such, the primary focus was engineering design.

1.2 Aim and objectives

The research reported in this thesis was motivated by a lack of clarity regarding the basic constitution of sustainability, and the need for a common basis among decision makers wishing to manage the sustainability of technical systems. The aim of the research was *to develop a generic model of technical system sustainability*, to address the lack of a: (i) consistent view on sustainability improvement, (ii) common approach to identifying appropriate SPIs, and (iii) fundamental formalism of sustainability.

To achieve the research aim, a number of objectives were defined:

O1. Identify issues facing sustainability research in order to define the research focus, and to provide a means to evaluate the model.

- O1.1 Establish the current state of knowledge on sustainability in a societal context.
- O1.2 Establish the current state of knowledge on sustainability in a technical systems context.

O1.3 Identify shortcomings in the literature on sustainability of society and technical systems.

O2. Construct a generic model of technical system sustainability on the basis of the literature.

O2.1 Gather observations on sustainability from the literature on sustainability of society and technical systems.

O2.2 Make inferences regarding the fundamental elements involved in sustainability, and the relationships among them.

O3. Evaluate the validity, utility, and applicability of the model.

O3.1 Apply the model to technical systems in industry.

O3.2 Elicit the opinions of technical systems experts on the model.

O3.3 Refine the model on the basis of the evaluation findings.

O4. Critique the work in order to identify advantages, disadvantages, and areas for future research.

1.3 Thesis structure

The adopted research approach is presented in Chapter 2. A discussion on the nature of research approaches and research philosophy is provided, before the philosophy, methodology, and research design adopted are detailed. The remainder of the thesis is organised into three parts, focusing on the development, evaluation, and critique of the S-Cycle/S-Loop models. The contents of each part are outlined below. The relationships between the objectives presented in Section 1.2 and different elements of the thesis are highlighted.

Part 1: Model development (Chapters 3, 4, 5 and 6)

Chapters 3, 4, and 5 centre on identification of the research focus (O1). Chapter 3 presents the findings of a review of research on the sustainability of society spanning nine sectors (O1.1). The meaning, value, and constitution of sustainability are examined, and the activities through which sustainability is realised are considered. Chapter 4 presents the findings of a review of research on sustainability in a technical systems context (O1.2), focusing on the nature of technical systems, sustainability-oriented engineering design, and sustainability performance evaluation. In Chapter 5, the findings presented in Chapters 3 and 4 are discussed, leading to the identification of shortcomings in current knowledge on sustainability (O1.3). Three key issues to be addressed by the research, focusing on a consistent view of sustainability improvement, a common approach for SPI identification, and a fundamental formalism of sustainability, are defined on this basis along with the overarching research aim.

Chapter 6 presents the findings of inductive literature research conducted to build the S-Cycle/S-Loop models, based on the same sectors considered in the literature review in Chapter 3 (O2). Observations on three central concepts involved in sustainability are gathered from the literature (O2.1), namely systems, activities, and knowledge. The fundamental elements involved in sustainability, and their interrelationships, are then inferred from these observations to construct the models (O2.2).

Part 2: Model evaluation (Chapters 7 and 8)

Chapter 7 presents the approach adopted to evaluate the S-Cycle/S-Loop models (O3). Three aspects to be evaluated are identified based on the issues identified in Chapter 5, i.e. validity, utility, and applicability. Four research methods applied during evaluation are then outlined: (i) two worked examples based on technical systems described in the literature; (ii) three case studies focusing on systems in industry (O3.1); (iii) expert appraisal workshops with engineering designers in industry (O3.2); and (iv) an analytical study of performance indicators. Chapter 8 presents the findings of the evaluation, and a refined version of the S-Cycle model based on these findings (O3.3).

Part 3: Reflections (Chapters 9 and 10)

Chapter 9 provides a discussion on the work as a whole, highlighting advantages and disadvantages. Recommendations for future work are made on the basis of the disadvantages and the research findings generally (O4). Chapter 10 concludes the thesis with a summation of the research, the key findings, and the advantages and disadvantages.

2 Research approach

According to Kumar (2011), in order for a process of inquiry to qualify as research, it must be controlled, systematic, reliable and verifiable, empirical, and critical. In this respect, defining a suitable research approach may be viewed as a crucial activity for a researcher. Generally speaking, a research approach can be considered to address two key aspects: (i) the research methodology adopted to achieve the research aim and objectives, and the sources from which data will be collected; and (ii) the research design, i.e. how the research methods, techniques, data sources, and research outputs relate to one another within the research process (the structure of the research). A clearly defined approach serves as a plan for conducting the research, but also allows readers to determine whether the research meets the criteria discussed by Kumar (2011) above.

This chapter outlines the approach adopted in this research. In Section 2.1, different types of research approach discussed in the literature are considered. It is generally accepted that a researcher's methodological decisions should be informed by their research philosophy. That is, their assumptions regarding the nature of reality and knowledge. Accordingly, two research philosophies dominating much of scientific inquiry are discussed in Section 2.2, namely positivism and realism. The adopted research approach is elaborated in Section 2.3. A summary of the chapter is provided in Section 2.4.

2.1 Research approaches

Grinnell et al. (2010, p.8) suggest that the nature of research may be understood through consideration of the two syllables comprising the term. That is: *re*, meaning to repeat or perform again; and *search*, meaning to examine thoroughly and conscientiously (Oxford English Dictionary, 2014). The term *research* may therefore be considered to refer to "a careful and systematic study in some field of knowledge," that is typically undertaken to contribute new knowledge to the area in question (Grinnell et al., 2010, p.20). Research may be: *pure*, i.e. seeking to advance academic theory and research methodology; or *applied*, i.e. addressing practical issues through the application of existing knowledge and research methodology (Kumar, 2011; Easterby-Smith et al., 2012). Research may also be described as descriptive, explanatory, or exploratory in nature. Descriptive research seeks to systematically describe a phenomenon, whilst explanatory research focuses on establishing and explaining the nature of relationships between different aspects of a phenomenon. Exploratory research explores a poorly understood area or determines the feasibility of a larger-scale study. The research reported in this thesis involves both descriptive and explanatory elements. That is, modelling sustainability of technical systems involves both describing the elements involved in the phenomenon, and establishing the relationships among them.

Regardless of the type of research undertaken, the adoption of a suitable approach may be viewed as critical with respect to conducting a controlled and systematic research process that yields valid and verifiable findings. Creswell (2014, p.3) defines a research approach as "plans and the procedures for research." A central element of any research approach is the particular combination of research methods and techniques to be applied. This may be termed a *research methodology*. As discussed by Reich (1994, p.263), certain researchers "equate methodology with method." However, as Reich highlights, the term *methodology* more broadly refers to "the theory of methods." They suggest that specifically, research methodology may be described as "a collection of methods for doing research and their interpretations." Similarly, Easterby-Smith et al. (2012, p.xv) define research methodology as referring to "the way research techniques and methods are grouped together to form a coherent picture." Thus, a research methodology may be seen to encompass not only the individual methods and techniques that will be used, but also the manner in which they are interpreted and combined by the researcher.

The terms *method* and *technique* appear to be defined rather inconsistently in the literature. In this thesis, a research method is considered to represent an identifiable way of working during the research process, whilst a technique is viewed as a specific means of collecting, analysing, or interpreting data in the context of a particular research method (Reich, 1994; Saunders et al., 2009; Easterby-Smith et al., 2012; Creswell, 2014). For example, in this thesis, case study is considered to represent a research method, whilst unstructured interviews and document analysis are viewed as techniques. Furthermore, interview in a general sense is considered to be a method, whilst unstructured interviews are viewed as a specific technique associated with this method. However, it is acknowledged that different terminology may be applied by other authors. For example, Saunders et al. (2009) describe case study as a "research strategy" rather than a method.

Research approaches may be classified as *quantitative* or *qualitative*. According to Saunders et al. (2009) the term quantitative refers to data collection or analysis techniques that generate or use numerical data, and qualitative to those that generate or use non-numerical data. Quantitative research approaches are those that employ largely quantitative techniques, and vice versa, qualitative approaches involve largely qualitative techniques. Saunders et al. (2009) suggest that whilst certain approaches may be predominantly quantitative or qualitative, most involve both types of technique to some extent. Therefore, the distinction between quantitative and qualitative approaches should be viewed as a continuum rather than a dichotomy. What are commonly termed *mixed methods* approaches may be considered to occupy the central position along this continuum (Creswell, 2014). That is, approaches employing a combination of quantitative and qualitative techniques. In addition to mixed methods approaches, Saunders and Tosey (2012, pp.58-59) outline two further variations of quantitative and qualitative approaches, namely:

- *Mono method*, i.e. the use of "a single data collection technique and corresponding analysis procedure." The technique may be quantitative or qualitative in nature.
- *Multi method*, i.e. the use of multiple techniques. Again, these may be quantitative or qualitative in nature.

Mixed and multi method approaches are commonly associated with the concept of *triangulation*. Pioneered by Denzin (1970), triangulation generally refers to the use of multiple methods to study the same phenomenon. Triangulation may be interpreted in different ways in the literature (Shih, 1998). The kind of triangulation associated with the work of Denzin (1970) is *multiple triangulation*, which focuses on triangulating multiple aspects of research to improve validity and objectivity (Wang and Duffy, 2009), and increase the researcher's "depth and breadth of understanding" (Shih, 1998, p.633). The aspects typically triangulated are data sources, investigators, theories, and methods (Wang and Duffy, 2009).

The notion of methodological pluralism conveys that no single approach is innately advantageous over another. In this respect, authors suggest that researchers should adopt the type of approach that is most suitable for addressing their particular research problem (Knox, 2004; Payne, 2006). Saunders et al. (2009, p.58) highlight that all researchers have "[their] own personal view of what constitutes acceptable knowledge and the process by which this is developed," as well as "the nature of the realities encountered" during the research process. That is, their research philosophy. This philosophy impacts upon how the research problem is understood and consequently, the kind of approach that is adopted to address it. Accordingly, the literature on research philosophies is explored in Section 2.2.

2.2 Research philosophies

Saunders et al. (2009, p.128) state that the overarching term *research philosophy* "relates to the development of knowledge and the nature of that knowledge." In this thesis, the term *worldview* is adopted as the basis for discussing philosophical assumptions, and is applied in the same sense as Guba (1990): "a basic set of beliefs that guide action" (Guba 1990, cited in Creswell, 2014, p.6). Reich (1994) models worldview in terms of three perspectives, namely:

- *Ontological*, i.e. focusing on assumptions regarding the nature of reality (Saunders et al., 2009). Reich (1994, p.265) suggests that a central ontological question is, "Do we know things about the 'real' world, or is our knowledge a reflection of our manipulation of the world?"
- *Epistemological*, i.e. focusing on assumptions regarding how humans "come to know" (Horváth and Duhovnik, 2005, p.3), and beliefs regarding what constitutes acceptable knowledge (Saunders et al., 2009).
- *Methodological*, i.e. focusing on "the methods for creating knowledge about the world and the interpretation of this knowledge in light of the ontological and epistemological positions" (Reich, 1994, p.265).

Saunders et al. (2009, p.116) outline what may be viewed as a fourth perspective of a worldview: *axiological*, which pertains to a researcher's "judgements about value" during the research process. The worldview adopted in this thesis considers all four perspectives outlined above, as illustrated in Figure 2-1.

Reich (1994, p.264) argues that "research methodology is intimately connected with, and constrained by, the world view it serves." In this respect, a researcher's ontological, epistemological, axiological, and methodological perspectives should be coherent with respect to the manner in which the real world and knowledge are interpreted. This has lead authors in the literature to categorise different types of approach and method with respect to specific research philosophies (e.g. Easterby-Smith et al., 2012; Saunders and Tosey, 2012). However, Saunders and Tosey (2012, p.59) suggest that the methodological boundaries between philosophies "are often permeable." The key consideration is whether the adopted approach can produce findings that are valid in light of the researcher's philosophical worldview (Knox, 2004). From this viewpoint, Easterby-Smith et al. (2012, p.19) suggest that an understanding of research philosophy can "contribute to the creativity of the researcher," e.g. by highlighting alternative or innovative data collection strategies.

Broadly speaking, two branches of philosophy may be considered to encompass the range of world views regarding human inquiry, namely scientism and practicism (Reich, 1994). Scientism may be considered to include the philosophies of positivism and realism, whilst practicism can be viewed as encompassing philosophies such as interpretivism and pragmatism (Saunders et al., 2009; Creswell, 2014). A discussion of the full range of research philosophies is beyond the scope of this thesis. Rather, Reich's (1994) position that those philosophies falling into the category of scientism are most prominent in engineering research is adopted. Consequently, given the focus of this thesis on technical systems and engineering design, the philosophies of positivism and realism are explored in Sections 2.2.1 and 2.2.2 below.

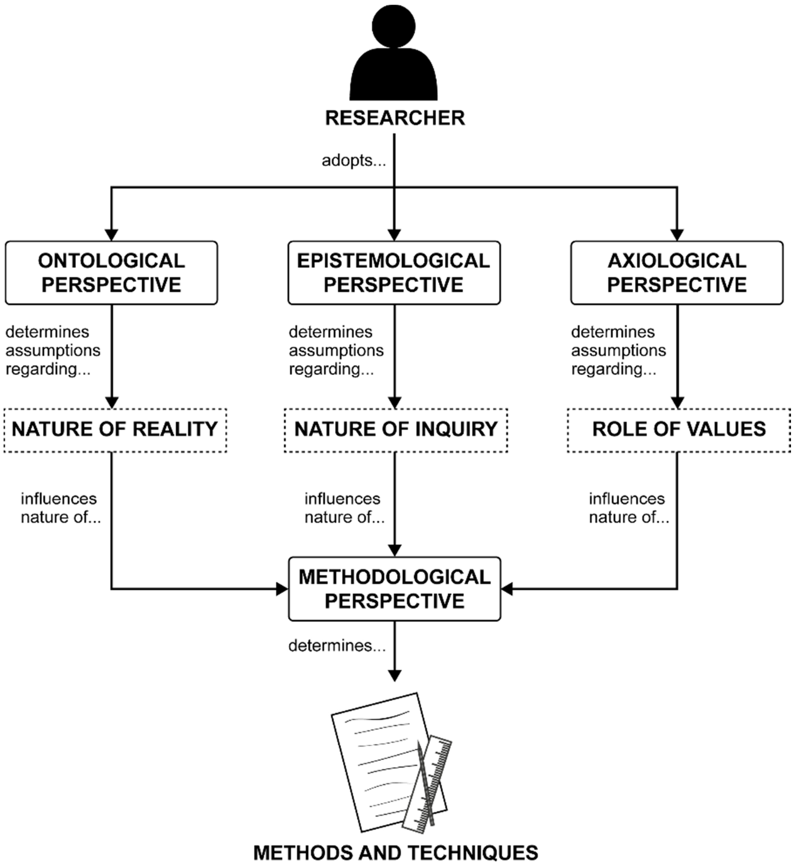


Figure 2-1: Model of worldview adopted in this thesis

2.2.1 Positivism

The philosophy of positivism is generally considered to have roots in the physical sciences (Kumar, 2011), and dominated much of scientific inquiry during the first half of the 20th century (Guba and Lincoln, 1994). Authors argue that in current philosophical thinking, a number of the assumptions held by positivism have been discredited (Reich, 1994; Trochim, 2006). However, the philosophy remains strongly associated with research in the physical sciences , and may also be applied in engineering research (Reich, 1994). Saunders et al. (2009) describe positivism as “the tradition of the natural scientist.” However, any researcher “concerned with observing and predicting outcomes” may be considered to reflect the philosophy of positivism. The ontological, epistemological, axiological, and methodological perspectives of positivism are outlined below.

Ontology

According to Saunders and Tosey (2012), positivists adopt the ontological position of objectivism. That is, they consider a reality to exist independent of social actors, and this reality can be observed in an objective manner. Furthermore, reality is viewed as deterministic, i.e. operates "according to cause-and-effect, free-context laws" (Reich, 1994, p.265).

Epistemology

Positivism asserts that science should only study those aspects of the world that we can be certain about, i.e. that we can observe, measure and independently verify (Easterby-Smith et al., 2012). Therefore, the study of subjective aspects such as a person's feelings or opinions about a particular situation, or the value and meanings attached to entities by humans, would not typically be of interest to positivists (Clark, 1998; Crossan, 2003; Saunders et al., 2009). In essence, positivists believe that humans cannot acquire knowledge of anything beyond what they can directly observe and measure (Trochim, 2006). It is assumed that objective knowledge about the real world can be acquired "through the employment of appropriate methodology" (Reich, 1994, p.265). Positivists are also typically reductionists – they believe that complex problems and situations may be better understood if broken down into smaller parts (Creswell, 2014).

Axiology

Saunders et al. (2009, p.114) suggest that a key characteristic of positivism is that "research is undertaken, as far as possible, in a value-free way." That is, the researcher remains independent of the data and takes an objective view. Saunders et al. question whether completely value-free research is achievable in practice, suggesting that both the decision to adopt a positivist stance, and the choice of research objectives and data to collect may entail value judgements.

Methodology

Positivism is often associated with quantitative approaches, employing methods such as experiments and surveys to study observable behaviour. A key characteristic of positivistic inquiry in this sense is that concepts must be operationalised in such a way that they can be measured. Typically, positivist approaches are empirical and largely deductive in their reasoning processes, i.e. they seek to explain causal relationships through the controlled testing of hypotheses derived from theory (Guba and Lincoln, 1994; Saunders et al., 2009). The emphasis is on "quantifiable observations that lend themselves to statistical analysis," and the positivist researcher is "likely to use a highly structured methodology in order to facilitate replication" (Saunders et al., 2009, p.104). Having said this, other authors argue that the use of certain qualitative techniques may also be valid within a positivist worldview (Knox, 2004; Kumar, 2011). Moreover, Knox (2004, p.120) suggests that whilst there is a tendency to associate the term "empirical" with quantitative data, it may be more generally interpreted as referring to "evidence drawn from concrete situations," which could be qualitative in nature.

2.2.2 Realism

The assumptions and assertions of positivism came under increasing scrutiny during the latter half of the 20th century (Guba and Lincoln, 1994). In particular, the philosophy has received considerable criticism in the social sciences where the focus of study is human behaviour and society (Kumar, 2011). Here, researchers argue that owing to its strongly objectivist ontology, reductionist outlook, and quest for generalisable mechanistic rules, positivism is not conducive to in depth investigation of humans and their behaviour (Clark, 1998; Crossan, 2003). These concerns have led to the emergence of alternative worldviews regarding the philosophy of science (Popper, 1959; Guba and Lincoln, 1994; Reich, 1994). Among these is *realism*, which is compared and contrasted with positivism by Saunders et al. (2009, p.114). The authors state that realism "is similar to positivism in that it assumes a scientific approach to the development of knowledge." However, there are fundamental differences in its ontological, epistemological, axiological, and methodological perspectives, which are outlined below.

Ontology

Like positivism, realism holds the ontological position of objectivism. However, the realists' stance in this respect is somewhat different to that of positivism. According to Saunders et al. (2009, p.114), realism considers there to be a reality that exists "quite independent of the human mind." Positivism assumes that this reality can be directly observed in an objective manner through measurement. In contrast, realism assumes that humans can only access reality indirectly through their senses (Saunders et al., 2009). Two forms of realism may then be distinguished on this basis: *direct realism*, and *critical realism*. The former asserts that "what you see is what you get: what we experience through our senses portrays the world accurately." The latter asserts that "what we experience are sensations," i.e. representations of things in the real world and "not the things directly" (Saunders et al., 2009, pp.114-115). For critical realists, reality "is interpreted through social conditioning" (Wahyuni, 2012, p.114). Drawing from the work of Bhaskar (1978), Easterby-Smith et al. (2012, p.29) highlight the notion of a structured ontology as a key feature of critical realism. Reality may be considered at three levels: (i) the empirical, comprising "the experiences and perceptions that people have;" (ii) the actual, comprising "events and actions that take place whether or not they are observed or detected;" and (iii) the real, comprising "causal powers and mechanisms that cannot be detected directly, but which have real consequences for people and society."

Epistemology

According to Saunders et al. (2009), direct realism and critical realism differ in their epistemological assertions. Direct realism argues that humans acquire knowledge of the world through sensing alone. In contrast, critical realism argues that humans come to know through the subjective processing of sensations. That is, humans sense a particular thing, and the resulting sensations are then processed within the mind via cognitive activities. Both direct and critical realists believe that knowledge is fallible – that is, subject to revision in light of new or updated observations (Guba and Lincoln, 1994). However, they differ in their justification for this belief. Direct realists claim that insufficient data may cause inaccuracies in human sensations, whilst critical realists claim that sensations are open to multiple interpretations, some of which may be faulty (Saunders et al., 2009). A final epistemological difference between direct and critical realism pertains to the context within which phenomena are studied. Direct realism typically considers the world to operate at a single "level" Easterby-Smith et al. (2012, p.29), e.g. a person, a group, *or* an organisation, and conducts inquiry accordingly (Saunders et al., 2009). Critical realism places importance on inquiry at multiple levels (e.g. a person, a group *and* an organisation). The belief is that different levels are composed of different sets of structures and processes that may alter the researcher's understanding of a particular phenomenon when observed (Saunders et al., 2009).

Axiology

Realism considers the researcher to be "biased by world views, cultural experiences and upbringing," all of which may have an impact on the research process and the findings produced. Consequently, realists view research as value-laden (Saunders et al., 2009, p.119). This may be contrasted with positivism, which argues that research is carried out in a value-free manner as discussed in Section 2.2.1.

Methodology

Methodologically, realism stipulates that methods may be quantitative and/or qualitative, as long as those selected fit the subject matter (Saunders and Tosey 2012). Realist approaches may employ deductive reasoning like positivist approaches, a combination of deduction and induction, or they may be largely inductive (Saunders et al., 2009). Induction moves from the particular to the general, e.g. the collection and analysis of detailed observations of a phenomenon to formulate a more general theory or model (Trochim, 2006). In particular, critical realism may be strongly associated with mixed and multi method approaches, and the notion of triangulation (Guba and Lincoln, 1994; Saunders et al., 2009; Wahyuni, 2012). This is largely due to the epistemological assertion that sensations are open to multiple and potentially faulty interpretations, and the axiological assumption that the researcher may be biased. The belief is that by triangulating methods, a researcher can gain multiple views on a phenomenon and potentially address faulty and biased interpretations, thereby providing greater confidence in the validity of the research findings (Shih, 1998; Creswell, 2014). It may also be argued that the stratified ontology of critical realism is suggestive of mixed and multi method approaches, because there is a need to inquire into the world at the level of both immediate experiences and the structures and processes that underpin these experiences (Saunders and Tosey, 2012).

2.3 Adopted research approach

Having discussed different types of research approach and the nature of research philosophy and methodology in Sections 2.1 and 2.2, the approach adopted in this research is elaborated in the following sub-sections. The adopted philosophy and methodology are outlined in Sections 2.3.1 and 2.3.2. Consideration has also been given to the means by which the research is disseminated, which are briefly discussed in Section 2.3.3. The overall research design is presented in Section 2.3.4.

2.3.1 Research philosophy

The aim of this thesis is *to develop a generic model of technical system sustainability*, to address the lack of a: (i) consistent view on sustainability improvement, (ii) common approach to identifying appropriate SPIs, and (iii) fundamental formalism of sustainability. This requires investigation of the nature of both sustainability and technical systems. Sustainability involves natural systems and processes that operate according to physical laws. As a concept, it may be interpreted in different ways by different people, resulting a variety of different meanings and definitions. Technical systems may also be considered to operate according to physical laws. They are the design artefact in the engineering design process and thus, are developed by humans in order to meet the needs of society. Therefore, it may be seen that modelling sustainability of technical systems entails investigation of both natural entities and social actors, and the relationships between the two.

On the basis of the above, critical realism is argued to be the most appropriate philosophy to guide the research. It adopts an objectivist ontology and scientific approach that are conducive to the study of natural processes and systems. Furthermore, its ontological, epistemological, axiological, and methodological perspectives are conducive to investigation of the subjective aspects of human beings. That is: the assumption that reality is multi-layered and subjectively interpreted; the recognition that research is inherently value-laden and that multiple interpretations are possible; and the assertion that the use of qualitative methods and inductive reasoning are valid research approaches. The worldview adopted in this research may therefore be summarised as:

- ***Ontology***: external and multi-layered. Reality exists independent of the human mind but is subjectively interpreted through social conditioning.
- ***Epistemology***: knowledge is acquired through sensing and cognitive processing, and is thus subject to multiple interpretations. Knowledge is fallible owing to the possibility of conflicting and faulty interpretations. Phenomena should be studied at multiple levels in order to be understood.
- ***Axiology:*** research is value-laden.
- ***Methodology***: the approach should fit the research problem. Mixed/multi method approaches and deductive/inductive processes are all acceptable. Research should be triangulated to address faulty interpretations and biases.

2.3.2 Research methodology

As discussed previously, the nature of the research problem is a fundamental consideration informing the choice of research methods from a critical realist perspective. In order to model sustainability of technical systems, it is necessary to identify the constituent elements of the phenomenon and the relationships between them. In this kind of study, where the researcher "does not know the important variables to examine," Creswell (2014, p.20) suggests that a qualitative approach, facilitating in depth examination of the phenomenon, is particularly suitable. Accordingly, the majority of the methods adopted are qualitative in nature. In accordance with the worldview of critical realism, the research methodology is multi method and triangulated to address potential misinterpretations and bias in the research process. The methodology is aligned with Denzin's (1970) notion of multiple triangulation. As mentioned in Section 2.1, multiple triangulation prescribes that research should be triangulated in terms of data sources, investigators, theories, and methods. All four aspects were triangulated in this research, as discussed further below. In order to achieve the research aim, a number of questions need to be addressed:

Q1. What prior research has been conducted on the phenomenon by other authors?
Q2. What kind of data is needed to model sustainability of technical systems?
Q3. Through what process should the model be developed?
Q4. How should the model be evaluated after it has been developed?

As a means to elaborate the adopted research methodology, the answers to these questions are discussed in the following paragraphs.

With respect to Q1, a literature review was conducted to identify the state-of-the-art in research on sustainability in both a societal context (Chapter 3) and a technical systems context (Chapter 4). This yielded knowledge of the area and the salient issues facing research. On the basis of this knowledge, the research problem was formulated, and the aim and objectives defined.

Regarding Q2, Wang and Duffy (2009, p.2) state that *data triangulation* "refers to the need to retrieve data from a number of different sources with similar foci for the purpose of validation." In this research, data were collected from:

- samples of the literature on sustainability of society and technical systems;
- technical documentation describing three technical systems designed by the companies Babcock and BAE Systems[3];
- engineering designers from BAE Systems and Company A; and
- a sample of performance indicators applied to assess the sustainability performance of technical systems by other authors.

The data collected were non-numerical, i.e. qualitative in nature. It should become apparent in the paragraphs below that the data generated by techniques applied in the research were also largely qualitative. However, numerical (i.e. quantitative) data were also generated to a limited extent.

With respect to Q3, Sim (2000, p.17) states that models do not fully represent reality, but are rather "abstract organisational ideas derived from inferences based on observations." Thus, model building may be viewed as a largely inductive process, where general elements and relationships are inferred from detailed observations of a phenomenon. In this research, detailed observations regarding the fundamental constitution of sustainability were made through a literature investigation, elaborated in Chapter 6. The S-Cycle and S-Loop models were then developed by inferring the general elements and relationships involved in sustainability from the findings of the investigation.

[3] Three companies were involved in the research, as discussed further in Chapter 7: BAE Systems Maritime and Babcock Marine, both specialising the the design and manufacture of warships; and Company A, who cannot be named for confidentiality reasons.

Regarding Q4, evaluation in this research focused primarily on the S-Cycle model owing to the time constraints of PhD research. The evaluation considered three aspects of the model, namely its validity, utility, and applicability (Chapters 7 and 8). These are aligned with three issues for sustainability research identified through the initial literature review (discussed in Chapter 5). To evaluate the model, the following process was undertaken:

- Two worked examples, where the model was applied to two systems described in the literature, were developed independently by different researchers.
- A guideline detailing a process for applying the model to technical systems was developed on the basis of the literature on performance measurement (the S-Cycle guideline). The guideline was then used to apply the model to three sub-systems of a warship in three separate case studies. These studies were carried out largely independently by three researchers. During the studies, two techniques were used to gather data: unstructured interviews with engineering designers, and analysis of documentation specifying and describing the systems under study. Additionally, the IDEF0 modelling language was applied to develop a function model of one of the systems studied using data gathered through the above techniques.
- The opinions of engineering designers, considered here as technical systems experts, were sought through two interactive workshops. Participants undertook a practical exercise where they were asked to apply the model to a technical system of their choosing using a predefined template. Following this, they indicated their opinions on the model through a self-report questionnaire consisting of Likert ratings and open responses. The workshops were preceded by a pilot study involving three engineering design researchers.
- An analytical study of 304 performance indicators applied to assess the sustainability performance of technical systems by other authors was conducted. The S-Cycle was applied to define a set of generic sustainability performance indicators for technical systems, and the reported indicators were then classified with respect to these.
- The collective findings yielded by the above methods were interpreted, resulting in a refined version of the model including an additional element and relationship that were not identified through the inductive model building process.
- Finally, overall conclusions regarding the model's validity, utility, and applicability were drawn from the findings.

The process may be viewed as deductive, in the sense that conclusions about the model were drawn from detailed observations gathered during its application to different systems in different contexts.
According to Wang and Duffy (2009, p.2), investigator, theory, and methodological triangulation may be described as follows:

- *Investigator triangulation*: where several investigators carry out observations of the same problem in an attempt to maintain objectivity and avoid bias.
- *Theory triangulation*: entails "the use of multiple perspectives to interpret a single set of data, or provide alternative explanations for the same phenomenon."
- *Methodological triangulation*: refers to the use of multiple methods as discussed above. Triangulation in this aspect may be "within-method," where the same method is used to study the same phenomenon on different occasions, or "between-method," where different methods are applied to study the same phenomenon.

It may be seen from the above discussion on the adopted research methodology that investigator triangulation was achieved through the involvement of three researchers to conduct the case studies. Theory was triangulated in the sense that an inductive process was undertaken to build the S-Cycle model, and a deductive process to evaluate it. Finally, both types of methodological triangulation were achieved: within-method triangulation was achieved through the two independent worked examples and three independent case studies; and between-method triangulation resulted from the application of five different research methods, namely an inductive literature investigation, worked examples, case study, expert appraisal through interactive workshops, and an analytical study of performance indicators.

2.3.3 Dissemination

The means by which findings will be disseminated may be viewed as an important consideration for two major reasons. Firstly, research publications are the means by which research is peer reviewed. That is, critically examined by experts within the wider research community. Peer review serves to maintain the quality and originality of research and in turn, the integrity of the knowledge production process (Blessing and Chakrabarti, 2009). Secondly, dissemination is the key mechanism by which the body of scientific knowledge is expanded. As stated by Griffiths (cited in Blessing and Chakrabarti, 2009, p.215), scientific research "is a communal achievement, for in learning something new the discoverer both draws on and contributes to the body of knowledge held in common by all scientists." On this basis, it may be concluded that the dissemination of research is fundamentally necessary for the advancement of scientific knowledge.

Different modes of research dissemination, and the process of writing up research, are given considerable attention in the Design Research Methodology (DRM) outlined by Blessing and Chakrabarti (2009). Three types of formal publication are employed to disseminate the findings of the research reported in this thesis:

- *Journal article*, i.e. a paper published in a journal. Given the importance of peer review and dissemination to the wider research community, the findings from three parts of the research are reported in journal articles that are included as appendices to this thesis: (i) the literature review on sustainability-oriented engineering design (Paper A, Appendix 1, relating to Section 4.2 of Chapter 4); (ii) the inductive research conducted to build the S-Cycle/S-Loop models (Paper C, Appendix 3, relating to Chapter 6); and (iii) the analytical study of performance indicators (Paper B, Appendix 2, relating to Section 7.3 of Chapter 7 and Section 8.2.3.2 of Chapter 8). Paper C is published in the Journal of Environmental Management. Paper A is under revision for re-submission to the Journal of Engineering Design, and Paper B is to be submitted to an appropriate engineering journal.
- *Technical report*, i.e. a paper intended for dissemination to engineering designers in industry. The findings of the case study conducted with BAE Systems are disseminated in a technical report (Paper D) that is included in Appendix 4 and primarily relates to Section 7.1.3.2 of Chapter 7.
- *Thesis*, i.e. a "detailed account of a piece of research undertaken for the purpose of obtaining a research degree," namely a Masters or a PhD (Blessing and Chakrabarti, 2009, p.216). That is, this document.

In addition to the publications outlined above, the S-Cycle and S-Loop models were disseminated to academics and industrialists in a poster presentation session at the 8th Annual Scottish Environmental and Clean Technology Conference, held on 26th June 2014 in Glasgow, United Kingdom.

2.3.4 Research design

Having outlined the adopted research approach and the modes of research dissemination in Sections 2.3.1 – 2.3.3, the research design is presented in Figure 2-2. That is, the overall structure of the research. As discussed in Section 2.3.2, the approach is largely qualitative, multi method, and triangulated in terms of data sources, investigators, theories, and methods.

It may be seen in Figure 2-2 that the research can be broken down into seven phases that correspond with chapters in this thesis:

1. **Literature review.**
   The state-of-the-art in sustainability research was mapped by reviewing two bodies of literature, i.e. research on the sustainability of society (Chapter 3), and the sustainability of technical systems (Chapter 4).

2. **Identification of research problem.**
   The findings from the literature reviews were considered as a whole, leading to the identification of three salient issues to be addressed by the research (Chapter 5).

3. **Definition of aim and objectives.**
   On the basis of the issues identified in phase 2, the research aim and objectives were defined (Chapter 1).

4. **Model building.**
   Observations regarding the constitution of sustainability were gathered through an inductive literature investigation. The S-Cycle and S-Loop models were then developed by inferring general elements and relationships involved in sustainability from the findings (Chapter 6).

5. **Model evaluation.**
   The validity, utility, and applicability of the S-Cycle model were evaluated through a deductive process involving several methods and techniques: worked examples developed independently by two researchers; case studies conducted independently by three researchers; expert appraisal through a workshop-based practical exercise and questionnaire; and an analytical study of performance indicators (Chapters 7 and 8).

6. **Reflection and refinement.**
   The evaluation findings were analysed leading to refinement of the S-Cycle model (Chapter 8). General conclusions were drawn regarding the validity, utility, and applicability of the model, and the advantages and disadvantages of the work were considered. On this basis, future work was recommended (Chapter 9).

7. **Consolidation.**
   Research findings were documented and disseminated via both formal publications and informal media (e.g. notebooks, logbooks, and internal

reports for supervisors) throughout the research process. The final phase in the research process focused on consolidating these pieces of writing to produce the thesis.

2.4 Summary

This chapter has outlined the approach adopted in this research. In Sections 2.1 and 2.2, different types of research approach and philosophy were explored as a basis for discussing the adopted approach in Section 2.3.

Owing to the focus of the research on sustainability, which involves natural and social entities and the interactions between them, the philosophy of critical realism was adopted to guide the research (Section 2.3.1). In accordance with the epistemological and methodological perspectives of critical realism, the adopted methodology is multi method and triangulated to address faulty interpretations and bias in the research process (Section 2.3.2). Multiple triangulation was achieved, i.e. with respect to data sources, investigators, theories, and methods. To achieve the research aim, it is necessary to identify the general elements and relationships involved in sustainability of technical systems. To facilitate in depth investigation in this respect, five largely qualitative methods were applied: literature review; worked examples; case study; expert appraisal through a workshop-based exercise; and an analytical study of performance indicators. The research is disseminated via three journal articles, a technical report, and this thesis (Section 2.3.3). Finally, the research design presented in Section 2.3.4 shows that the research process may be broken down into seven phases, ranging from the initial literature reviews to consolidation of the work to produce the thesis.

In the next two chapters, the findings of the literature reviews on sustainability of society (Chapter 3) and technical systems (Chapter 4) are presented, before the research aim is delineated in Chapter 5.

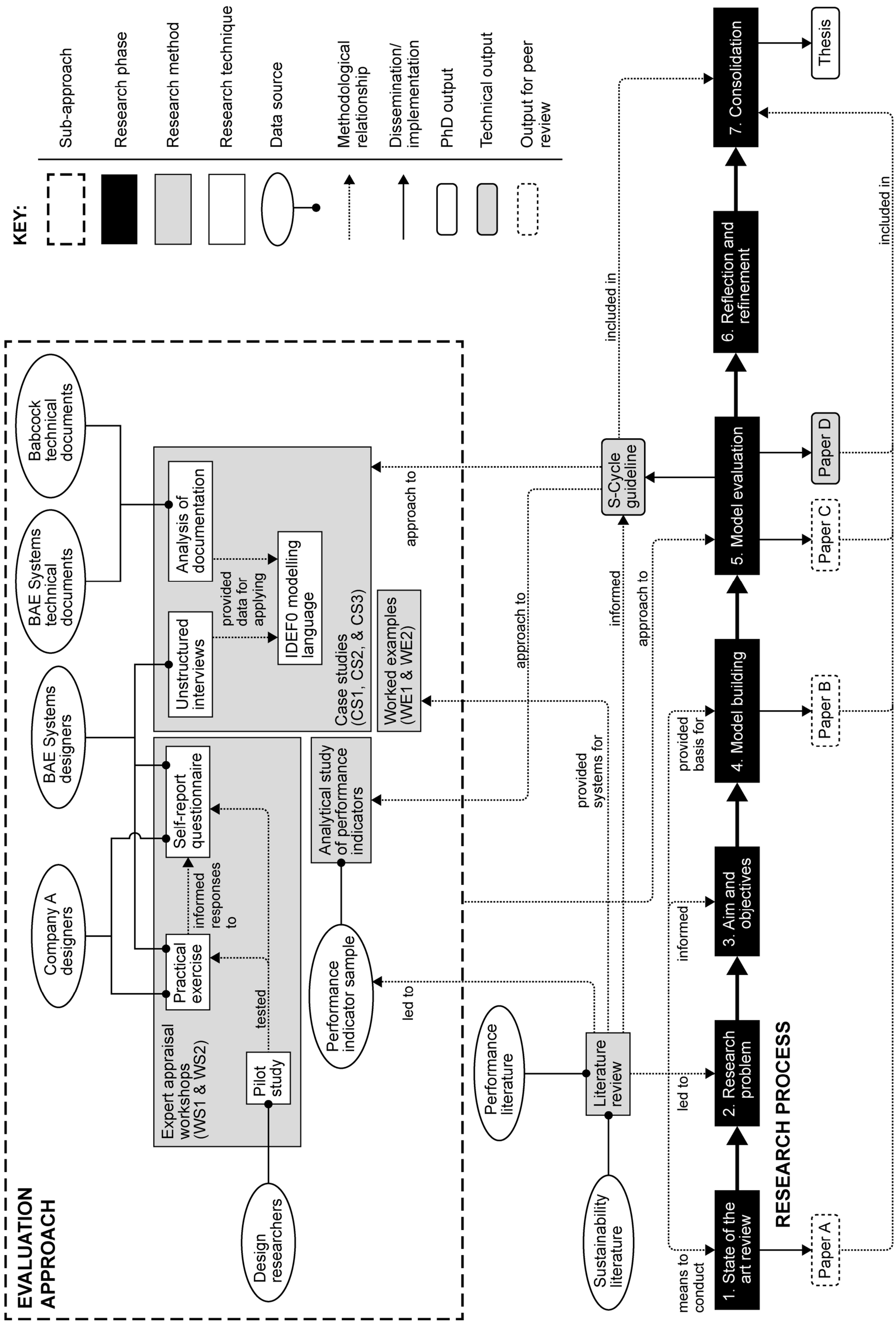


Figure 2-2: Research design

Figure 2-2: Research design

Part 1: Model development

3 A review of research on the sustainability of society

The roots of the sustainability concept can be traced back to the eighteenth century, where the "Nachhaltigkeitsprinzip" (sustainability principle) was defined in the German forestry literature as a basis for forestry management (Wiersum, 1995, p.322). In recent decades, sustainability has emerged as a central aim for society, owing largely to the mounting evidence suggesting that human activity in the Earth system is following an unsustainable trajectory. In 1987, the World Commission on Environment and Development (WCED), led by Gro Harlem Brundtland, applied the sustainability concept to the socio-economic development process in the seminal work, *Our Common Future* (WCED, 1987). Since then, research on sustainability has proliferated across numerous sectors of society and the economy, resulting in hundreds of different interpretations and definitions of the concept (Kidd, 1992; Vos, 2007; Kajikawa, 2008).

The expanding scope of sustainability research is mirrored by the expanding size of the literature that documents it. For example, a search for titles containing 'sustainab*' through the Web of Science service (Web of Science, 2014) between 1900 and 1986 returns 197 records. In contrast, conducting the same search between 1987 and 2014 returns just under 50,000 results. However, within this considerable body of literature, there is a lack of integrative research focusing on the fundamental constitution of sustainability (Hannon and Callaghan, 2011; Turner et al., 2003). That is, research outlining the basic aspects that characterise sustainability in any context. Knowledge in this respect can in turn provide a solid basis for understanding the specific characteristics of sustainability in individual contexts.

This chapter presents a review of sustainability research spanning nine sectors, providing an overview of the state of the art and identifying the elements that are common to all contexts. The following sectors were considered:

- agriculture (e.g. Conway, 1986; Hansen, 1996; Tilman et al., 2002; Pretty, 2008; Walter and Stützel, 2009; Darnhofer et al., 2010);
- business (e.g. Dyllick and Hockerts, 2002; Hart and Milstein, 2003; Figge and Hahn, 2005; Rainey, 2006; Lo, 2010; Hahn and Figge, 2011);
- design (e.g. Wahl and Baxter, 2008; Chapman, 2011; Gagnon et al., 2012);
- economics (e.g. Daly, 1990a,b; Daly, 1992; Costanza and Daly, 1992; Solow, 1993; Odum, 1994; Brown and Ulgiati, 1997; Ekins et al., 2003; Neumayer, 2003; Baumgärtner and Quaas, 2010; Derissen et al., 2011; Heal, 2012);

- fisheries (e.g. Larkin, 1977; Gaichas, 2008; Standal and Utne, 2011; Norse et al., 2012);
- forestry (e.g. Noss, 1993; Wiersum, 1995; Pearce et al., 2003; Hahn and Knoke, 2010);
- socio-economic development (e.g. Brown et al., 1987; WCED, 1987; Shearman, 1990; Lele and Norgaard, 1996; Jamieson, 1998; Wackernagel and Yount, 1998; Holling, 2001; Vos, 2007; Dawson et al., 2010; Vucetich and Nelson, 2010; Burger and Christen, 2011; Rametsteiner et al., 2011; UNDP, 2011; Bodini, 2012; Eurostat, 2013);
- sustainability science (e.g. Kajikawa 2008; Quental et al. 2010; Spangenberg 2011); and
- urban studies (e.g. Maclaren, 1996; Marcuse, 1998; Dempsey et al., 2011).

As discussed in Chapter 1, the sectors were selected on the basis of a citation analysis and an integrative review conducted by Kajikawa et al. (2007) and Kajikawa et al. (2008), respectively. Kajikawa et al. provide a sector-based view on sustainability research, identifying the sectors making the most significant contributions to sustainability science and knowledge through an analysis of the citation network underlying the literature. Integrative reviews providing an idea-historical view on sustainability research may also be identified in the literature, e.g. Kidd (1992) and Quental et al. (2010). However, these were not considered to provide a suitable basis for delimiting the literature review. As discussed in depth in Chapter 4, technical systems are ubiquitous throughout different sectors of society, from agriculture and forestry to business and design. Thus, it is argued that a sector-based review of sustainability research provides a more appropriate foundation for investigating sustainability of technical systems than an idea-historical view.

Sections 3.1 to 3.3 report the findings of an analysis of 60 sources from the above body of literature. The literature sample is presented in Table A5- 1 in Appendix 5A. Definitions and explanations of sustainability provided by authors were analysed, leading to the identification of three different viewpoints on the sustainability concept. These are: (i) lexical definitions of sustainability (Section 3.1.1); (ii) sustainability objectives, encapsulating what is to be sustained and for how long (Section 3.1.2); and (iii) interpretations of the basic constitution of sustainability (Section 3.2). Section 3.3 presents an overview of different types of sustainability emerging from the literature, highlighting different perspectives adopted by authors in relation to each of the viewpoints outlined in Sections 3.1 and 3.2. Sustainable development is positioned as among the most prolific types of sustainability discussed in the literature, and it is shown that sustainability may be considered from either an anthropocentric or non-anthropocentric standpoint.

Sections 3.4 and 3.5 present a review of research on the realisation of sustainability, i.e. how it is achieved and assessed. In Section 3.4, the sustainability goals typically used as a means to influence human activities and systems towards sustainability are reviewed. Following on from this, in Section 3.5 the assessment approaches typically applied to obtain information on the sustainability of entities are outlined. Finally, Section 3.6 provides a summary of the key points covered.

Note that certain sections in this chapter draw from Paper C (Appendix 3). Sections 3.1 and 3.2 are an expansion on points discussed in Section 2 of the paper, whilst Sections 3.4 and 3.5 draw from material covered in Section 5.

3.1 The meaning and value of sustainability

Authors highlight the position held by sustainability researchers at the confluence of the physical and social sciences (Lele and Norgaard, 1996) and more fundamentally, at the divide between science and politics (Rametsteiner et al., 2011). As such, it may be seen that the concept of sustainability occupies something of a conflicted (but also potentially unifying (Quental et al., 2010)) position within the overall research landscape. Accordingly, hundreds of different definitions of sustainability (Vos, 2007) may be identified in the literature, originating from different sectors and contexts. Before these specific definitions are considered in Section 3.3, lexical definitions are outlined here (Section 3.1.1). In turn, it is shown how more specific definitions may be formulated by specifying sustainability objectives, which are ultimately selected on the basis of what people value (Section 3.1.2).

3.1.1 Lexical definitions of sustainability

The term sustainability may be etymologically derived from the Latin verb "sustenere," meaning "to uphold" (Rametsteiner et al., 2011). Kajikawa (2008, p. 218) notes that in the most literal sense, sustainability means "the ability to sustain." Authors seeking a deeper understanding of the meaning of sustainability have undertaken lexical examinations of the word, often drawing from dictionary entries. Note that in the following paragraphs, the term "meaning" is employed in reference to the "sense or signification of a word" (Oxford English Dictionary, 2014).

Lele and Norgaard (1996, p. 355) argue that sustainability means "the ability to maintain something undiminished over some time period." This view is supported by Marcuse (1998, p. 106), who writes that sustainability typically means "the preservation of the status quo" – that is, by inference, the ability to maintain a particular situation. Shearman (1990, p. 3) argues that the lexical meaning of sustainability is clear, writing that the word "has been consistently used, either explicitly or implicitly, to mean "a continuity through time,"" pointing to the meaning of sustainability as the ability to continue. This view may be seen to be supported by Dempsey et al. (2011, p. 293) who write, in the context of urban studies, that the sustainability of a community is about "the ability of society itself, or its manifestation as local community" to "reproduce itself at an acceptable level of functioning." Given that "reproduce" may be interpreted as meaning "To effect or bring about [...] again" (Oxford English Dictionary, 2014), the statement by Dempsey et al. (2011) may be seen to suggest the meaning of sustainability as the ability to continue. In other words, the ability to bring about some circumstance again.

From certain perspectives, sustainability is discussed in terms of both continuity and maintenance. For example, Chapman (2011, p. 173) writes that in order for a system to be sustainable "it must possess the ability to be maintained indefinitely and must be capable of continuation *ad infinitum*." Voinov (2007, p. 489) highlights that all definitions of sustainability, regardless of their lexical form or contextual focus, "talk about maintenance, sustenance, continuity of a certain resource, system, condition, relationship," supporting the ideas that sustainability literally means the ability to sustain, and may be interpreted as meaning the ability to maintain something or the ability to continue.

It may be seen from the above that four lexical definitions of sustainability can be identified in the literature: (i) the ability to sustain; (ii) the ability to continue; (iii) the ability to maintain something; and (iv) the ability to be maintained by something. Shearman (1990) distinguishes between the *lexical* meaning of sustainability, and the *implicative* meaning of the term. They suggest that it is not the lexical meaning of sustainability that should be disputed, but rather the *implicative* meaning that arises from the term when it is used in different contexts. As such, it may be concluded that fundamentally, sustainability can be defined as the ability to sustain, the ability to continue, the ability to maintain something, or the ability to be maintained by something regardless of context.

3.1.2 Determining the value of sustainability

The lexical definitions of sustainability identified in Section 3.1.1 are general – they make reference to sustaining/maintaining/continuing *something*, without indicating what that "thing" is or how long it is to be sustained for. It may be seen that in order to move from these abstract definitions of sustainability to a more concrete one, humans must decide what is to be sustained, and for how long (Lele and Norgaard, 1996; Solow, 1993; Vos, 2007). In other words, they must specify their sustainability objectives (Gasparatos et al., 2008; Kajikawa, 2008). At the highest level, and from an anthropocentric perspective (discussed further in Section 3.3.4), sustaining human society indefinitely may be viewed as the ultimate sustainability objective (Komiyama and Takeuchi, 2006; Voinov, 2007; Beddoe et al., 2009). However, precisely what kind of society is a matter for considerable debate (Parris and Kates, 2003; Kajikawa, 2008). Lele and Norgaard (1996) argue that in deciding what specific aspects to sustain, humans must make value judgements. In other words, as humans, what we choose to sustain over time depends upon what we value (Chapman, 2011; Lindsey, 2011; Liu et al., 2010). In turn, humans determine the value of entities by interpreting them, as discussed below. Note that the term “entity” is employed in a broad sense throughout the following discussion, referring to both tangible (e.g. physical resources and systems) and intangible objects (e.g. functions and properties) (Reber, 2011).

According to Reber (2011, pp.95-96), value is subject to (i) situatedness, and (ii) interpretation. Situatedness refers to the idea that “every human thought and action is adapted to the environment where it is situated, because what people perceive, how they conceive their activity, and what they physically do all develop together.” Interpretation in this context refers to the notion that the value of an entity is determined by a human on the basis of the “entity’s interpretation.” That is, in order for a human to determine the value of an entity, they must interpret that entity. Gero and Kannengiesser (2004, p.378) suggest that interpretation occurs through the “interaction of sensation, perception and conception processes” in humans. Overall, therefore, it may be seen that the determination of an entity’s value made by a human depends largely upon (i) the situation in which that human resides, and (ii) their interpretation of the entity in question.

In order to illustrate the influence of value on the specification of sustainability objectives, let us consider the lexical definition of sustainability as the ability to maintain something, in the specific context of economics. It may be seen that value judgements require to be made on what to maintain. For example, do we wish to maintain the process of economic growth, or the present size of the economy (Daly, 1990a)? An economist working under the Neoclassical paradigm may value the former option, given the paradigm’s focus on growth as a necessary goal of economic activity (Beder, 2011). Conversely, an ecological economist may determine the latter option to hold more value given the emergence of the “steady state economy” as a key concept in ecological economics (Daly, 1992). From the perspective of a citizen, perhaps it is suggested instead to maintain current living standards (Heal, 2012), or a steady increase in wellbeing over time (Eurostat, 2011a). A wealthy citizen may value the former option, given the security of their own current situation. In contrast, a citizen experiencing poverty may determine the latter option to hold more value, given the shortcomings in their own current situation. It may be seen that further value judgements must be made regarding the length of time over which we wish to sustain something. For example, if we choose to maintain current living standards, do we maintain them for fifty years, five hundred years, or indefinitely? Answers to such a question may be seen to be at least partially dependent upon the value that present humans determine the lives of future humans to have relative to their own (Costanza and Daly, 1992; Marks, 2011).

Given that value is subject to situatedness and interpretation, the specific nature of the sustainability objectives specified in a particular context depends largely upon the decision makers involved. As such, it would be beyond the scope of this thesis to explicitly highlight the full range of sustainability objectives described in the literature. However, an overview of the entities commonly forming the foci of such objectives is provided below:

- *a state or situation*, such as: a certain stage in a system's life pattern (Voinov, 2007), a desirable state or set of conditions (Maclaren, 1996), and the health of ecosystems (Vucetich and Nelson, 2010) and people (Walter and Stützel, 2009);
- *an action, activity, or process*, such as: all human and business activities (Rainey, 2006), nutrient cycles (Noss, 1993), the act of fulfilling needs for fish (Standal and Utne, 2011), the act of meeting stakeholder needs (Dyllick and Hockerts, 2002), the process of improving human well-being (Eurostat, 2013), and the production of timber (Pearce et al., 2003);
- *functions*, such as: environmental functions (Ekins et al., 2003), the functioning of ecosystems (Brown et al. 1987; Gagnon et al. 2012), and the functioning of social systems (Gagnon et al. 2012);
- *organisms and species*, such as: human beings and the human species (Brown et al., 1987), and fish populations (Gaichas, 2008);
- *outcomes of social/economic activities*, such as: a civilization (Vos, 2007), a lifestyle (Heal, 2012), agrarian culture (Hansen, 1996), current living standards (Heal, 2012), quality of life (Brown et al., 1987), subjectively perceived well-being (Wackernagel and Yount, 1998), the value of natural and financial capital (Vos, 2007), and utility (Daly, 1990a);
- *performance metrics*, such as: level of capital use (Figge and Hahn, 2005), level of yield or catch (Pearce et al., 2003; Gaichas, 2008), system quality (Bell and Morse, 2008), and the productivity of an agricultural system (Conway, 1986);

- *properties/attributes of a system*, such as: a socio-ecological system's characteristic diversity of functional groups, processes, services, and utility (Dawson et al., 2010), adaptive capability (Holling, 2001), ecological infrastructure (Wiersum, 1995), ecosystem food webs (Noss, 1993), the abundance and diversity of species in an ecosystem (Gatto, 1995), and the capacity to produce economic well-being (Solow, 1993);
- *resources*, such as: a firm's economic, social, and environmental capital base (Dyllick and Hockerts, 2002), human-made capital (Standal and Utne, 2011), land resources (Brown et al., 1987), the physical stock of non-substitutable natural capital (Neumayer, 2003), and total natural capital (Costanza and Daly, 1992);
- *whole systems*, such as: a farm (Darnhofer et al., 2010), all components of the biosphere (Brown et al., 1987), Earth's life support systems (Walter and Stützel, 2009), ecological systems, and social systems (Figge and Hahn, 2005), and human beings (Brown et al., 1987).

With respect to the time periods over which these entities are intended to be sustained, it may be seen in the literature that sustainability is typically discussed in terms of either a finite or an indefinite time period. For example, Neumayer (2003, p. 7) suggests that development may be considered to be sustainable when "it does not decrease the capacity to provide non-declining per capita utility for infinity." Conversely, Larkin (1977, p. 6) argues that with respect to maximum sustainable yield, the level of yield cannot be sustained for "more than 50 to 100 years," further remarking that the time period "certainly isn't forever and ever."

As highlighted in Section 3.1.1, Shearman (1990) distinguishes between the *lexical* meaning of sustainability, and the *implicative* meaning of the term. They suggest that the lexical meaning of sustainability, i.e. those definitions identified in Section 3.1.1, should be undisputed. In contrast, the author argues that the implicative meaning of sustainability changes when the term is used in different contexts. That is, the meaning that the term "sustainability" implies in the specific context that humans are attempting to achieve it (Oxford English Dictionary, 2014). It may be seen from the above discussion that this implicative meaning depends upon what humans consider to be valuable sustainability objectives in a particular context. In Section 3.3, the implicative meaning of sustainability is discussed in greater depth.

3.2 Interpretations of the basic constitution of sustainability

It may be seen from the literature covered in Section 3.1 that there are different interpretations of the meaning and value of sustainability depending on the context. In the discussion on lexical definitions of sustainability provided in

Section 3.1, sustainability was presented as an ability. That is, the ability to sustain fundamentally constitutes an ability in the same vein as the ability to drive a car, the ability to read, and the ability to write (although these are all qualitatively different abilities). It would seem that the lexical definitions of sustainability as the ability to sustain, maintain, or continue something unequivocally point to this interpretation. However, alternative interpretations of the basic constitution of sustainability may be seen to emerge from the literature, as discussed below.

Firstly, as suggested by the word "sustainability" *per se*, sustainability may be interpreted as constituting an *ability* of some kind. For example, the wording of a definition of sustainability provided by Lele and Norgaard (1996, p. 355) may be seen to suggest the basic constitution of sustainability as an ability to maintain something: "Shorn of specific connotations and nuances, sustainability is simply the ability to maintain something undiminished over some time period." Similarly, Hansen (1996, p. 119) suggests that a certain conception of sustainability in the context of agriculture "interprets sustainability either as an ability to fulfil a diverse set of goals or as an ability to continue." Likewise, Dempsey et al. (2011, p.293) remark that sustainability "is about the ability of society itself, or its manifestation as local community, to sustain and reproduce itself at an acceptable level of functioning." Finally, Kajikawa (2008, p.218) suggests that sustainability "literally means the ability to sustain."

It appears that sustainability may also be interpreted as constituting a *process of change*. For instance, Kim and Oki (2011, p.248) remark that sustainability is a "dynamic process that requires building resilience and an ability to manage it wisely." Similarly, Wahl and Baxter (2008, p.72) describe sustainability as a "continuous process of learning and adaptation." Voinov (2007, p.490) remarks that, "As long as [a] system can adapt it is sustainable." In other words, "the system can go through change."

Wahl and Baxter (2008, p.73) referenced above also highlight a third interpretation of the basic constitution of sustainability: a *property or attribute of an entity*[4]. They refer to sustainability as "an emergent property of appropriate interactions and relationships among active participants in the complex cultural, social, and ecological processes that constitute life in the twenty-first century."

[4] Generally speaking, a "property" and an "attribute" may be viewed as slightly different concepts. Both refer to particular qualities of an entity; however, a property may be considered to be an intrinsic quality of an entity, and an attribute a quality that is ascribed to an entity by humans. For instance, a person may have a certain height as a property, and the attribute of being either tall or short. Nonetheless, in the sustainability literature (as in other contexts), the term "attribute" appears to be used as a synonym for "property", and thus they are considered to have equivalent meanings here (Paper C).

Along similar lines, Bodini (2012, p.140) remarks that sustainability "is an overall attribute that emerges from the internal processes that characterize human-environmental systems." Conway (1986, p. 23) highlights sustainability among a range of different properties of agroecosystems. They write that the complexity of such a system "can be captured by four system properties which, together, describe the essential behaviour of agroecosystems," namely: "productivity, stability, sustainability and equitability." Finally, in the context of socio-economic development Eurostat (2013, p.23) describe sustainability as "a property of a system, whereby it is maintained in a particular state through time."

Eurostat (2013) also highlight a final interpretation of the basic constitution of sustainability: a *state of an entity*. For instance, in the context of flow-networks, Goerner et al. (2009, p.77) suggest that "sustainability can reasonably be defined as the optimal balance of efficiency and resilience," i.e. some optimal state of the network. In a similar vein, Heal (2012, p.153) suggests that sustainability "is a potential dynamic equilibrium of some type", i.e. a state of equilibrium. Spangenberg (2011, p.275) provides further support for this interpretation, remarking that sustainability is "a normative ethically justified utopia, describing a state of economy, society and environment considered optimal."

3.3 Contextualising sustainability

In Sections 3.1 and 3.2, different viewpoints on the sustainability concept that may be identified in the literature were outlined: V1 – lexical definitions of sustainability (Section 3.1.1); V2 – sustainability objectives, encapsulating what is to be sustained and for how long (Section 3.1.2); and V3 – interpretations of the basic constitution of sustainability (Section 3.2). In the following sub-sections, these viewpoints are considered in relation to research on sustainability in various contexts. In Section 3.3.1, different types of sustainability emerging from key sustainability research categories are described, and it is shown that authors may adopt different perspectives in relation to each of the above viewpoints. In Section 3.3.2, sustainable development is highlighted as among the most prolific types of sustainability identifiable in the literature, and discussed in depth. Finally, in Section 3.3.4, different standpoints on the significance of human beings with respect to sustainability in the Earth system are delineated: anthropocentrism, and non-anthropocentrism.

3.3.1 Types of sustainability

As touched upon in the introduction to this chapter, sustainability research spans numerous sectors of society and the economy. This body of research may be broadly split into two major streams, each containing different categories of research as shown in Figure 3-1:

- research on the sustainability of *activities*, including categories of research on the sustainability of agriculture (e.g. Conway, 1986; Brown et al., 1987; Hansen, 1996; Tilman et al., 2002; Pretty, 2008; Walter and Stützel, 2009; Darnhofer et al., 2010), business (e.g. Dyllick and Hockerts, 2002; Hart and Milstein, 2003; Figge and Hahn, 2005; Rainey, 2006; Hahn and Figge, 2011; Lo, 2010), design (e.g. Wahl and Baxter, 2008; Chapman, 2011; Gagnon et al., 2012), development (e.g. WCED, 1987; Wackernagel and Yount, 1998; Holling, 2001; Vos, 2007; Burger and Christen, 2011; Vucetich and Nelson, 2010; Eurostat, 2011a; UNDP, 2011), fishing (e.g. Larkin, 1977; Gaichas, 2008; Standal and Utne, 2011; Norse et al., 2012), forest use (e.g. Noss, 1993; Wiersum, 1995; Pearce et al., 2003; Hahn and Knoke, 2010), and yield production (e.g. Larkin, 1977; Gaichas, 2008); and
- research on the sustainability of *systems*, including categories of research on the sustainability of complex systems (Holling, 2001; Voinov, 2007; Goerner et al., 2009; Dawson et al., 2010; Bodini, 2012), economies (e.g. Costanza and Daly, 1992; Solow, 1993; Brown and Ulgiati, 1997; Ekins et al., 2003; Neumayer, 2003), ecosystems (e.g. Brown et al., 1987; Gatto, 1995; Goerner et al., 2009), organisms (e.g. Costanza and Daly, 1992), society as a whole (e.g. Brown et al., 1987; Dempsey et al., 2011), and urban areas (e.g. Maclaren, 1996; Dempsey et al., 2011).

Note that the term "activity" is interpreted here as some goal-directed physical or cognitive action (Boyle et al., 2009), and the term "system" as a "set or assemblage of things connected, associated, or interdependent, so as to form a complex unity" (Oxford English Dictionary, 2014). The nature of activities and systems is explored in depth in Chapter 6.

Given the size of the sustainability literature as indicated in the introduction to this chapter, the two streams of sustainability research presented here are not intended to be comprehensive in their coverage of distinct categories of research. For instance, it may be seen that certain research categories presented here can be viewed as sub-categories of others. In particular, design may be thought of as a sub-activity of business, as may production, depending upon the nature of what is being produced. Conversely, business may be viewed as a necessary sub-activity in the activities of agriculture, forest use, fishing, and production. Similarly, an urban area may be viewed as a sub-system of society, and an organism as a sub-system of an ecosystem. Additionally, sustainability has been studied by researchers in areas such as tourism and health, which are not explicitly covered in this thesis. As such, the research categories presented here are rather intended to represent those that emerge most prominently from the literature as key focus areas of sustainability research.

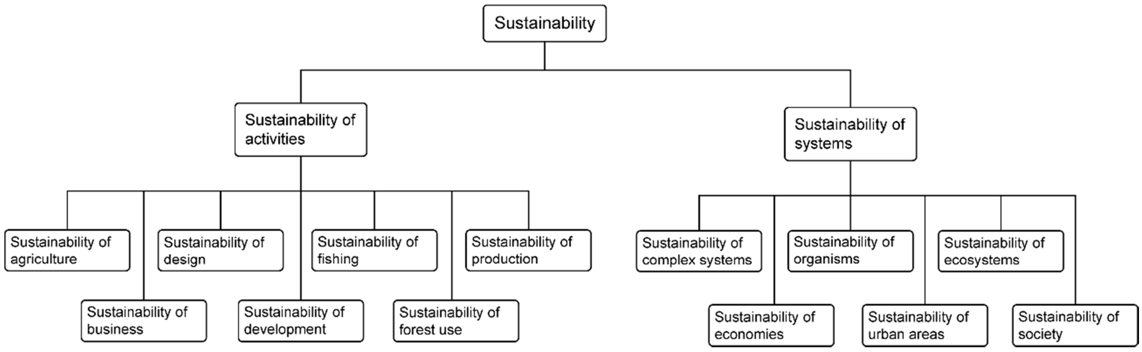


Figure 3-1: Major streams and categories of sustainability research identifiable in the literature

Emerging from the research categories outlined in Table 3-1 are context-specific *types* of sustainability. A selection of these types is illustrated in Figure 3-3. It should be noted that this figure does not represent the output a systematic literature review, but is rather a visual summary of the author's analysis of the literature sample described in the introduction to Chapter 3. A type of sustainability is considered here to represent a specific conception of sustainability developed within a particular research category and explicitly named in the literature. It may be seen in Figure 3-3 that certain types of sustainability overlap two research categories. For instance, sustainable business development may be viewed as emerging from both the business and development research categories (Rainey, 2006). Such overlap may be seen to reflect the multi-, inter-, and trans-disciplinary characteristics of the sustainability concept and sustainability research (Kajikawa et al., 2007; Kajikawa, 2008). As shown in Table 3-1 and illustrated in Figure 3-2, each type may be characterised with respect to the three viewpoints outlined in Sections 3.1 – 3.2, i.e. V1 (Section 3.1.1), V2 (Section 3.1.2); and V3 (Section 3.2). A selection of sustainability types identifiable in the literature is presented in Table 3-1. The full literature sample used as a basis to construct Figure 3-3 and Table 3-1 is presented in Table A5- 1 in Appendix 5A, alongside examples of the definitions/explanations considered. Appendix 5B presents an excerpt from the analysis that led to identification of the three viewpoints and associated perspectives in Figure 3-2, as well as the sustainability types presented in Figure 3-3 and Table 3-1.

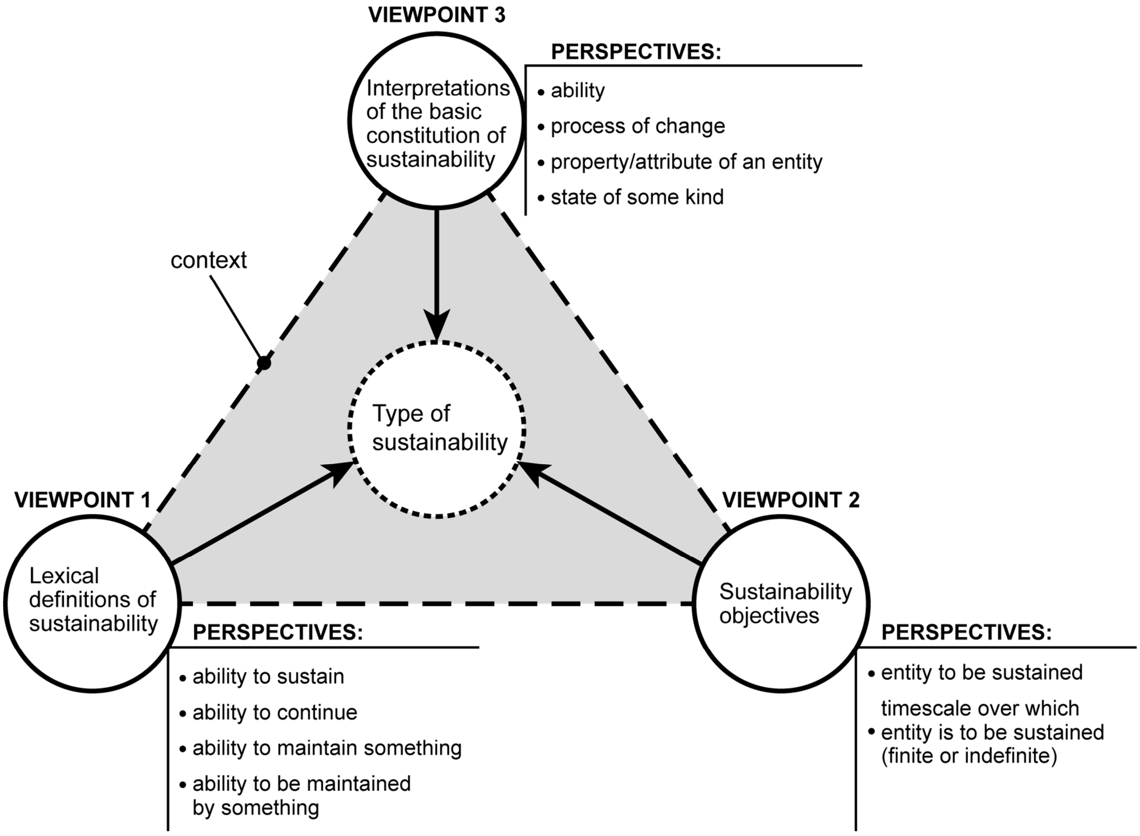


Figure 3-2: Three conceptual viewpoints on sustainability identifiable in the literature, along with different perspectives that may be adopted in relation to each

It may be seen in Table 3-1 that authors discussing types of sustainability in the literature may adopt different perspectives in relation to the three viewpoints (illustrated in Figure 3-2). Firstly, whilst two types of sustainability may be referred to by similar terms in the literature and emerge from the same research category, they may be classed as distinct types in this thesis. For instance, in Figure 3-3 the types "sustainable agriculture" and "agricultural sustainability" are described in similar terms, with one appearing to simply represent the lexical inverse of the other. However, authors discussing these two types of sustainability (Table 3-1) may adopt different perspectives with respect to the viewpoints outlined above. For example:

- Agricultural sustainability is described by Conway (1986, p.23) as "the ability of a [agricultural] system to maintain productivity in spite of a major disturbance such as is caused by intensive stress or a larger perturbation." From this, it may be inferred that: (i) the lexical definition underlying agricultural sustainability in this case is the ability to maintain something; (ii) the sustainability objective is to maintain the productivity of a system indefinitely; and (iii) sustainability is interpreted as being an ability.

- Tilman et al. (2002, p.671) "define sustainable agriculture as practices that meet current and future societal needs for food and fibre, for ecosystem services, and for healthy lives, and that do so by maximizing the net benefit to society when all costs and benefits of the practices are considered." From this, it may be inferred that: (i) the lexical definition underlying sustainable agriculture is the ability to continue; (ii) the sustainability objective is to continue satisfying human needs indefinitely; and (iii) sustainability is interpreted as being an ability.

Thus, although Conway (1986) and Tilman et al. (2002) are classified in the same research category, and both appear to interpret sustainability as an ability, they may be seen to adopt different perspectives with respect to the lexical definition of sustainability and sustainability objectives. As such, agricultural sustainability and sustainable agriculture are considered here as representing two distinct conceptions of sustainability.

Secondly, in certain cases authors were observed to discuss the same type of sustainability, but provide different perspectives with respect to certain viewpoints. For example, Brown et al. (1987), Rainey (2006), and Spangenberg (2011) were all observed to discuss global sustainability. Although their perspectives with respect to several viewpoints are not clear from the definitions they provide, it can be seen that their sustainability objectives differ with respect to the entity being sustained:

- Brown et al. (1987, p.717) provide three progressively broadening definitions of global sustainability: (i) "the indefinite survival of the human species across all regions of the world"; (ii) "virtually all humans, once born, live to adulthood and that their lives have quality beyond mere biological survival"; and (iii) "the persistence of all components of the biosphere, even those with no apparent benefit to humanity." From this, it may be inferred that: (i) the human species is to be sustained; (ii) the human species and quality of life is to be sustained; and (iii) the whole Earth system is to be sustained.
- Rainey (2006, p.33) remarks that "[the] notion of "sustainability" usually implies that all human and business activities are carried out at rates equal to or less than the Earth's natural carrying capacity to renew the resources used and naturally mitigate the waste streams generated." From this, it may be inferred that all human and business activities are to be sustained.
- Spangenberg (2011, p.275) define sustainability as "a normative ethically justified utopia, describing a state of economy, society and environment considered optimal." From this, it may be inferred that some state of the economy, society, and environment is to be sustained.

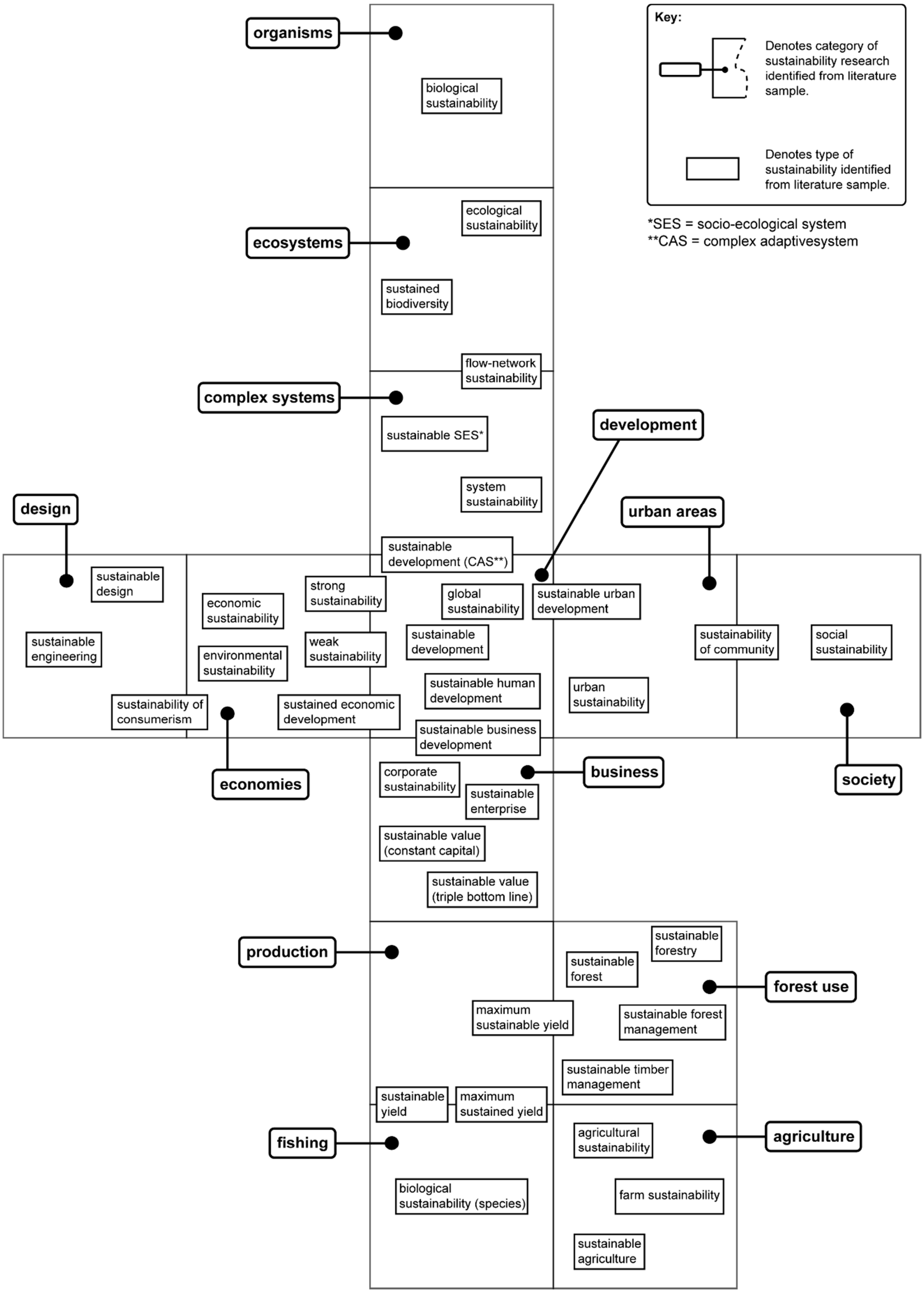


Figure 3-3: A visual summary of sustainability types identified through analysis of the literature sample presented in Appendix 5 (60 sources)

Similarly, both Conway (1986) and Hansen (1996) were seen to discuss agricultural sustainability, but provide different perspectives on the basic constitution of sustainability (i.e. V3):

- As highlighted above, Conway (1986, p.23) defines agricultural sustainability as "the ability of a [agricultural] system to maintain productivity in spite of a major disturbance such as is caused by intensive stress or a larger perturbation." Additionally, the author includes sustainability in a list of system properties that "describe the essential behaviour of agroecosystems." From this, it may be inferred that sustainability is interpreted as both an ability and a property of a system.
- Hansen (1996) highlights two major perspectives on the basic constitution of sustainability identifiable in the literature on agricultural sustainability: (i) "sustainability as an ideological or management approach to agriculture"; and (ii) "sustainability interpreted as a property of agriculture" (Hansen, 1996, p.117). With respect to the latter, they further remark that "[the] system-describing concept interprets sustainability either as an ability to fulfil a diverse set of goals or as an ability to continue" (Hansen, 1996, p.119). From this, it may be inferred that sustainability is interpreted as an ability, a process of change (i.e. via management), and a property of a system.

Finally, the above discussion highlights that individual authors may provide multiple perspectives with respect to the same viewpoint. For instance, it is shown above that Conway (1986) interprets the basic constitution of sustainability as both an ability and a property of a system. In a similar vein, Wahl and Baxter (2008, pp.72-82) may be seen to interpret the constitution of sustainability as both "an emergent property" and "a process of coevolution and co-design" (i.e. a process of change). As discussed in Section 3.1.1, certain authors may be seen to discuss the lexical definition of sustainability in terms of both continuation and maintenance. This is evident in Table 3-1, where it may be seen that several authors consider sustainability to mean (from a lexical point of view) both the ability to continue and the ability to maintain something. For example:

- Wackernagel and Yount (1998, p.513) define regional sustainability as "the continuous support of human quality of life within a region's ecological carrying capacity." They elaborate on this definition, remarking that "we mean that people's subjectively perceived well-being [...] must be at least maintained (or possibly improved, in the case of the poor)."
- Ekins et al. (2003, pp.172-173) define environmental sustainability as "the maintenance of important environmental functions and therefore, the maintenance of the capacity of the capital stock to provide those functions." In turn, they remark that from an anthropocentric point of view, "what

matters about the environment is not particular stocks of natural capital per se, but the ability of the capital stock as a whole to be able to continue to perform the environmental functions which make an important contribution to human welfare."

- Pearce et al. (2003, p.229) remark that sustainable timber management "implies taking steps to ensure forests continue to produce timber in the longer-term, while maintaining the full complement of environmental services and non-timber products of the forest."

Hannon and Callaghan (2011, p.877) suggest that there may be "confusion over the basic concepts of sustainability," resulting in what they term a "sustainability fog" for those attempting to understand sustainability. Indeed, as shown in the above paragraphs, authors discussing types of sustainability in the literature may be seen to adopt different perspectives in relation to the three viewpoints outlined in Sections 3.1 and 3.2, i.e.: (i) lexical definitions of sustainability; (ii) sustainability objectives; and (iii) interpretations of the basic constitution of sustainability. Given that these viewpoints focus on basic conceptual aspects of sustainability, this may be seen to support the observations made by Hannon and Callaghan (2011) to some extent. However, with respect to V1, it may be seen that the terms *sustain*, *continue*, and *maintain* are essentially synonymous. For example, the Oxford English Dictionary (Oxford English Dictionary, 2014) defines "sustain" as, "To support, *maintain*, uphold." In turn, "maintain" is defined as, "To *continue* in, preserve, retain […] in spite of disturbing influences." Finally, "continue" is defined as to "carry on, keep up, *maintain*, go on with, persist in." Thus, although authors may choose different terms to describe the lexical definition of sustainability, it appears that the same basic meaning is being conveyed in each case. With respect to V2, it was shown in Section 3.1.2 that humans specify sustainability objectives by making value judgements regarding what to sustain in a particular context and for how long (Lele and Norgaard, 1996; Liu et al., 2010; Chapman, 2011). In turn, the value that humans determine an entity to have depends largely upon the situation in which they reside, and their interpretation of that entity (Reber, 2011). Thus, it is suggested that differences in perspectives on lexical definitions (V1) and sustainability objectives (V2) reflect differences in the backgrounds, values, and worldviews of decision makers, rather than a lack of conceptual clarity with respect to sustainability.

Table 3-1: A selection of different types of sustainability emerging from research on the sustainability of activities and systems[5]

Types	Objective		Lexical definition	Interpretation	Source
	E	T			
Agricultural sustainability	Per	ID	M	A; P	Conway, 1986
	N/C	N/C	N/C	A; P; Prc	Hansen, 1996
Biological sustainability	Sys	F	C	A	Costanza and Patten, 1995
Corporate sustainability	AAP	ID	C	A	Dyllick and Hockerts, 2002
Economic sustainability	P/A	ID	M	A	Solow, 1993
Environmental sustainability (economics)	F	ID	C; M	A	Ekins et al., 2003
Flow-network sustainability	P/A	ID	N/C	S	Goerner et al., 2009
Global sustainability	O; Org; Sys	ID	C	A	Brown et al., 1987
	AAP	ID	N/C	S	Rainey, 2006
	N/C	ID	N/C	P; Prc	Wahl and Baxter, 2008
	S/S	ID	N/C	S	Spangenberg, 2011
Maximum sustained yield	Per	F	C	A	Larkin, 1977
Regional sustainability	O	ID	C; M	A	Wackernagel and Yount, 1998
Strong sustainability	R	ID	M	A	Daly, 1990b; Costanza and Daly, 1992
Sustainability of community	F; Sys	ID	C	A	Dempsey et al., 2011
Sustainable socio-ecological systems	P/A	ID	C; M	A	Dawson et al., 2010
Sustainable agriculture	AAP	ID	C	A	Tilman et al., 2002
Sustainable development	AAP	ID	C	A	WCED, 1987
Sustainable development (complex adaptive systems)	P/A	ID	M	A	Holling, 2001
Sustainable development (economics)	P/A	ID	M	A	Neumayer, 2003
Sustainable human development	O	ID	C	A	UNDP, 2011
Sustainable timber management	AAP; O; R	ID	C; M	A	Pearce et al., 2003
Sustainable yield	Per	ID	C; M	A	Gaichas, 2008
Urban sustainability	S/S	ID	C	S	Maclaren, 1996
Weak sustainability	R	ID	M	A	Costanza and Daly, 1992

[5] A = ability; AAP = an action, activity, or process ; C = ability to continue; E = entity; F = finite timescale; F = function; ID = indefinite timescale; M = ability to maintain something; N/C = not clear from author's stated definition/explanation; O = outcomes of social/economic activities; P = property; P/A = properties/attributes of a system; Per = performance metrics; Prc = process of change; R = resources; S = state of an entity; S/S = a state or situation; Sys = whole systems; T = timescale.

3.3.2 Sustainable development

Sustainable development may be viewed as among the most prolific types of sustainability highlighted in Figure 3-3/Table 3-1 in Section 3.3.1 (Quental et al., 2010; Quental and Lourenço, 2011). As mentioned in the introduction to Chapter 3, sustainable development was originally defined by the WCED in the seminal publication *Our Common Future*, as: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). With respect to achieving sustainable development, Eurostat (2013, p.23) argue that the focus is on "sustaining the process of improving human well-being." Thus, it may be seen that the sustainability objective in a development context is to sustain the process of improving human well-being indefinitely. However, as noted by Kajikawa (2008, p.218), this objective diffuses into objectives such as "environmental conservation" and "economic development." That is, the maintenance of basic entities required for the continued improvement of human well-being within the Earth system, such as natural resources and manufactured capital, as well as economic production *per se* (Costanza and Daly, 1992; Solow, 1993; Daly, 1992; Ekins et al., 2003; Ekins, 2011). Hahn and Figge (2011, p.325) highlight that this triad of environmental, economic, and social concerns is commonly referred to as the "three pillars" of sustainable development (Dalal-Clayton and Bass, 2002; Kemp and Martens, 2007; Heijungs et al., 2010). Certain authors note that the three pillars were not explicitly defined by the WCED in *Our Common Future* (Dawson et al., 2010; Klöpffer and Ciroth, 2011), being developed later in a series of international declarations on sustainable development (UNDP, 2011).

The concept of sustainable development may be seen to be adopted as the basis for definitions of sustainability in contexts other than socio-economic development. For example, Tilman et al. (2002, p.671) define sustainable agriculture as: "practices that meet current and future societal needs for food and fibre, for ecosystem services, and for healthy lives, and that do so by maximizing the net benefit to society when all costs and benefits of the practices are considered." This may be seen to mirror the definition of sustainable development provided by the WCED to some extent, making reference to the continued satisfaction of human needs but in an agricultural context. Similarly, in a business context, Dyllick and Hockerts (2002, p.131) define corporate sustainability as "meeting the needs of a firm's direct and indirect stakeholders (such as shareholders, employees, clients, pressure groups, communities etc), without compromising its ability to meet the needs of future stakeholders as well." The authors explicitly cite *Our Common Future* as the basis for their definition.

The influence of the sustainable development concept on sustainability definitions in other contexts is such that in certain cases, it appears that "sustainable development" is wholly equated with "sustainability." For instance, Walter and Stützel (2009, p.1275) above explain that they "use the terms 'sustainable development' and 'sustainability' synonymously." Similarly, Todorov and Marinova (2011) appear to use the two terms in equivalent senses throughout their review of approaches to modelling sustainability. Kajikawa (2008, p.218) remarks that "the concept of sustainable development or sustainability represents an attempt to link the environment with development." Going one step further, Bettencourt and Kaur (2011, p. 19544) completely exclude definitions of sustainability that refer solely to "the general continuation or maintenance of a process" in their review of the structure and evolution of sustainability science.

In contrast with the authors referenced above, others appear to distinguish sustainability from sustainable development. For example, Kajikawa et al. (2007, p.222) argue that, "While sustainable development is associated with the human exploitation of nature, "sustainability" does not include such a connotation. In fact, the meaning of sustainability depends on the context, in which it is applied." Similarly, in their work on sustainability indicators, Bell and Morse (2008, p.5) provide the following discussion on sustainable development and sustainability:

"…since it is the 'sustainable' part of sustainable development which particularly interests us, we have tended to refer to 'sustainability' in a generic sense, and our discussions of sustainability could be employed to anything that has sustainable as an adjective. Therefore, the same broad points we make apply to sustainable agriculture, sustainable coastal zones, sustainable cities, sustainable communities, and sustainable organizations and institutions […]. This may appear to be rather cavalier; but 'sustainable' in each case refers to much the same, although the detail can be quite different. Taking sustainability in a broad sense allows us to compare and contrast facets of application across these domains, and to apply lessons from one arena to another."

These remarks appear to suggest that sustainable development is simply one application of the sustainability concept. This perspective may be seen to be implicit in references to the "sustainability of development" made by a number of authors in the literature. For example:

- Barbier (1987, p.108) writes of the need for "appropriate applied analysis of the sustainability of development projects and policies at the local, regional, and sectoral, levels."

- In *Our Common Future*, the WCED remark that, "The sustainability of development is intimately linked to the dynamics of population growth" (WCED, 1987, p.55).
- In Agenda 21, the United Nations argue that a failure to holistically consider environmental, economic, and social concerns in national decision making "influences the actions of all groups in society, including Governments, industry and individuals, and has important implications for the efficiency and sustainability of development" (United Nations, 1992, p.245).
- Finally, Scerri and James (2009, p.228) describe how certain social themes can "provide a background to qualitatively assessing, and community self-assessing, the sustainability of 'development' over time."

As highlighted in Section 3.3.1, Hannon and Callaghan (2011, p.877) conclude that there may be "confusion over the basic concepts of sustainability," resulting in what they term a "sustainability fog" for those attempting to understand sustainability. It was suggested in Section 3.3.1 that differences in the perspectives adopted by authors in relation to key conceptual viewpoints on sustainability support this conclusion to some extent. Given the conflicting views outlined above, it seems that there may also be confusion, in certain spheres at least, over the differentiation of sustainable development from other types of sustainability and the concept of sustainability *per se*.

3.3.3 Eco-efficiency and eco-effectiveness

Fundamental to the overarching socio-economic development process discussed in Section 3.3.2 are the processes of economic consumption and production (OECD, 1997). That is, the consumption and production of economic goods and services. The inception of the sustainable development concept in 1987 intensified debates regarding the sustainability of economic activity in the Earth system started by the likes of Hardin (1968), Georgescu-Roegen (1971), Meadows et al. (1972), and Daly (1992). Generally speaking, research on the sustainability of consumption and production may be understood in terms of two distinct but related concepts, namely: (i) eco-efficiency; and (ii) eco-effectiveness. These are briefly outlined in the following paragraphs.

The production and consumption of a product is typically considered to involve four key stages known as the life cycle, which are discussed further in Chapter 4: (i) extraction and processing of the raw materials required to make the product; (ii) manufacturing and transportation of the product; (iii) use of the product to carry out functions; and (iv) disposal or recycling of the product's constituent parts and materials (Lindahl, 2001; Stasinopoulos et al., 2009). Recent decades have seen a growing consensus that all of these stages have impacts upon supporting ecosystems that must be managed to ensure the environmental sustainability of the process (Braungart and McDonough, 2008; Stasinopoulos et al., 2009). Both eco-efficiency and eco-effectiveness may be viewed as strategies for managing these impacts; however, proponents of each may be considered to differ fundamentally in their perspectives on *how* impacts should be managed, as discussed below.

The notion of eco-efficiency emerged from the 1992 Rio Earth Summit, in response to growing concerns among industrialists over the possibility of environmental limits to production activities in the Earth system (United Nations, 1992; Braungart and McDonough, 2008). According to Wang and Côté (2011, p.65), eco-efficiency centres on "creating more goods and services while using fewer resources and creating less waste and pollution." In other words, improving the efficiency of production from an ecological perspective (OECD, 1998), or "doing more with less" (Braungart and McDonough, 2008, p.51). The concept is typically associated with what may be termed a cradle-to-grave view of the life cycle; that is, resource consumption and waste production should be reduced at all stages, from materials extraction (the cradle of production) to disposal (the grave of products) (Braungart and McDonough, 2008). The implementation of eco-efficiency may be understood in terms of what are commonly termed the three Rs: *reduce*, as discussed above, *reuse*, and *recycle*. Reuse and recycling of product components and materials, particularly at the end-of-life stage but also during earlier stages (e.g. manufacturing) are considered as a means to reduce levels of waste (Braungart and McDonough, 2008; Chapman, 2011; Wang and Côté, 2011).

The notion of eco-efficiency has received significant criticism in recent years, perhaps most notably from Braungart and McDonough (2008). The basis of this criticism is the argument that eco-efficiency essentially focuses on making a "bad" system of production "less bad." Braungart and McDonough (2008, p.65) suggest that "efficiency has no independent value: it depends on the value of the larger system of which it is a part." That is, improving the efficiency of a system that is considered to have destructive effects in the first place may simply "make destruction more insidious." As a solution to this issue, the authors outline the concept of eco-effectiveness. That is, "working on the right things" rather than "making the wrong things less bad." Efficiency is presented as a valuable tool, but only when "implemented as a tool within a larger, effective system that intends positive effects." From this perspective, eco-efficiency and eco-effectiveness may be viewed as compliments (Abukhader, 2008; Wang and Côté, 2011). Nonetheless, Abukhader (2008) notes that implementation of eco-effectiveness remains limited in comparison to eco-efficiency, which has been broadly applied to a range of products and production processes.

Eco-effectiveness is associated with what is known as a cradle-to-cradle view of the life cycle (Braungart and McDonough, 2008; Wang and Côté, 2011). As discussed above, the cradle-to-grave view associated with eco-efficiency prescribes that waste should be reduced at all stages of the life cycle. In contrast, the cradle-to-cradle view is founded on the observation that in natural systems, "waste equals food." In other words, all waste produced is consumed as a resource and as such, the human conception of "waste" does not truly exist (Abukhader, 2008; Braungart and McDonough, 2008). The cradle-to-cradle view may be considered to form the basis of the circular economy concept (Ellen MacArthur Foundation, 2013). According to Kajikawa (2008, p.226), a circular economy is "a mode of economic development based on the ecological circulation of natural materials." Braungart and McDonough (2008, p.104) highlight two cycles underlying economic activity in the Earth system: the biological metabolism, i.e. "the cycles of nature," and the technical metabolism, i.e. "the cycles of industry, including the harvesting of materials from natural places." The basic principle of a circular economy is products are "composed of either materials that biodegrade and become food for *biological cycles*, or of technical materials that stay in closed-loop *technical cycles*" (Braungart and McDonough, 2008, p.104).

3.3.4 Anthropocentric and non-anthropocentric sustainability

It may be concluded from the discussion in Sections 3.3.2 and 3.3.3 that *people* are at the heart of the sustainable development concept. The focus is on sustaining those aspects of society and the wider Earth system that are considered to be essential for the continued well-being of humans within the Earth system (Solow, 1993; Kajikawa, 2008; Eurostat, 2013). Indeed, Kajikawa et al. (2007, p.222) argue that "sustainable development is associated with the human exploitation of nature." However, Solow (1993, p.167) states that discussion of sustainability is often "an occasion for the expression of emotions and attitudes." Along these lines, it should be noted that with respect to sustainability in the Earth system, two different perspectives may be adopted on the significance of people: (i) an anthropocentric perspective; and (ii) a non-anthropocentric perspective (Williams and Millington, 2004; Voinov, 2007; Vucetich and Nelson, 2010), as discussed below.

In the literature, anthropocentrism and non-anthropocentrism may be discussed in relation to the economic conceptions of weak and strong sustainability (Williams and Millington, 2004), which are included as sustainability types in

Table 3-1 (Section 3.3.1). Ekins (2011, p. 632) delineates the relationship between capital and human wellbeing in economics: "capital stocks provide a flow of goods and services, which contribute to human wellbeing." Underlying sustainability research in economics is the idea that in addition to manufactured capital, natural capital – that is, natural resources – also contributes to human wellbeing (Daly, 1992; Meadows, 1998; Ekins et al., 2003; Derissen et al., 2011; Ekins, 2011). Four types of capital may be identified in the literature:

- *Natural capital* "consists of the stocks and flows in nature from which the human economy takes its materials and energy (sources) and to which we throw those materials and energy when we are done with them (sinks)" (Meadows, 1998, p.x). That is, "the matter of the planet, the sun's energy, the bio-geochemical cycles, the ecosystems and the genetic information they bear, and the human being as an organism" (Meadows, 1998, p.42).
- *Manufactured capital*, also known as *built capital*, consists of "tools, machines, factories" and also "processed material and energy" (Meadows, 1998, p.41).
- *Human capital* may be viewed as "educated, skilled, experienced, and healthy people" (Goodland, 1995, p.15). Meadows (1998, p.41) highlights "skilled labor" as an example of human capital.
- *Social capital* is considered to include aspects such as "health, wealth, knowledge, [and] leisure" (Meadows, 1998, p.43). Goodland (1995, p.15) states that human capital "is largely lost at the death of individuals, and so it must be renewed each generation, whereas social capital persists in the form of books, knowledge, art, family, and community relations." This may be seen to indicate that human capital pertains to individual people, and social capital to people collectively.

To a certain extent, human, manufactured, and social capital may act as substitutes for natural capital that is depleted in order to support society and ensure continued wellbeing (Daly, 1990a). The notions of weak and strong sustainability fundamentally differ with respect to the degree of substitutability afforded among these different types of capital, particularly natural and manufactured capital (Goodland, 1995; Ekins 2011; Chen et al., 2012):

- Weak sustainability "is maintaining total capital intact without regard to the partitioning of that capital among the four kinds" (Goodland, 1995, p.15). In particular, manufactured and natural capital are typically considered to be perfect substitutes for one another (Daly, 1990b; Ramos and Caeiro, 2010), leading certain authors to term weak sustainability the "perfect substitutability paradigm" (Garmendia et al., 2010). According to Ekins (2011, p. 633), this assumption originates from the belief that well-being "is not normally dependent on a specific form of capital" and may therefore be ensured in the face of natural capital depletion by substituting manufactured capital for natural capital. A central tenet of weak sustainability is the belief that through creativity and innovation, humans will develop technological substitutes for irreversibly depleted natural capital, and the rising price of increasingly scarce resources will slow rates of consumption (Phillis et al. 2010; UNDP 2011).

- Strong sustainability "requires maintaining separate kinds of capital" (Goodland, 1995, p.15). In particular, Ekins (2011, p. 633) highlights the belief among strong sustainability advocates that "substitutability of manufactured for natural capital is seriously limited by such environmental characteristics as irreversibility, uncertainty and the existence of 'critical' components of natural capital, which make a unique contribution to welfare." That is, whilst certain forms of manufactured capital may be substituted for certain types of natural capital (although according to Daly, (1990a), examples in this respect are limited), there are certain forms of natural capital that have no artificial substitutes with respect to human well-being. The United Nations Development Programme suggests the atmosphere as an example of such a resource, remarking that "the accumulation of physical or other kinds of capital cannot compensate for Earth's warming" (UNDP 2011, p. 15). Thus, a central assumption of strong sustainability is that "natural and human-made capital are not perfect substitutes" (Goodland 1995, p.15). Rather, they may be viewed as complements (Daly, 1990a; Goodland, 1995). For example, Goodland (1995, p.16) argues that "[a] sawmill (human-made capital) is worthless without the complementary natural capital of a forest." Furthermore, a sawmill clearly cannot be substituted for a depleted forest.

Williams and Millington (2004) suggest that weak sustainability aligns with an anthropocentric perspective on the relationship between society and the environment. They position strong sustainability, on the other hand, as aligning with a non-anthropocentric perspective on this relationship. Vucetich and Nelson (2010, p.540) present the difference between anthropocentrism and non-anthropocentrism in sustainability research as a dichotomy: "Does human need define ecosystem health, or does ecosystem health define the limits of human need?" In this respect, Williams and Millington (2004, pp.101-102) argue that proponents of weak sustainability "focus on the resource-side of the equation so as to conjoin resources and demands" through, for example, technological development. Adopting the terminology of Vucetich and Nelson (2010) above, compromised ecosystem health in the form of e.g. depleted resources is acceptable, as long as human demands continue to be met. In contrast, Williams and Millington (2004) argue that advocates of strong sustainability "focus upon changing the demands made on the Earth," which may involve "rethinking our attitude towards nature as well as our view of economic progress and 'development.'" In other words, humans must alter their needs and wants to preserve ecosystem health. The authors suggest that this perspective is motivated by a belief that nature has "a right to remain unmolested that does not require justification in human terms – just as there are inalienable 'human rights' that require no justification." The sustainability problem facing society is essentially reduced to the idea that "these biotic rights are not currently being respected." In reality, Williams and Millington (2004, p. 101) suggest that weak and strong sustainability represent "a spectrum of contrasting perspectives rather than an either/or dualism." Thus, it is possible to adopt a position somewhere between weak and strong sustainability, i.e. to tend towards "weaker" or "stronger" sustainability.

In the above paragraphs, it may be seen that from an anthropocentric perspective, natural resources should be maintained because they are instrumental to the continued operation of human activities and society. In contrast, from a non-anthropocentric perspective, natural resources should be maintained out of respect for their "biotic rights," or for their intrinsic value. The majority of the definitions associated with the sustainability types presented in Table 3-1, Section 3.3.1 (Appendix 5A) explicitly focus on people, society, and/or human activities and thus, may be viewed as anthropocentric to some degree. Voinov (2007, p.495) states that: "By definition, sustainability is all about livelihood for humans as part of the ecosystem. We do not talk about sustainability of ecosystems in the absence of humans." Echoing these sentiments, Jamieson (1998, p.184) remarks that it is "human survivability and well-being that ultimately matter" with respect to sustainability – "nature enters the picture only as a means." Given that the research documented in this thesis focuses on the sustainability of technical systems, i.e. anthropogenic systems enabling human activities (Hubka and Eder, 1988) (discussed further in Chapter 4), an anthropocentric perspective on sustainability will be adopted throughout.

3.4 Sustainability goals for human activities and systems

In Sections 3.1 and 3.2, different viewpoints on the sustainability concept that may be identified in the literature were outlined. In Section 3.3, an overview of different types of sustainability emerging from the literature was presented, highlighting the different perspectives that may be adopted by authors in relation to each of the aforementioned viewpoints. It was also shown that sustainability may be considered from both an anthropocentric and a non-anthropocentric perspective (Williams and Millington, 2004). An anthropocentric perspective on sustainability is adopted throughout this thesis owing to the focus of the work on technical systems, i.e. anthropogenic systems enabling human activities (Hubka and Eder, 1988). However, before the literature on sustainability in a technical systems context is reviewed in Chapter 4, the next two sections in this chapter focus on the realisation of sustainability in a human context generally. That is, how sustainability may be achieved (Section 3.4) and assessed (Section 3.5) in the context of human activities and systems.

As shown in Section 3.2, one interpretation of sustainability is as a process of change. Related to this interpretation is the notion of what may be termed a "sustainability transition" in the literature. That is, the process involved in practically shifting human activities and systems towards sustainability (Clark and Dickson, 2003; Parris and Kates, 2003; Quental et al., 2010), whatever this overarching goal may represent (given the different sustainability types outlined in Section 3.3.1). From a human perspective, this transition is typically facilitated through the formulation and implementation of *sustainability goals* (Maclaren, 1996; Parris and Kates, 2003; Jordan et al., 2010; Quental et al., 2011; Eurostat, 2013). According to Parris and Kates (2003, p.8068), sustainability goals are "broad, qualitative, statements about objectives." As discussed in Section 3.1.2, humans specify sustainability objectives encapsulating what is to be sustained and for how long. Thus, sustainability goals may be viewed as statements about these objectives. That is, statements about what is required in order to sustain the chosen entity over the intended timescale.

As discussed in Section 3.1.2, although sustaining human society *per se* indefinitely may be viewed as the ultimate sustainability objective in a human context (Komiyama and Takeuchi, 2006; Voinov, 2007; Beddoe et al., 2009), precisely what *kind* of society is a matter for considerable debate (Parris and Kates, 2003; Kajikawa, 2008). In turn, a broad range of different entities may be seen to form the foci of sustainability objectives in the literature, including both tangible and intangible entities. Consequently, the specific nature of sustainability goals for human activities and systems may vary with context (Kajikawa, 2008). Nonetheless, sustainability goals identifiable in the literature may be broadly split into two types, formulated from different viewpoints. Vucetich and Nelson (2010, p.540) highlight that the "relationship between the environment and society" is central to the sustainability issues facing society. They argue that this relationship "involves a physical aspect […] and an ethical attitude." Accordingly, as shown below, sustainability goals may be formulated from two viewpoints on sustainability and human society: (i) a *physical* viewpoint, considering what we physically *can* and *cannot* sustain given the natural laws and limits of the Earth system (Daly, 1990a,b; UNEP, 2012); and (ii) an *ethical* viewpoint, considering what we *should* and *should not* sustain given the moral/social standards of human beings (Marcuse, 1998; Rametsteiner et al., 2011). Examples of sustainability goals formulated from each of these two viewpoints are presented and discussed in turn in the following paragraphs.

A broadly-applicable set of physical sustainability goals may be seen to derive from the notion that the "Earth System provides the basis for all human societies and their economic activities" in the form of resources and waste processing capacity (UNEP, 2012, p.xviii). In other words, the continuation of all human activities and systems within the Earth system is fundamentally dependent upon the availability of resources and the mitigation of waste (Daly, 1990a,b; Meadows, 1998; Rainey, 2006). Accordingly, as touched upon above, physical sustainability goals are typically determined by the natural laws and limits of the Earth system with respect to these aspects (Daly, 1990a,b; Odum, 1994; Brown and Ulgiati, 1997; UNEP, 2012). For instance, the renewability of resource stocks may be viewed as the basis for defining resource-focused sustainability goals (Daly, 1990a). That is, the degree to which stocks can be renewed over a certain timescale (Meadows, 2008). In the context of anthropocentric sustainability, renewability may be considered with respect to anthropological timescales of thousands of years (Daly, 1992). To illustrate the concept of renewability, a stock of resources being consumed by a human activity is represented in Figure 3-4. The movement of the stock level over time depends on the relative rates of activity resource consumption and stock regeneration. In this respect, four possible cases are illustrated, i.e. (a) – (d). As shown below, these cases relate to basic physical sustainability goals identifiable in the work of ecological economist Herman Daly (1990a, 1992).

Case (a) – depletion of non-renewable resource stocks: Daly (1990a, p.2) states that non-renewable resources "cannot be maintained intact short of nonuse." That is, since they are not believed to regenerate significantly along anthropological timescales of thousands of years (Daly, 1992), depletion of non-renewable resource stocks may be considered to be irreversible. This is illustrated in case (a) in Figure 3-4, where the stock is depleted from its initial level (L1) to L2 as it is consumed over time, and is not regenerated. Since human activities and systems are dependent on resources for their continued operation as highlighted by UNEP (2012), the use of non-renewable resources should be minimised, ideally to zero. Thus, *minimise non-renewable resource use* may be viewed as a basic physical sustainability goal for society (Keoleian and Menerey, 1994; Coelho et al., 2012). However, certain authors in an economics context propose an alternative goal for non-renewable resource use: *consume non-renewable resources no faster than the rate at which renewable substitutes are developed* (Daly, 1990a; Goodland, 1995).

This may be seen to directly relate to the notions of weak and strong sustainability and the issue of substitutability, discussed in Section 3.3.4.

Cases (b), (c), and (d) – depletion, maintenance, and generation of renewable resource stocks: With respect to renewable resources, Daly (1990a, p.2) argues that "harvest rates should equal regeneration rates." In other words, using renewable resources faster than stocks are regenerated may lead to depletion of renewable resource stocks (Campbell and Garmestani, 2012). This is illustrated in case (b) in Figure 3-4, where the stock is depleted from its initial level (L1) to L2 as it is consumed over time, and is regenerated to a level lower than the initial level (L3) because the consumption rate exceeds the regeneration rate. Again, because human activities and systems are reliant upon resources for their continued operation, they should use renewable resources at rates (i) equal to or (ii) less than the regeneration rate of resource stocks to avoid depletion. Thus, *minimise rate of renewable resource use* may be viewed as a second physical sustainability goal for society (Goodland, 1995; Blizzard and Klotz, 2012). When (i) occurs, the stock will be maintained. This is illustrated in case (c) in Figure 3-4, where the stock is depleted from its initial level (L1) to L2 as it is consumed over time, and is regenerated back to the initial level (L1). When (ii) occurs, additional stock will be generated. This is illustrated in case (d) in Figure 3-4, where the stock is depleted from its initial level (L1) to L2 as it is consumed over time, and is regenerated to a level higher than the initial level (L4) because the regeneration rate exceeds the consumption rate.

For their continued operation, human activities and systems are physically dependent upon the mitigation of waste as well as the resource stocks illustrated in Figure 3-4, as discussed above. Since the Earth system is currently essentially closed, from the perspective of resources and waste at least (Daly, 1992; Wackernagel and Rees, 1997; Cabezas et al., 2005), any waste produced by an activity or system operating within the Earth system must in turn be processed within that system (Meadows, 1998; Lindsey, 2011). To illustrate this, two activities operating in the Earth system are represented in Figure 3-5: one producing waste, and the other processing it. Daly (1990a, p.2) writes that for sustainability, "waste emission rates should equal the natural assimilative capacities of the ecosystems into which the wastes are emitted." As shown in Figure 3-5, producing waste faster that it can be processed may lead to accumulations of waste within the Earth system. These accumulations may be harmful to biological entities and have undesirable effects on the functioning of other activities and systems (Daly, 1992; Meadows, 1998). To avoid waste accumulations, human activities and systems should produce waste at rates less than or equal to the rate that it can be processed in the wider Earth system. Thus, *minimise rate of waste production* may be viewed as a third physical sustainability goal for society (Meadows, 1998; Lindsey, 2011).

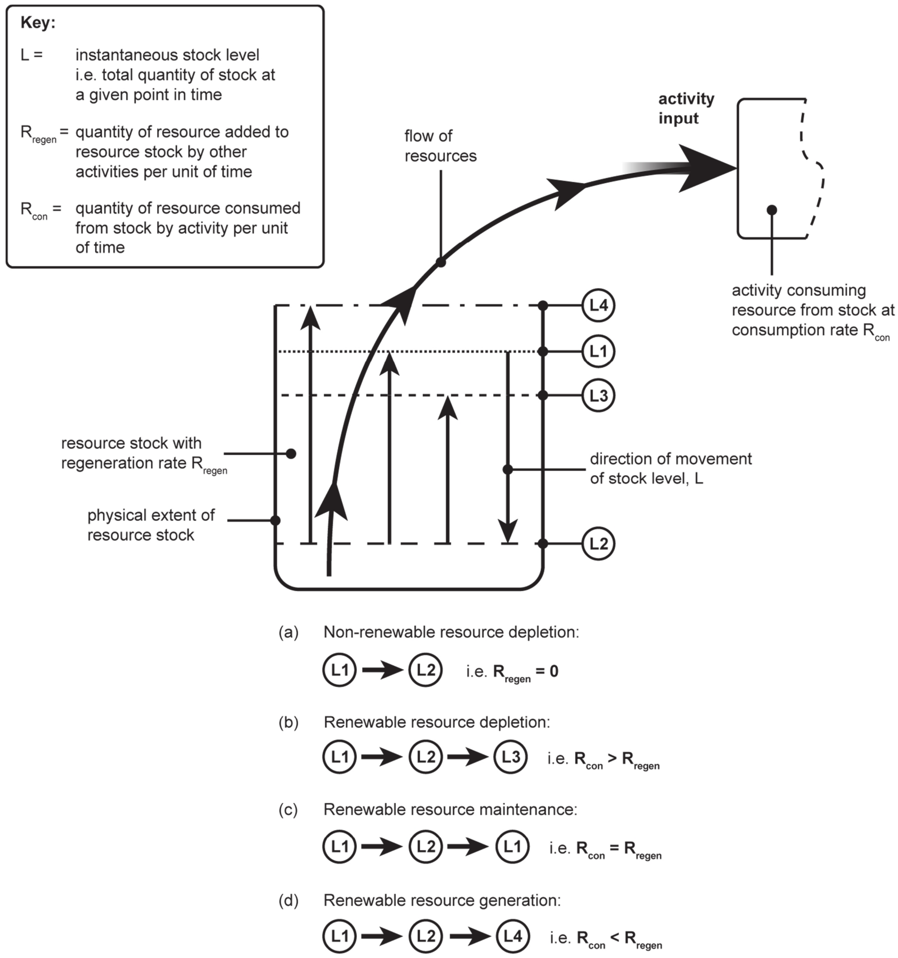


Figure 3-4: Resource consumption by human activities (adapted from Paper C)

As discussed above, sustainability goals may be formulated from (i) a physical viewpoint and (ii) an ethical viewpoint. As shown above, physical sustainability goals focus on sustaining those elements of the Earth system that are required by human activities and systems so that they can physically continue to operate over time (e.g. the resource base and waste processing capacity). In contrast, sustainability goals formulated from an ethical viewpoint typically focus on sustaining what Vucetich and Nelson (2010, p.540) refer to as "normative concepts," such as the satisfaction of human needs and the health of ecosystems. Examples of goals formulated from viewpoint (ii) may be identified in a list of sustainability goals for agriculture provided by Walter and Stützel (2009, p.1276). The list also includes physical sustainability goals focusing on resources and waste similar to those discussed above, although the terminology adopted is different.

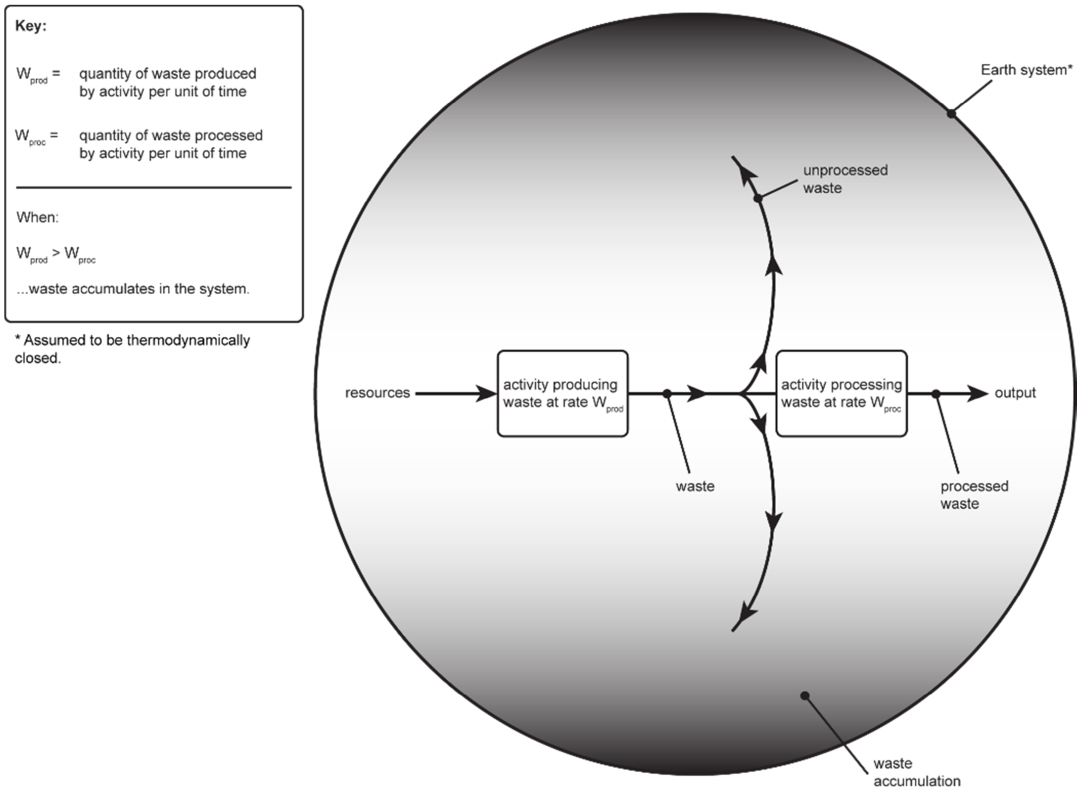


Figure 3-5: Waste mitigation in the Earth system (Adapted from Paper C)

The physical and/or ethical nature of each goal is highlighted in square brackets below. The authors write that "to be sustainable, agriculture must:

- Supply humanity with food and fibre of sufficient quantity and quality [physical with respect to the supply of food and fibre *per se* (i.e. the continued operation of agricultural activity), and ethical with respect to the notions of what is a sufficient quantity and quality of food and fibre];
- Not endanger Earth's life support systems (such as the climate system and the functioning of ecosystems) or natural resources (including biotic and abiotic resources, soils and biodiversity) [physical];
- Allow producers to make a secure livelihood [ethical];
- Contribute to rural development and the enhancement of rural communities [ethical]
- Ensure the health of workers, rural populations and consumers [ethical];
- Be equitable, just and produce in a socially accepted way [ethical]."

Vucetich and Nelson (2010, p.540) argue that a focus on sustaining "normative" concepts, e.g. the notions of equity, health, and security mentioned in the above goals, means that sustainability can be either "virtuous" or "vulgar", depending upon the ethical standards of those seeking it. They cite the concepts of "human needs" and "ecosystem health" as an example, suggesting that, "Depending on how societies understand these concepts, sustainability could mean anything from "exploit as much as desired without infringing on future ability to exploit as much as desired" to "exploit as little as necessary to maintain a meaningful life."" They argue that as such, "understanding and achieving sustainability requires addressing it as both a scientific and an ethical issue." Thus, the moral standards of decision makers formulating sustainability goals, along with the norms of wider society, may be seen to play a key role in formulating sustainability goals from an ethical viewpoint. This may be contrasted with physical sustainability goals, which are primarily determined by the natural laws and limits of the Earth system as discussed above.

A final point emerging from the literature on sustainability goals pertains to a potential relationship between physical sustainability goals (such as those inferred from the work of Daly (1990a, 1992) above) and ethical sustainability goals (such as the goals stated by Walter and Stützel (2009)). Marimon et al. (2012, p.132) highlight the statement by ISO (2010) that "environmental responsibility is a precondition for the survival and prosperity of human welfare." This may be seen to suggest that physical goals focusing on e.g. resources and waste may be viewed as fundamental to ethical goals focusing on normative aspects. That is, ethical goals may not be achievable if the physical goals are not attained. This notion may be seen to be reflected in a framework for developing and managing sustainable development indicators (discussed in Section 3.5) presented by Meadows (1998, p.41), and based on the work of Daly (1990a, 1992). The framework, known as the "Daly triangle", is illustrated in Figure 3-6 and briefly discussed below.

In the Daly triangle, the four types of capital discussed in Section 3.3.4 (i.e. natural, manufactured, human, and social) are organised into hierarchical categories of "means" and "ends" contributing to human well-being. It may be seen in Figure 3-6 that human and social capital derive from built (i.e. manufactured) capital, which is created from natural capital through scientific and technological development. Meadows (1998, p.43) describes human and social capital as representing "the goals that governments promise and economies are expected to deliver," focusing on normative concepts such as health, leisure, and wealth, and also consumer goods as a valuable output of the economy. Finally, human and social capital are transformed into human well-being through some kind of ethic, philosophy, or religion that "can answer the question: what are health, wealth, and education *for*?" Meadows (1998, p.43) concludes that although well-being is not a material concept *per se*, "it requires the whole material triangle underneath to support it." Thus, it may be seen that the achievement of what may be viewed as ethical sustainability goals – human well-being ultimately, but also wealth, health, product value, and so on – are fundamentally dependent on the continued availability of natural capital, e.g. materials, energy, and waste processing capacity (Costanza and Daly, 1992; Meadows, 1998) that form the focus of physical sustainability goals.

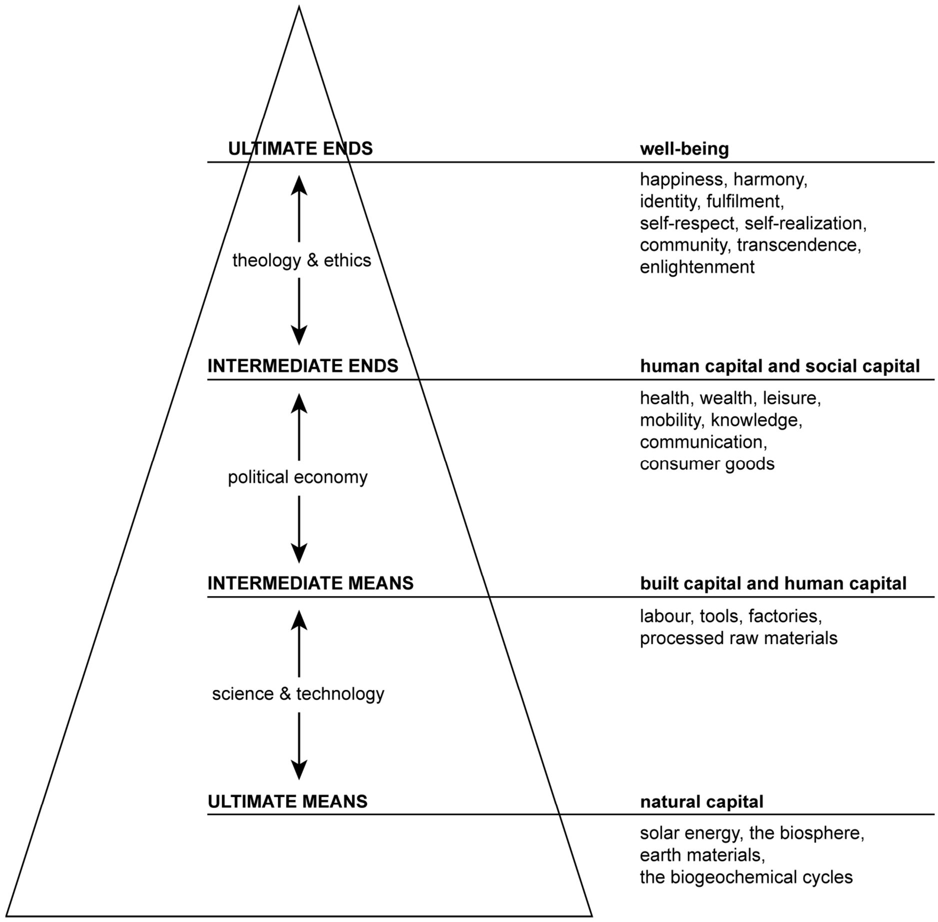


Figure 3-6: The Daly triangle (adapted from Meadows (1998), p.4**2**)

3.5 Sustainability assessment

To implement sustainability goals for a particular entity, humans carry out actions that are expected to result in the entity fulfilling the goals (Parris and Kates, 2003; Eurostat, 2011a). However, Ness et al. (2007, p.498) highlight that defining and implementing sustainability goals alone is not sufficient to shift human activities and systems towards sustainability – "for the transition to sustainability, goals must be assessed." In the words of Meadows (1998, p.3): "We can't steer accurately, if we don't know where we are." Sustainability assessment, as it is commonly termed in the literature (Ness et al., 2007; Bodini, 2012), provides humans with information on the behaviour and performance of entities from a sustainability perspective (Meadows, 1998; Bell and Morse, 2008; Singh et al., 2012). This information may in turn be used to make decisions relating to the sustainability of an entity (De Smedt, 2010; Heijungs et al., 2010; Ness et al., 2007; Rametsteiner et al., 2011; Ramos and Caeiro, 2010).

In the following sections, literature on sustainability assessment in the context of human activities and systems is reviewed. Ness et al. (2007) present a classification of sustainability assessment approaches, including the following categories: indicators/indices; product-related assessment; and integrated assessment. Sections 3.5.1 and 3.5.2 follow a similar scheme, although there are certain differences as highlighted below. The literature on indicator-based approaches is reviewed in Section 3.5.1. Ness et al. (2007) classify indicators applied at the global/national level separately from those applied at the product level. However, it should be noted that in Section 3.5.1, indicators identifiable in the literature are instead classified with respect to the kinds of activities and systems they are applied to, and the approaches through which they are evaluated. It is then shown that indicators may be evaluated at different spatial scales as highlighted by Ness et al. (2007). Assessment approaches with a life cycle perspective, such as life cycle assessment and life cycle costing, are highlighted by Ness et al. (2007) as key in product-related sustainability assessment. Accordingly, the literature on these is reviewed in Section 3.5.2.1. Finally, an overview of key integrated approaches applied in sustainability assessment is provided in Section 3.5.2.2.

3.5.1 Sustainability indicators

Among the most prolific approaches to sustainability assessment are those based around the use of sustainability indicators (SIs) (Scerri and James, 2009; Ramos and Caeiro, 2010; Hak et al., 2012). Hak et al. (2012, p.46) suggest that although it is not possible to put an absolute figure on the number of SIs currently in use, “we can assume the existence of hundreds of various indices and sets of indicators or even several thousands of such metrics if individual indicators are included.” Furthermore, Dalal-Clayton and Bass (2002) position indicator-based approaches as among the best sustainability assessment approaches with respect to several criteria including transparency, consistency, and usefulness for decision making. The literature on SIs is reviewed in this section, in order to gain insight into the nature of SIs and the factors affecting their definition and evaluation.

According to Parris and Kates (2003, p.8068), SIs are “quantitative measures that are selected to assess progress toward or away from a stated [sustainability] goal.” This is supported by McCool and Stankey (2004, p.298), who write of the need to link “specific measurable variables” to sustainability goals. Similarly, Jordan et al. (2010, p.1535) suggest that SIs should be “linked directly to the goals” and "measurable in common units." However, other authors suggest that SIs need not necessarily be quantitative in nature (Reed et al., 2006; Scerri and James, 2009). For instance, Meadows (1998, p.9) distinguishes between objective and subjective SIs. She writes that the former are those that are "sensed by instruments outside the individual – thermometers, voltmeters, counters, dials, rulers. They can be verified by others. They can be expressed in numbers". In contrast, she remarks that subjective SIs are those that "are sensed only within the individual by means that may not be easily explained and in units that are probably not numerical." In short: "Objective indicators primarily measure quantity. Subjective indicators primarily measure quality" (Meadows, 1998, p.9). On the basis of the above, a SI may be described as a quantitative or qualitative variable linked to a sustainability goal, that provides information on the fulfilment (or otherwise) of the goal when evaluated.

Analysing the range of SIs identifiable in the literature reveals that they may be broadly split into four categories, each involving a different evaluation approach: accounting indices; energetic and physical flow indicators; sustainable development indicators; and ecological indicators. A categorisation of sustainability indicators and the approaches used to evaluate them is shown in Figure 3-7. Given the plethora of SIs identifiable in the literature (discussed by Hak et al. (2012), as highlighted in the introduction to Section 3.5.1), the categories outlined below are not claimed to be exhaustive. Rather, based on the literature, they are intended to represent the SI types most commonly encountered in sustainability assessment research:

- *Accounting indices* (AIs) primarily focus upon the environmental, economic, and social impacts of socio-economic development and/or growth in the Earth system (Ness et al., 2007; Galli et al., 2012; Singh et al., 2012). AIs are typically evaluated retrospectively through natural resource accounting (Galli et al., 2012), national wealth accounting (Alfsen and Greaker, 2007), and green national accounting (World Bank, 2010) approaches. Examples include the Ecological Footprint (Wackernagel and Yount, 1998; Galli et al., 2012), the Adjusted Net Savings index (World Bank, 2010), and the Genuine Progress Indicator (Posner and Costanza, 2011).
- *Energetic and physical flow indicators* (EPFIs) primarily focus upon the use of resources by individual products and systems (Balta et al., 2010; Aydin et al., 2013), production activities (Brown and Ulgiati, 1997; Coppola et al., 2009; Liao et al., 2011) and regional systems (Gasparatos et al., 2009a,b; Campbell and Garmestani, 2012). EPFIs are typically evaluated retrospectively through energy analysis (Ertesvag, 2005; Liao et al., 2011), exergy analysis (Gasparatos et al., 2009b), emergy accounting (Campbell and Garmestani, 2012; Liu et al., 2012), and material flow analysis (Ness et

al., 2007; Eurostat, 2011b) approaches. Examples include energy efficiency (Liao et al., 2011), exergy efficiency (Rosen et al., 2008; Gasparatos et al., 2009b), percent renewable emergy (Brown and Ulgiati, 1997; Campbell and Garmestani, 2012), and resource productivity (Eurostat, 2013).

- *Sustainable development indicators* (SDIs) primarily focus upon the environmental, economic, and social impacts of socio-economic development activities in the Earth system (Ness et al., 2007; Ramos and Caeiro, 2010; Pülzl et al., 2011; Eurostat, 2013). SDIs are typically evaluated retrospectively through progress monitoring approaches (Dalal-Clayton and Bass, 2002; van Zeijl-Rozema and Martens, 2010; Eurostat, 2013). Examples include the Eurostat set of SDIs (Eurostat, 2013), and the United Nations Commission on Sustainable Development's set of over one hundred Indicators of Sustainable Development (United Nations, 2007).
- *Ecological indicators* (EIs) are holistic measures focusing upon the use of resources by whole systems (Ulanowicz et al., 2009; Bodini, 2012). EIs are typically evaluated retrospectively through ecological network analysis (Li and Yang, 2011; Bodini, 2012). Examples include ascendency (Ulanowicz, 1980; Ulanowicz et al., 2009; Li and Yang, 2011; Bodini, 2012), total system throughput, and overhead (Ulanowicz, 1980; Ulanowicz et al., 2009; Bodini, 2012). This category of indicators is considerably less developed than the others outlined above (Bodini, 2012).

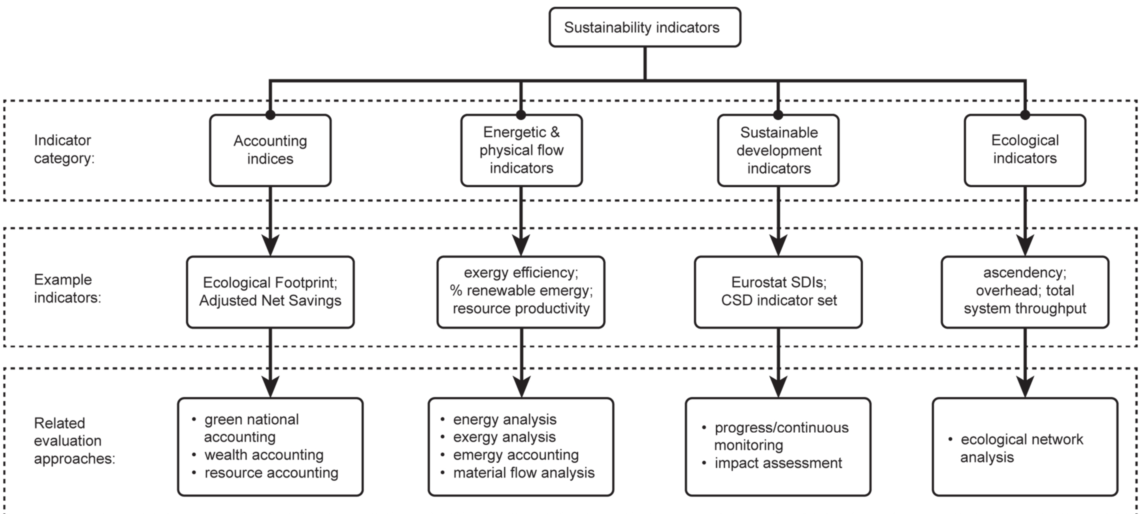


Figure 3-7: Classification of sustainability indicators identifiable in the literature and their associated evaluation approaches (adapted from Paper C)

SIs may be evaluated from different temporal perspectives (Ness et al. 2007; Rametsteiner et al. 2011). Parris and Kates (2003, p.8068) refer to the assessment of "progress toward or away from" sustainability goals. That is, retrospective assessment, considering the actual behaviour of an entity that has occurred in the past. However, SIs may also be used to assess sustainability prospectively, i.e. evaluating the potential behaviour of an entity that may occur in the future. Prospective assessment may be carried out to determine the likely impacts of certain policies or actions on the sustainability of an entity. For example, Werhahn-Mees et al. (2011, p. 92) employ SIs prospectively to assess the potential impacts of increasing resource use intensity on the sustainability of bioenergy production chains. The chronology of indicator-based sustainability assessment is illustrated in Figure 3-8. As shown, actual and potential behaviour may be contrasted with instantaneous behaviour. The former are essentially human perceptions of behaviour that has either already unfolded, or might unfold in the future. The latter refers to behaviour occurring in the present moment that may be observed and/or experienced by humans.

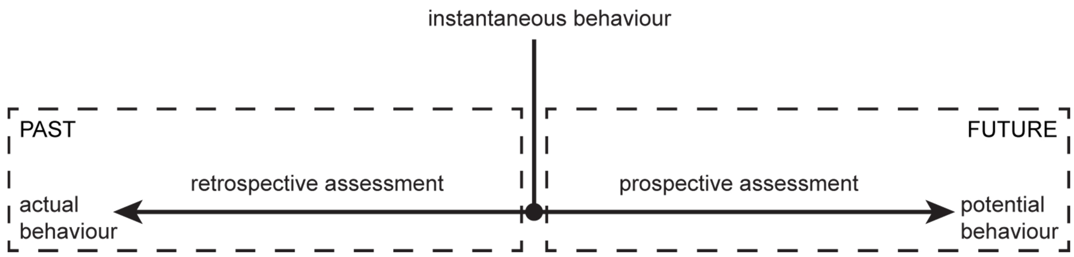


Figure 3-8: The chronology of sustainability assessment

As discussed in Section 3.3.1, sustainability objectives may encapsulate either an indefinite or a finite timescale. That is, the length of time over which some entity is intended to be sustained. Along these lines, Bell and Morse (2008, p.16) highlight that the timescale over which SIs are evaluated may influence the way that an entity's behaviour is interpreted during sustainability assessment. The authors demonstrate that the behaviour of an entity may fluctuate considerably over long time periods. As such, depending upon the intervals at which this behaviour is assessed, "the interpretation of the trend [from the perspective of sustainability] in each block of time may be quite different" to one another, and to the interpretation of the behaviour of the entity over multiple intervals i.e. in the longer term. Consequently, they argue that the "choice of the starting point" or baseline for a sustainability assessment effort "can influence the results."

SIs may also be evaluated at different spatial scales. Typically, these are referred to as local, regional, and global. For example, Ulgiati et al. (2011, p.177) discuss sustainability assessment of technological and social systems. They write that at the local scale, only the direct inputs to and outputs from the system need to be considered. At the regional scale, however, the indirect inputs and outputs associated with the implementation of the system must also be evaluated. Finally, at the global scale, they argue that "the ecosystem services that contribute to a process sustainability, such as wind for dilution of emissions, solar radiation and rain water for photosynthesis, the cycling of nutrients" should also be included in the assessment. In turn, they remark that the "value of a given indicator is only 'true' at the scale at which it is calculated." Lutter et al. (2009, p.9) describe these different scales in the context of socio-economic development, using the terms micro, meso, and macro rather than local/regional/global. They write that at the macro level, "the impacts of total consumption, production and trade flows of a country are addressed." At the meso level, "individual sectors of an economy or aggregated product groups come into focus". Finally, at the micro level, "attention is turned to individual products or product groups." Essentially, as the scale of sustainability assessment increases, the boundary of the assessment expands to include more activities than were considered at the previous scale (illustrated in Figure 3-9).

The definition and selection of SIs for human activities and systems is by no means an easy task (Meadows, 1998; Bell and Morse, 2008; Rametsteiner et al., 2011). Firstly, there may be a range of potential SIs that could be used to assess the behaviour of an entity in relation to sustainability goals (Meadows, 1998). As such, Meadows (1998, p.9) highlights that the "very choice of an indicator is based upon some value, some inner human purpose that tells us what is important to measure." Furthermore, Oram (2010, p.31) highlights that as a central issue for society, sustainability is "everyone's concern." In turn, authors have emphasised the importance of involving multiple stakeholders in discussions on SIs (Celino and Concilio, 2010; Garmendia and Stagl, 2010; Robinson et al., 2011; Yang et al., 2011), including both expert stakeholders (e.g. natural scientists, sociologists, and engineers), and citizen stakeholders and their representatives (e.g. product users, local inhabitants, and politicians), to account for different values and perspectives (Pülzl et al., 2011; Rametsteiner et al., 2011). However, these differences mean that considerable negotiation may be involved in efforts to define or select SIs, which can be time consuming and fraught with intractable disagreements (Meadows, 1998).

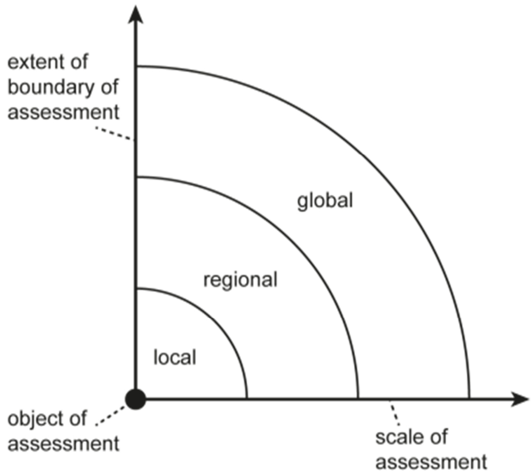


Figure 3-9: The different spatial scales of sustainability assessment (Paper C)

A second difficulty in defining and selecting SIs arises from the issue of complexity. As discussed in Section 3.3.1, sustainability research may be broadly split into two major streams: research on the sustainability of activities, and research on the sustainability of systems. Focusing momentarily on the latter, Meadows (1998, p.10) remarks that "[when] a system is extremely complex, it takes trial, error, and learning to produce a serviceable set of indicators." Complex systems are typically characterised by a high degree of connectivity (Holling, 2001; Meadows, 2008; Quental et al., 2010; Bodini, 2012); however, the relationships may not always be clearly revealed to humans attempting to formulate sustainability goals and indicators to assess them (Komiyama and Takeuchi, 2006; Dawson et al., 2010; Quental et al., 2010). Bodini (2012, p.140) suggests that relationships may reach such a high degree of complexity that "our perception of cause and effects is confounded." As a result, the goals and SIs that humans implement may lead to unexpected and/or undesired system behaviour (Holling and Goldberg, 1971; Quental et al., 2010).

Bodini (2012, p.140) highlights that the intricacy of the systems being assessed is compounded by the complexity of sustainability *per se.* The author remarks that sustainability "is a complex feature [of a system] that implies multiple dimensionality, but that also pertains to the system as a whole." In other words, multiple aspects of a system's behaviour may affect its sustainability, but its sustainability *per se* is a "whole system trait" (Bodini, 2012, p.146). In turn, Bodini (2012, p.140) argues that, "Multidimensionality and wholeness are two features that make the search for indicator systems to monitor sustainability very difficult." On the one hand, the goals and actions implemented by humans attempting to shift a system towards sustainability "operate at the single issue/single process level." On the other hand, the intended outcome of these goals and actions, i.e.

sustainability, emerges at the whole system level. Thus, authors write of the need to adopt a holistic perspective on behaviour in sustainability assessment, i.e. one that considers the multiple dimensions of behaviour that contribute to a system's sustainability, as well as how these dimensions interrelate to produce sustainability performance at the whole system level (Gasparatos et al., 2008; Darnhofer et al., 2010; Li and Yang, 2011; Lozano and Huisingh, 2011; Bodini, 2012; Singh et al., 2012; IISD, 2013). That is, decision makers should "review […] the whole system as well as its parts" in a sustainability assessment (IISD, 2013). This kind of perspective may also be referred to as a systems perspective (Bell and Morse, 2008; Meadows, 2008).

Based on the above discussion, the basic elements involved in indicator-based sustainability assessment approaches are illustrated in Figure 3-10 below.

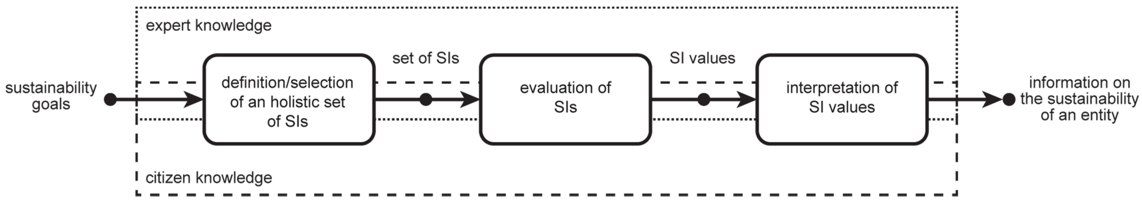


Figure 3-10: Key elements of indicator-based sustainability assessment approaches (adapted from Paper C)

3.5.2 Other approaches applied in sustainability assessment

As noted in Section 3.5.1, SI-based approaches are among the most prevalent approaches to sustainability assessment. Furthermore, Dalal-Clayton and Bass (2002) position this kind of approach as having the greatest potential with respect to various criteria including transparency, consistency, and usefulness for decision making. Nonetheless, Ness et al. (2007) highlight two other types of approach that may be applied under the umbrella of sustainability assessment. The first of these is life cycle assessment, discussed in Section 3.5.2.1. The authors also highlight a number of integrated assessment approaches, which are "used for supporting decisions related to a policy or a project in a specific region" (Ness et al., 2007, p.503). These are briefly outlined in Section 3.5.2.2.

3.5.2.1 Life cycle assessment

Life cycle assessment (LCA) approaches may be utilised to quantify and assess the environmental, economic, and/or social impacts of products and production systems throughout their life cycle (Kloepffer 2008; Zhang et al. 2010; Sharma et al. 2011). Accordingly, different types of LCA approaches may be identified in the literature including: environmental LCA, social LCA, and life cycle costing (LCC). Klöpffer and Ciroth (2011) propose that life cycle sustainability assessment (LCSA) is the combined application of environmental LCA, social LCA, and environmental LCC.

The approach generally referred to as 'life cycle assessment' in the literature focuses upon quantifying and interpreting the environmental impacts of products over their life. It may be termed 'environmental LCA' by authors (Benoît et al. 2010; Jørgensen et al. 2010; Zhang et al. 2010; Klöpffer and Ciroth 2011) to distinguish it from other types of LCA (discussed below). LCA has been standardised by the International Standards Organisation (ISO) in ISO 14040/2006 and ISO 14044/2006 (Ulgiati et al., 2011). It involves four stages, namely: (i) goal and scope definition; (ii) life cycle inventory analysis; (iii) life cycle impact assessment; and (iv) interpretation of results (Ofori-Boateng and Lee, 2014). According to Zhang et al. (2010, p. 2235), LCA focuses on "the most important processes in the life cycle and relies on detailed data about resource use and emissions of each process." LCA involves the evaluation of what are known as impact indicators. These indicators focus on various environmental aspects (e.g. climate change, acidification, eutrophication, ozone depletion, and so on), and are evaluated by assigning material/energetic flows to impact categories and converting them to equivalent units so that they may be compared and consolidated (SAIC, 2006).

Social LCA (SLCA) focuses upon quantifying and interpreting the social and socio-economic impacts of products throughout their life cycle (Benoît et al. 2010; Jørgensen et al. 2010). The function of SLCA is "to promote improvement of social conditions and of the overall socio-economic performance of a product throughout its life cycle for all of its stakeholders" (Benoît et al., 2009). The United Nations Environment Programme (UNEP), in conjunction with the Society of Environmental Toxicology and Chemistry (SETAC), have developed a set of guidelines for conducting SLCA, entitled "Guidelines for Social Life Cycle Assessment of Products" (Benoît et al. 2009; Benoît et al. 2010). The SLCA methodology draws extensively from the environmental LCA approach. Like LCA, it involves goal and scope definition, life cycle inventory, and life cycle impact assessment stages. SLCA uses indicators to quantify the social and socio-economic impacts of a product, which may be qualitative or quantitative in nature. SLCA considers the impacts of products on different groups of stakeholders: workers/employees, local community, society (national and global), consumers, and value-chain actors (Benoît et al. 2010; Jørgensen et al. 2010).

Finally, life cycle costing (LCC) focuses upon quantifying and interpreting the costs of products throughout their life cycle (Kloepffer 2008; Benoît et al. 2009). LCC approaches traditionally dealt with financial costs, but more recent approaches account for environmental as well as economic costs. Such approaches have been referred to as environmental LCC (ELCC) by authors. Kloepffer (2008) argues that for LCSA, only ELCC is appropriate for assessing life cycle costs. SETAC have issued a code of practice for ELCC. According to Swarr et al. (2011, p. 389), ELCC involves "conceptual foundations and methodological approaches" that are "distinct and different" to those of LCA. For example, ELCC does not involve impact assessment and does not use impact indicators. Rather, the results of ELCC are presented in an aggregated form as a "calculated cost per functional unit expressed in one of the well known currencies" (Kloepffer 2008, p. 91). Key steps in LCC and ELCC include defining cost categories, selecting methods for measuring costs, setting system boundaries, and setting a discount rate (Benoît et al., 2009). According to Swarr et al. (2011, p. 390), it is important to avoid "counting the same environmental impacts in both financial and physical terms" during the assessment, an error known as double counting.

3.5.2.2 Integrated assessment approaches

As noted in the introduction to Section 3.5.2, integrated assessment approaches are "used for supporting decisions related to a policy or a project in a specific region" (Ness et al., 2007, p.503). Impact assessment may be viewed as a key integrated assessment approach (Ness et al., 2007). De Smedt (2010) analyses the use of impact assessment tools in relation to the EU sustainable development strategy. They delineate sustainability impact assessment as "a process that prepares […] evidence on the advantages and disadvantages of possible policy options by assessing their potential effects." The European Union has developed an IA system intended to be used to assess "all significant economic, social and environmental impacts of possible new initiatives" within the European Community. They outline five key elements involved in the analysis of the impacts of policies, which may be paraphrased here as: identification of direct and indirect economic, social and environmental impacts and how they occur; identification of who is affected and in what way; assessment of the impacts against the baseline in qualitative, quantitative and monetary terms; identification and assessment of administrative burden/simplification benefits; and consideration of the risks and uncertainties in the policy choices, including obstacles to transposition/compliance (European Commission 2009, p. 5).

There are a number of tools and methods for sustainability impact assessment (IA). For example, the Tool for Sustainability Impact Assessment (ToSIA) may be used to assess the impacts of potential forestry sector activities on forestry-wood chains to decision-makers, through specially developed software (Lindner et al., 2010). A similar tool, called the Sustainability Impact Assessment Tool (SIAT) has been developed for assessing the impacts of potential policies and actions in land-use sectors (SENSOR 2009; Päivinen et al. 2010). Indicator models and simulations of particular systems or regions may also be used to gain insights into the potential environmental, economic and social impacts of policies and actions on the system over time (Pülzl et al. 2011; Rametsteiner et al. 2011). In any case, Ness et al. (2007) suggest that impact assessment tools tend to be based on methodologies that capture the viewpoints and preferences of multiple stakeholders.

In addition to impact assessment, Ness et al. (2007, pp.503-504) highlight several other approaches falling into the category of integrated assessment approaches, namely:

- conceptual modelling, used for "visualising and detecting where changes in a given system can be made for increasing sustainability";
- systems dynamics, referring to "the building of computer models of complex problem situations and then experimenting with and studying the behaviour of these models over time" (Caulfield and Maj (2001), cited in Ness et al. (2007, p.504);
- multi criteria analysis, used to identify goals and objectives and to "spot the trade-offs between them," with the ultimate goal of "identify[ing] the optimal policy";
- risk analysis, involving the identification of a particular risk, followed by "a qualitative and/or quantitative assessment of the risk" and "communication with stakeholders concerning the assessment and the corresponding decisions involved with minimising the risk";
- uncertainty analysis, which is closely tied to risk analysis and involves estimating "the probability of events and predicting the events using the knowledge that is available";
- vulnerability analysis, which "evaluates the vulnerability of coupled human–environment systems" and aims to "determine how sensitive and resilient systems are to changes, and how capable systems are to cope with changes"; and
- cost-benefit analysis, a method originating in welfare economics that in a sustainability context, involves "weighing the social costs and benefits of different alternatives in connection with e.g. energy and transports."

3.6 Summary

This chapter has presented a review of sustainability research spanning multiple sectors of society, namely: agriculture, business, design, socio-economic development, economics, fisheries, forestry, urban studies, and sustainability science. In Sections 3.1 and 3.2, three different viewpoints on the sustainability concept that may be identified in the literature were outlined, i.e. V1, V2, and V3. In Section 3.3, an overview of different types of sustainability emerging from the literature was presented. Finally, Sections 3.4 and 3.5 explored the realisation of sustainability, i.e. how it is achieved and assessed. In Sections 3.1 – 3.3, the following key points were discussed:

- four lexical definitions of sustainability (V1) may be identified in the literature, which can be viewed as synonymous from the perspective of dictionary entries: (i) the ability to sustain; (ii) the ability to continue; (iii) the ability to maintain something; and (iv) the ability to be maintained by something (Section 3.1.1);
- to move from the abstract definitions above to a more concrete one, humans make value judgements regarding what entities to sustain and for how long (Section 3.1.2) – that is, they specify sustainability objectives (V2);
- four interpretations of the basic constitution of sustainability (V3) may be seen to emerge from the literature, i.e. sustainability interpreted as: (i) an ability; (ii) a process of change; (iii) a property or attribute of an entity; and (iv) a state of an entity (Section 3.2);
- sustainability research may be broadly split into two streams of research on the sustainability of activities and the sustainability of systems in different sectors, with different categories of research emerging from each stream (e.g. the sustainability of design from the activities stream, and the sustainability of complex systems from the system stream) (Section 3.3.1);
- different types of sustainability may be seen to emerge from each research category, e.g. agricultural sustainability (Section 3.3.1);
- each type of sustainability may be considered from the three viewpoints outlined in Sections 3.1 – 3.2, , with authors often adopting different perspectives in relation to these viewpoints (Section 3.3.1);
- sustainable development may be viewed as among the most prolific types of sustainability discussed in the literature – however, certain authors may be seen to equate sustainable development with sustainability *per se*, suggesting a lack of clarity with respect to the relationship between the two concepts (Section 3.3.2); and
- sustainability may be considered from an anthropocentric and/or a non-anthropocentric perspective – owing to the focus of this thesis on technical

systems, an anthropocentric perspective will be adopted throughout (Section 3.3.4).

The key points discussed in Sections 3.4 and 3.5 may be summarised as:

- sustainability goals may be viewed as the means by which humans shift their activities and society towards sustainability – that is, statements about what is required in order to achieve sustainability objectives (Section 3.4);
- sustainability goals identifiable in the literature may be seen to be formulated from two different viewpoints on sustainability and society: (i) a physical viewpoint, considering what we physically *can* and *cannot* sustain given the natural laws and limits of the Earth system; and (ii) an ethical viewpoint, considering what we *should* and *should not* sustain given the moral/social standards of human beings (Section 3.4);
- sustainability goals formulated from viewpoint (i), i.e. physical, typically focus on sustaining those elements of the Earth system that are required by human activities and systems so that they can physically continue to operate over time, e.g. the resource base and waste processing capacity (Section 3.4);
- sustainability goals formulated from viewpoint (ii), i.e. ethical, typically focus on sustaining normative concepts, e.g. health, social equity, and livelihood security (Section 3.4);
- sustainability assessment may be seen to provide humans with information on the behaviour and performance of entities from a sustainability perspective, which may in turn be used to make decisions in efforts towards sustainability (Section 3.5);
- indicator-based sustainability assessment approaches emerge from the literature as among the most prolific, and four different categories of sustainability indicators may be identified (Section 3.5.1): accounting indices, ecological and physical flow indicators, sustainable development indicators, and ecological indicators;
- indicators may be evaluated at different spatial scales ranging from local to regional to global, along different timescales, and from different temporal perspectives, i.e. retrospective or prospective (Section 3.5.1);
- a holistic perspective on behaviour is required in sustainability assessment, i.e. one that considers the multiple dimensions of behaviour that contribute to an entity's sustainability, and how these impact upon sustainability at the whole system level (Section 3.5.1); and
- in addition to SIs, two other kinds of approach may be applied in sustainability assessment: life cycle assessment (environmental, social, and

cost-based); and integrated approaches such as impact assessment and multi criteria analysis (Section 3.5.2).

In Section 3.4, a framework for developing and managing sustainable development indicators, known as the Daly triangle, was outlined. In this framework, four types of capital typically considered in research on sustainability in an economics context (i.e. manufactured, natural, human, and social, as discussed in Section 3.3.4) are organised into categories of "means" and "ends" contributing to human well-being. Among these four types of capital is what may be termed "built" (Meadows, 1998, p.41), "manufactured," or "human made" (Ekins, 2011, p.633) capital. According to Meadows (1998, p.53), manufactured capital may be viewed as "the human-made tools, machines, factories, smelters, electric generators, pumps, trucks that create output without themselves being consumed (or at least that create output while themselves depreciating only slowly)." In other words, technical systems. That is, artificial systems designed and built by humans to meet the needs of society (Hubka and Eder, 1988).

Meadows (1998, p.43) provides examples of the range of technical systems serving the economy, including "steel mills, cement plants, car factories, construction equipment, lathes, tractors, buildings, oil wells, chainsaws, [and] power plants." Indeed, technical systems may be viewed as ubiquitous throughout the sectors considered in the literature review presented in this chapter. Thus, they play a fundamental role in driving economic production and ultimately, the societal progress that may result from such production (Hubka and Eder, 1988). However, Meadows (1998, p.43) highlights the potential impacts of technical systems on the wider Earth system: "a piece of built capital – a furnace, say, or a paper mill, or an irrigation system – requires a specific stream of throughput from natural capital (materials, energy, water) in order to function. It [also] releases a specific stream of waste and pollution." Accordingly, the sustainability of technical systems is increasingly under scrutiny (Park et al., 2005). To understand the key issues and challenges for research in this area, a review of the literature on sustainability of technical systems is presented in Chapter 4.

4 Research on sustainability in a technical systems context

In Chapter 3, sustainability research spanning multiple sectors of society was reviewed, providing an overview of key perspectives on: (i) the meaning, value, and constitution of sustainability, in both a general sense and within specific contexts; (ii) sustainability goals for human activities and systems; and (iii) sustainability assessment of human activities and systems. Technical systems were introduced as ubiquitous elements of manufactured capital throughout the sectors reviewed, driving economic production and consumption and ultimately, the societal progress that may result from economic activity.

Goodland (1995, p.7) remarks that although there is no true consensus on whether or not society is actually unsustainable, "What is not contestable is that the modes of production prevailing in most parts of the global economy are causing the exhaustion and dispersion of a one-time inheritance of natural capital – topsoil, groundwater, tropical forests, fisheries, and biodiversity." This sentiment is reflected in the more current work of Ehrlich and Ehrlich (2013, p.1). The authors highlight recent studies examining society's ecological footprint, which indicate that supporting "*today's* population of seven billion sustainably (i.e. with business as usual, including current technologies and standards of living) would require roughly half an additional planet; to do so, if all citizens of Earth consumed resources at the US level would take four to five more Earths." Chapman (2011, p.33) argues that the "comprehensive axiom" governing human activity in the twenty first century may be described thus: "production and consumption in their current guises are both inequitable, and without a future."

Daly (1990a, p.3) highlights that "[in] production a flow of matter and energy from nature is transformed into a flow of finished products by a stock of transformers, namely labor and capital." In Chapter 3, four types of capital that may be considered in sustainability research were introduced and illustrated in the Daly triangle (Daly, 1992; Meadows, 1998). Labour may be viewed as an element of what is termed human capital (Goodland, 1995; Meadows, 1998). Additionally, manufactured capital, natural capital, and social capital may also be discussed in relation to economic production. The "capital" carrying out the transformation described by Daly (1990a) above is manufactured capital, i.e. entities such as "steel mills, cement plants, car factories, construction equipment, lathes, tractors, buildings, oil wells, chainsaws, [and] power plants" (Meadows, 1998, p.43). In other words, technical systems. That is, artificial systems designed and built by humans to meet the needs of society (Hubka and Eder, 1988).

As highlighted at the end of Chapter 3, a technical system "requires a specific stream of throughput from natural capital (materials, energy, water) in order to function. It [also] releases a specific stream of waste and pollution" (Meadows, 1998, p.43). In the 1980s, Hubka and Eder (1988, p.32) suggested that the "equilibrium of […] ecosystems should be respected and considered" in the development and operation of technical systems. Today, there is a general consensus that these systems may have a considerable impact on the resource base and the wider Earth system throughout their life cycle (Ulgiati et al., 2006; Stasinopoulos et al., 2009). Accordingly, the sustainability of technical systems is increasingly under scrutiny. For instance, organisations in the business of designing and manufacturing technical systems typically need to evaluate and report the performance of their technical products as part of a comprehensive sustainability report (ISO, 1999; Park et al., 2005; Global Reporting Initiative, 2013a). Additionally, whilst sustainability reporting is generally a voluntary activity (Lozano and Huisingh, 2011), organisations are also under increasing regulatory pressure to improve the sustainability of their technical products (Park et al., 2005; Holan Fenwick Willan, 2013; Brynolf et al., 2014).

Technical systems may be viewed as ubiquitous throughout the sectors considered in the literature review presented in Chapter 3. Thus, they play a fundamental role in driving economic production across society (Hubka and Eder, 1988). Technical systems may also be consumed, in an economic sense, in the form of consumer products such as electronic goods, domestic appliances, cars, and even simplistic products such as cooking and eating utensils, pens, and domestic fixtures and fittings including taps, door handles, light fittings, and so on (Hubka and Eder, 1988; Eder, 2003). Given the increasing attention paid to the sustainability of these systems, this chapter presents a review of the literature on sustainability research in a technical systems context. The aim is to provide an overview of the key concepts involved, as well as perspectives on sustainability and its nature in this area. In Section 4.1, the nature of technical systems is explored. The technical system life cycle is introduced, and design is highlighted as a key activity with respect to improving the sustainability of technical systems. Accordingly, in Section 4.2, research on sustainability-oriented engineering design is reviewed, centring on five sustainability-oriented design philosophies and their associated methods/tools as discussed in the literature. Performance evaluation is revealed as a key activity, providing information to support decision making during sustainability-oriented design. In Section 4.3, literature on sustainability performance evaluation of technical systems in a broader organisational context is considered, providing greater insight into the methods and indicators applied. Finally, Section 4.4 provides a summary of the key points covered.

Certain sections in this chapter draw from papers appended to this thesis. Section 4.1 expands upon material covered in Sections 3 and 4 of Paper B (Appendix 2). Section 4.2 presents a summary of certain key points and observations from Paper A (Appendix 1). Finally, Section 4.3 presents a summary of material covered in Sections 2 and 3 of Paper B.

4.1 The nature of technical systems

As highlighted in Hubka and Eder (1988, p.7), technical systems may be viewed as "the "technical means" by which the human achieves his [or her] "ends"." That is, artificial systems designed and built by humans to satisfy their needs. The label encompasses all technical products and processes, from simple consumer products up to large scale, complex systems such as ships and aircraft (Hubka and Eder, 1988; Eder, 2003). As noted by Hubka and Eder (1988, p.58), the technical systems developed to meet the needs of society are "practically unlimited in numbers, quantity, and variety." As a form of manufactured capital, they may be viewed as both outputs of economic production and key enablers of human activity generally. Technical systems may also be consumed, in an economic sense, in the form of consumer products (Eder, 2003; Chapman, 2011). The role of technical systems in driving human activity is illustrated in Hubka and Eder's (1988) model of a socio-technical transformation system, briefly discussed in Chapter 1 (Section 1.1.1) and presented in Figure 4-1. As shown in Figure 4-1, technical systems exert effects that drive the transformation of an operand from an input state to an output state. They are managed and influenced by human systems and what is termed the "active environment" – that is, information systems and management systems for goal-setting. As discussed in Chapter 1, the transformation system and consequently, the technical systems driving it, have relationships with ecosystems in terms of inputs of resources from natural stocks, and outputs of waste to natural sinks. An overview of certain technical systems employed in major branches of the economy is provided in Table 4-1, representing a fraction of the total range of technical systems in existence (Hubka and Eder, 1988).

Technical systems are conceived and developed through the processes of engineering design (Hubka, 1982; Hubka and Eder, 1988) and, particularly in the case of large-scale, complex technical systems, systems engineering (Blanchard and Fabrycky, 1981; Sage, 1992; Stasinopoulos et al., 2009). In each case, the process begins with knowledge of some human need (Hubka and Eder, 1988; Sage, 1992), that is typically based on "a "want" or "desire" for some item(s) arising out of a perceived deficiency" (Blanchard and Fabrycky, 1981, p.240). This knowledge is then evolved through various design and engineering activities to produce a system design that is refined into a detailed final layout with the properties required to satisfy the initial need. The system is then realised through production and manufacturing processes, and enters into its operational life where it will "serve industry and mankind" (Hubka and Eder, 1988, p.27) until it is decommissioned and recycled or disposed of (Blanchard and Fabrycky, 1981; Hubka and Eder, 1988; Ulrich and Eppinger, 2008). Collectively, these stages – manufacturing (including transportation of components), operation, and recycling and disposal – may be termed the "life cycle" of a technical system (Blanchard and Fabrycky, 1981; Lindahl, 2001; Stasinopoulos et al., 2009), illustrated in Figure 4-2. Additionally, extraction and processing of the raw materials required to manufacture the system may also be included as a stage preceding manufacture in the life cycle (Ulgiati et al., 2011; Adams and McManus, 2014) . The design and development of the system may also be viewed as part of the life cycle (Stasinopoulos et al., 2009). Here, these activities are considered to be part of the manufacturing stage. As discussed in Chapter 3 (Section 3.3.3), in efforts to manage the environmental impacts associated with these various stages, the life cycle may be considered from either a cradle-to-grave or a cradle-to-cradle perspective. That is, focusing on either the reduction or elimination of waste, respectively. As will be shown in Section 4.3, the life cycle is a key concept in sustainability assessment of technical systems.

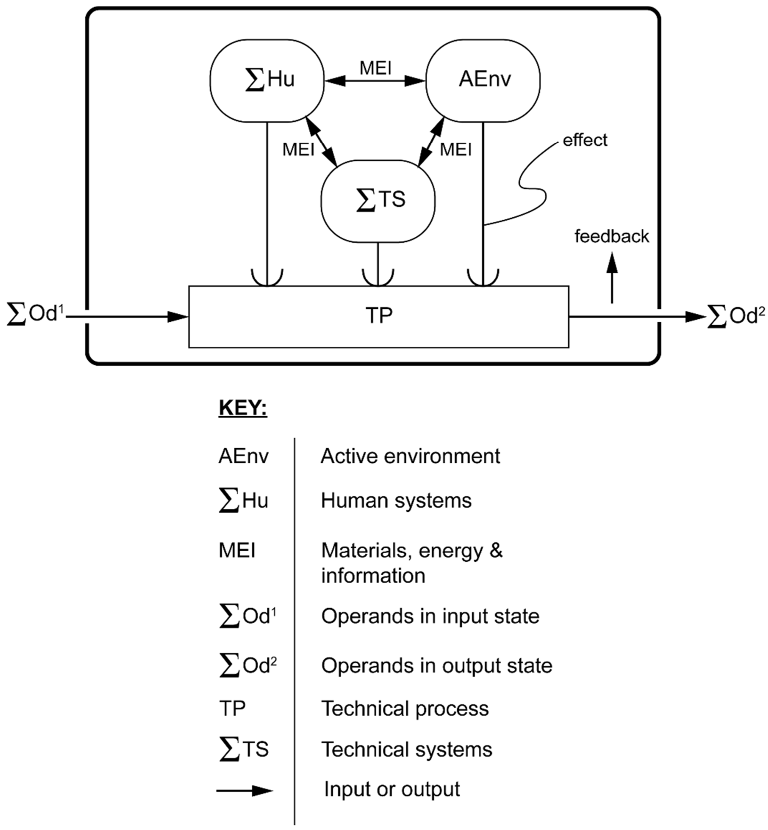


Figure 4-1: Model of a socio-technical transformation system (adapted from Hubka and Eder (1988, p.23))

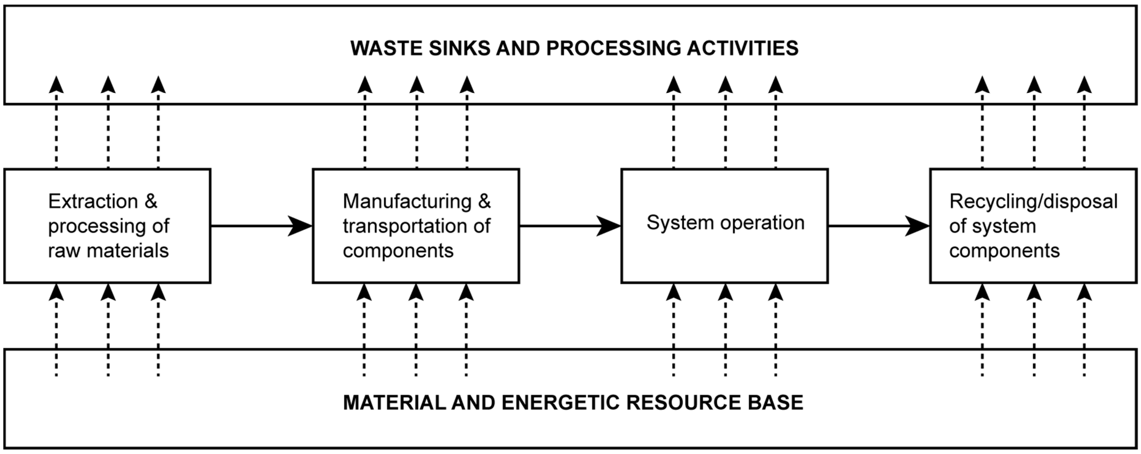


Figure 4-2: The technical system life cycle

Table 4-1: Examples of technical systems driving activity in different sectors of the economy (adapted from Hubka and Eder 1988, p.94)

Economic sector	Examples of typical technical systems
Agriculture	Chain saw
	Combine
	Tractor
Chemical industry	Distillation column
	Piping
	Pressure vessel
Construction	Block press
	Concrete mixer
	Drill rig
	Personnel lift
	Scraper
Distribution and trade	Check out
	Wrapping machine
Energy generation	Gas turbine
	Generator
	Steam boiler
	Steam turbine
	Water conditioner
	Water turbine
Food industry	Centrifuge
	Concentrator
	Press
Information technology	Monitor
	PC/laptop
	Printer
Medicine	Artificial heart
	Prosthesis
	X-ray apparatus
Metalworking industry	Forging hammer
	Forming machine
	Furnace

Economic sector	Examples of typical technical systems
	Jigs and fixtures
	Machine tool
	Press
Mining	Conveyer
	Cutting machine
	Screening machine
Smelting	Blast furnace
	LD oxygen processor
	Rolling mill
Textile industry	Sewing machine
	Spinning machine
	Weaving loom
Transportation	Locomotive
	Passenger liner
	Rocket
	Wagon

As discussed above and illustrated in Figure 4-3, technical systems are developed in response to human needs. These needs are met during the operation phase of the life cycle, where the system carries out the *function(s)* it was designed for (Blanchard and Fabrycky, 1981; Hubka and Eder, 1988). Function refers to 'what the technical system is for' (Gero and Kannengiesser, 2004). Note that whilst elementary systems may fulfil a single function, more complex systems are likely to have multiple functions (Hubka and Eder, 1988). The basic nature of technical systems may be understood from the perspective of function along with two other interrelated elements, illustrated in Figure 4-3: *behaviour* and *structure*. Behaviour refers to 'what a system does' (Gero and Kannengiesser, 2004; Wang et al., 2008). A technical system fulfils its function by exhibiting a certain kind of purposeful behaviour (Hubka and Eder, 1988; Wang et al., 2008). This behaviour is manifested through the system's structure and its interactions with its surrounding environment. The structure of a system refers to "what its components are, how they are connected, and what passes across those connections" (Tully, 1993, p.46). That is, the individual *system components* and the *relationships* among them (Gero and Kannengiesser, 2004; Meadows, 2008). Humans may interpret the behaviour of a technical system by measuring the *performance* that it produces (Wang et al., 2008), again illustrated in Figure 4-3. Information on performance may be used to support decision making with respect to the system and various aspects of its life cycle, as discussed in Sections 4.2 and 4.3.

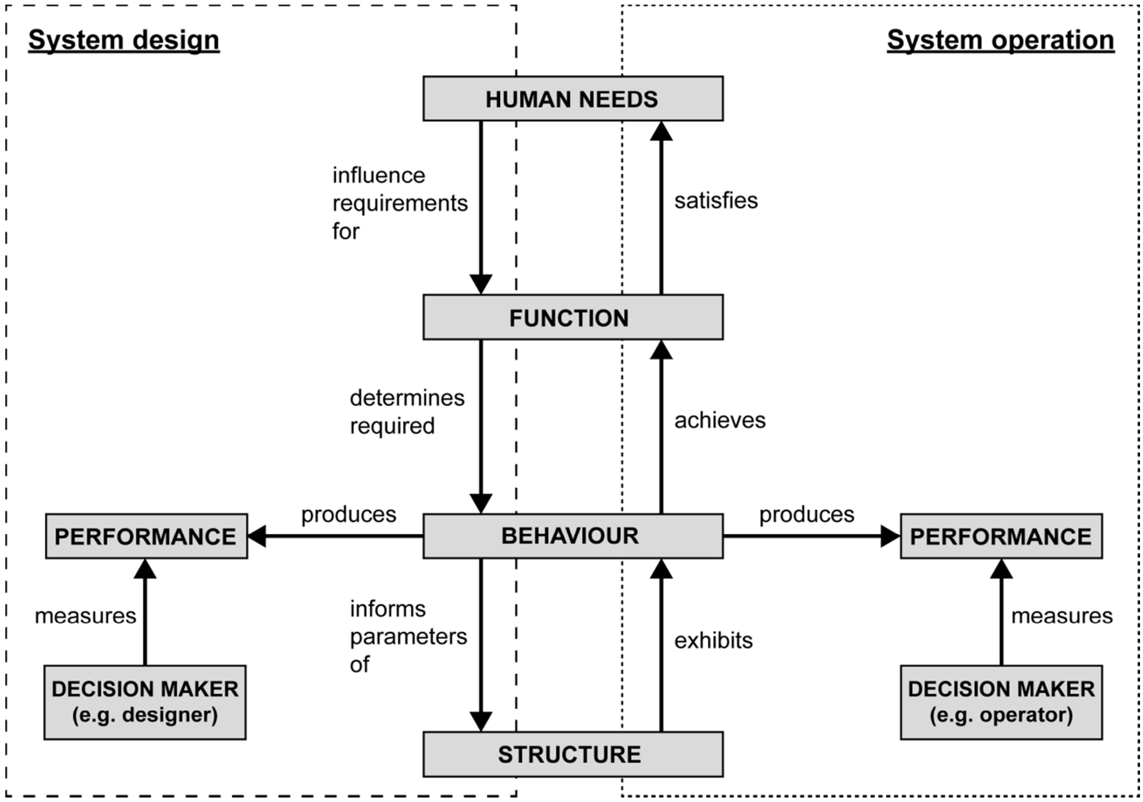


Figure 4-3: Technical system function, behaviour, performance, and structure in relation to humans

To illustrate the rather abstract notions of function, behaviour, and structure, consider a car, a common example of a technical system. A car satisfies a human need for the transportation of people and other entities by fulfilling the function of moving objects from one place to another. Key components of a car include the fuel system, the engine, the drivetrain, the wheels, the exhaust system, and the chassis. In turn, these components may be seen to be interrelated in a number of ways: the fuel system supplies fuel and air to the engine; the engine combusts this fuel and air to produce mechanical power, which is transmitted to the wheels by the drivetrain; the exhaust system channels the byproducts of combustion away from the engine; and the chassis contains the other components and protects them from damage. On a high level, the purposeful behaviour exhibited by the car in relation to its function may be described as the transformation of a fuel source into translational motion of the whole car and its load via a series of sub-transformations (e.g. the transformation of fuel and air into torque, torque into rotational motion, and rotational motion into translational motion).

Tully (1993, p.46) highlights that unlike natural systems, the structure of a technical system is "controlled by the engineer." In designing a technical system, an engineer is essentially defining and refining a structure that will exhibit the behaviour required to fulfil a certain desired function (Tully, 1993; Gero and Kannengiesser, 2004; Wang et al., 2008), as shown in Figure 4-3. As such, a technical system may be generally defined as a system comprised primarily of artificial components (Hubka and Eder, 1988), where most of the structural parameters have been defined by humans so that the system will behave in a particular way (Tully, 1993).

As discussed in the introduction to Chapter 4, organisations are under increasing regulatory pressure to improve the sustainability of their technical products (Park et al., 2005; Holan Fenwick Willan, 2013; Brynolf et al., 2014). In this respect, design may be viewed as a key activity in the development of a technical system (Park et al., 2005; Stasinopoulos et al., 2009; Spangenberg et al., 2010). For instance, Unger et al. (2008, p.14) remark that "[it] is assumed that about 80% of all environmental effects associated with a product are determined in the design phase of development." In particular, authors position the early stages of design as holding the greatest potential for significant sustainability improvements to products (Park et al., 2005; Lu et al., 2011; Bovea and Pérez-Belis, 2012). Given the potential significance of design with respect to the sustainability of technical systems, research on sustainability-oriented design in a technical systems context is reviewed in Section 4.2.

4.2 Designing sustainable technical systems

In Chapter 3 (Section 3.3), design was highlighted as a key category of sustainability research emerging from the stream of research focusing on the sustainability of activities. In turn, as discussed in Section 4.1, design is cited as a key activity with respect to improving the sustainability of technical systems. Accordingly, the literature on sustainability-oriented engineering design is reviewed in this section. The intention is to provide an overview of key perspectives on sustainability in engineering design, and the major design methods and tools applied in designing sustainable technical systems.

4.2.1 Overview of sustainability-oriented engineering design

As discussed in Section 4.1, technical systems are typically a product of engineering design and/or systems engineering. From a social and technical perspective, design has undergone considerable evolution over the years (Duffy, 2005), from early craft based design (Hubka, 1982; Jones, 1991), through to design-by-drawing, system designing (Jones, 1991), and the notion that design is a fundamental activity of human life generally (Papanek, 1972; Jones, 1991; Wahl and Baxter, 2008). From the latter perspective, design may be viewed as a driver of socio-technical change (Lopes et al., 2012), defined by Jones (1991, p.32) as "the fitting of products and systems to newly emerging forms of society." O'Donnell and Duffy (2002, p.1199) position design as an element of product development processes, which are viewed as a type of business process. In turn, business processes may be viewed as sub-processes of larger scale consumption and production processes operating within an economy, using labour and capital and contributing goods and services to the economy (Dyllick and Hockerts, 2002; McDonough and Braungart, 2002a; Figge and Hahn, 2004). Finally, economic consumption and production may be considered to contribute to the overarching socio-economic development processes driving societal progress (Costanza and Daly, 1992; Tischner and Charter, 2001; Eurostat, 2013). In short, design may be viewed as ultimately contributing to the socio-economic development process forming the focus of the sustainable development concept (Tischner and Charter, 2001; Chapman, 2011; Spangenberg et al., 2010), discussed in Chapter 3 (Section 3.3.2). The relationship between design and higher-order processes is illustrated in Figure 4-4.

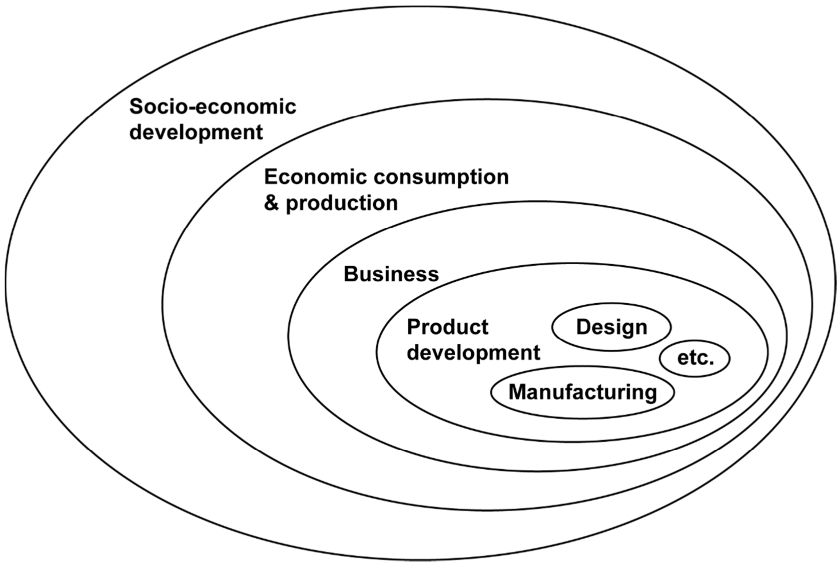


Figure 4-4: The relationship between design and higher-order socio-economic processes
(based on O'Donnell and Duffy (2002, p.1199) and Tischner and Charter (2001, p.120)

Socio-technical change is argued to be a necessary element of the transition to sustainability that was discussed in Chapter 3 (Kemp and Parto, 2005; Beddoe et al., 2009; Laitala et al., 2011; The Royal Society, 2012). Accordingly, given its nature as discussed above, design is positioned by authors as a key driver of this change and in turn, of the sustainability transition (Tischner and Charter, 2001; Shedroff 2009; Spangenberg et al., 2010; Lopes, Fam, and Williams 2012). However, design is also argued to be a root cause of the sustainability problems it is now expected to address (Shedroff, 2009). Over forty years ago, Papanek (1972, p.57) remarked upon the need to develop a particular kind of "social and moral responsibility" in design, suggesting that designers are responsible for "nearly all of our environmental mistakes." The author argues that by "repeating his [or her] mistakes a millionfold or more through designs affecting all of our environments, tools, machines, shelters, and transportation devices, the designer-planner has finally put murder onto a mass production basis." Since then, Bhamra and Lofthouse (2007, p.2) highlight that "there has been a growing feeling in many environmental circles that design and manufacture is responsible for many of the man-made stresses imposed on the planet."

The realisation that design may have negative impacts on the environment and society has resulted in a drive to integrate sustainability considerations into design thinking and practice. In this respect, a number of authors have provided new perspectives on design and proposed new approaches. The intention is generally to foster a greater sense of ethical responsibility in the designer, and to integrate environmental, economic, and/or social considerations into designing with a view to improving the impacts of design (e.g. Papanek, 1972; Tischner and Charter, 2001; Manzini, 2006; Braungart and McDonough, 2008; Chapman, 2011). This may be seen to align with the three pillars of sustainable development introduced in Chapter 3 (Section 3.3.2), i.e. the triad of environmental, economic, and social sustainability objectives typically pursued in a socio-economic development context. In a design context, the pillars may be discussed in terms of what is known as the triple bottom line (McDonough and Braungart, 2002a; Fiksel, 2003; Hindle, 2009), a set of sustainability objectives for business: "profitability," "environmental quality," and "social justice" (Elkington, 1998, p.xiii). Certain authors present the integration of sustainability considerations into design over the decades as a gradual broadening of the designer's remit, as shown in Figure 4-5. That is, from a relatively narrow focus on conventional design considerations such as aesthetics, cost, and quality, to the inclusion of environmental considerations in designing, and finally integrating considerations regarding the social and economic impacts of products alongside these (Tischner and Charter, 2001; Bhamra and Lofthouse, 2007).

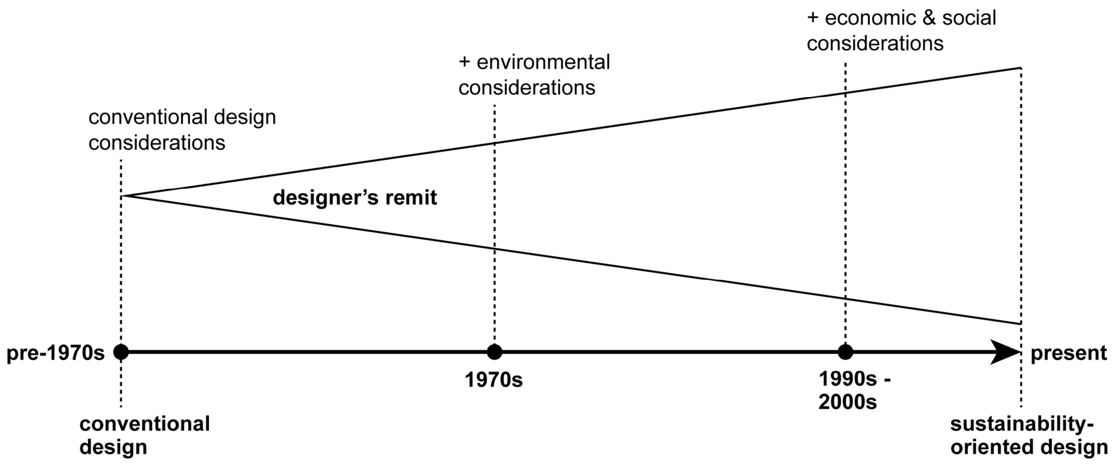


Figure 4-5: The increasing integration of sustainability considerations into design (based on Bhamra and Lofthouse (2007, pp.38-39))

As discussed in Section 4.1, designing a technical system involves defining and refining a structure that will exhibit the behaviour required to fulfil a certain desired function (Tully, 1993; Gero and Kannengiesser, 2004; Wang et al., 2008). This highlights two fundamental elements of designing: (i) the design artefact, i.e. what is being designed (a technical system in this case, hereafter referred to as a technical artefact); and (ii) the design activity, i.e. the processes by which the artefact is developed and refined (Hubka, 1982; O'Donnell and Duffy, 2005; Wang et al., 2013). Jones (1991, xi) remarks that, "Designing, if it is to survive as an activity through which we transform our lives, on earth, and beyond, has itself to be redesigned, continuously." Along these lines, Wahl and Baxter (2008, p.72) suggest that in order to effectively tackle sustainability issues through design, there is a need to redesign both the "way we think about" design and the "practices" we adopt in carrying it out. This may be seen to highlight two means by which sustainability considerations may be integrated into design:

- *The development and application of sustainability-oriented design philosophies* (Bhamra and Lofthouse, 2007). A design philosophy may be viewed as an overarching design concept, that expresses certain values and perspectives on design held by an individual (e.g. a lone designer) or a group of individuals (e.g. the design department of an organisation) (Yoshikawa, 1989; Evbuomwan et al., 1996; Hernandez, 2010) . Typically, a design philosophy may be articulated in terms of broad aims and basic principles for design (Yoshikawa, 1989; Bhamra and Lofthouse, 2007; Hernandez, 2010; Gould, 2011) . Essentially, a design philosophy defines the designer's frame of reference for carrying out design activities. Thus, design philosophies may be seen to guide the way that designers *think* about design (Evbuomwan et al., 1996).

- *The development and application of new design methods and tools, and/or the modification of existing ones* (Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010). A design method may be viewed as an identifiable way of working that supports a designer in meeting design goals or finding a solution to a problem (Lindahl, 2006; Cross, 2008) . The notion of a design tool is closely related to that of a design method, and may be viewed as a physical or intangible means that supports a designer in meeting design goals or finding a solution to a problem (Lindahl, 2006). Generally speaking, a design tool may be used to support the application of a particular design method (Cross, 2008). For instance, the House of Quality may be viewed as a tool to support the application of the Quality Function Deployment method (Bovea and Wang, 2007). Essentially, design methods and tools provide formal guidance to designers with respect to the practical elements of design activities. Thus, they may be seen to guide the way that designers *carry out* design (Lindahl, 2006; Cross, 2008).

A number of sustainability-oriented design philosophies have emerged over the decades (Bhamra and Lofthouse, 2007; Chapman, 2011; Skjerven, 2012), and a plethora of design methods and tools are now positioned as conducive to the delivery of more sustainable artefacts (Waage, 2007; Bovea and Pérez-Belis, 2012; Gagnon et al., 2012). Certain authors suggest that the literature on sustainability-oriented design has expanded to such a degree that something of a saturation point has been reached. For example, from a practical perspective, Byggeth et al. (2007a, p.1) highlight the work of Baumann et al. (2000), who claim that "there is too much tool development and too few studies and evaluations of existing tools." Chapman (2011, p.172) remarks that, "Large amounts of time and energy are spent attempting to define whether what you do is design for environment, ecodesign, sustainable design, design for sustainability, low-impact design, green design, clean design, and so on, and so on." They argue that, "The way in which we both discuss and name our practice […] needs resolving, and fast." Thus, it may be concluded that there is a lack of clarity regarding the nature and differentiation of current approaches to sustainability-oriented design. This may be seen to be supported to some extent by Tischner and Charter (2001, p.120), who remark that terms such as "'sustainable product design', 'ecodesign', 'design for environment' and even 'product design' are often confused and are not clearly defined or well known."

In order to clarify the range of sustainability-oriented design philosophies and methods/tools currently discussed and applied in the design of technical systems, a literature investigation was undertaken. A sample of 83 sources primarily drawn from the engineering design literature was considered, including a mixture of sources reporting the development, practical application, and evaluation/analysis of philosophies, methods, and tools. Literature reviews focusing on design philosophies, methods, and tools from the perspective of sustainability were also included. The literature sample is presented in full in Table 1 of Paper A, Appendix 1. As highlighted in Paper A, sources were drawn from a number of contexts within the broad area of engineering design. Additionally, certain sources from an industrial design context were included, given that industrial design may be viewed as occupying a position "between art and engineering" (Bhamra and Lofthouse, 2007, p.3). In the interests of transparency, the contexts considered were:

- architecture and building design, e.g. Gamage and Hyde (2012) and Wigum et al. (2011);
- electrical/ electronic design, e.g. Unger et al. (2008) and Boks and Stevels (2003);
- industrial design, e.g. Rodriguez and Boks (2005) and Bhamra and Lofthouse (2007);
- process design, e.g. Hossain et al. (2010) and Taras and Woinaroschy (2012);
- product design and development, e.g. Byggeth et al. (2007a) and Chapman (2011); and
- systems design, e.g. Stasinopoulos et al. (2009) and Alfaris et al. (2010).

It should be noted that systematic reviews providing a more detailed and comprehensive treatment of certain parts of the literature on sustainability-oriented design have been conducted by other authors. For instance, Pigosso et al. (2011)conducted a systematic review of 560 sources from the ecodesign literature, revealing and classifying 105 ecodesign methods and tools. Similarly, Blizzard and Klotz (2012) systematically reviewed 49 sources on sustainable design in order to characterise a framework for sustainable whole systems design. In contrast with these, as stated above, the aim of the review reported in this section is to provide a general overview of key perspectives on sustainability in engineering design, and the major design methods and tools broadly applied in designing sustainable technical systems. The findings of the literature investigation are presented in full in Paper A (Appendix 1); however, certain key points and observations are discussed in Sections 4.2.2 and 4.2.3. Given the aim, a detailed discussion on the nature of every design philosophy, method, and tool identified from the sample falls outside the scope of this section. Rather, a summary of the state of the art is provided. Certain key issues emerging from the state of the art that are relevant with respect to the aim of this thesis are discussed in Chapter 5. Readers are referred to Paper A for more extensive discussion on the concepts discussed in the following sub-sections. Additionally, the complete range of design philosophies, methods, and tools identified from the sample, along with the full list of supporting authors, is included in Appendix 6. The analysis conducted to calculate percentages presented in Figures 4-5, 4-6, 4-8, and 4-9 is also outlined in this appendix.

4.2.2 Design philosophies

In total, fifteen sustainability-oriented design philosophies (hereafter "S-philosophies") were identified from the sample described above, as shown in Table 4-2. Of these, five were observed to be discussed considerably more frequently than others, namely (Figure 4-6):

- sustainable design (SD) was discussed in 33 sources, i.e. 39.8% of the sample
- ecodesign (ED) was discussed in 20 sources, i.e. 24.1% of the sample;
- design for environment (DfE) was discussed in 16 sources, i.e. 19.3% of the sample;
- design for sustainability (DfS) was discussed in 10 sources, i.e. 12.0% of the sample; and
- whole system design (WSD) was discussed in six sources, i.e. 7.2% of the sample.

As shown in Table A6-1 in Appendix 6, the remaining 10 S-philosophies were found to be discussed in no more than 2 sources each (i.e. 2.4% of the sample). Consequently, it may be concluded that the five philosophies listed above are those emerging most prominently from the literature.

As shown in Sections 4.2.2.1 – 4.2.2.3 below, the major S-philosophies may be categorised and differentiated on the basis of similarities and differences in their aims and perspectives on design and sustainability. One of the key observations made during the investigation is that authors in the literature on sustainability-oriented engineering design rarely define sustainability of the technical artefact – this is discussed at length in Chapter 5 (Section 5.3). However, based on their aims and perspectives, each category of S-philosophy may be inferred as being oriented towards a different type of sustainability (see Chapter 3, Section 3.3 for a discussion on sustainability types). These orientations are discussed in Sections 4.2.2.1 – 4.2.2.3.

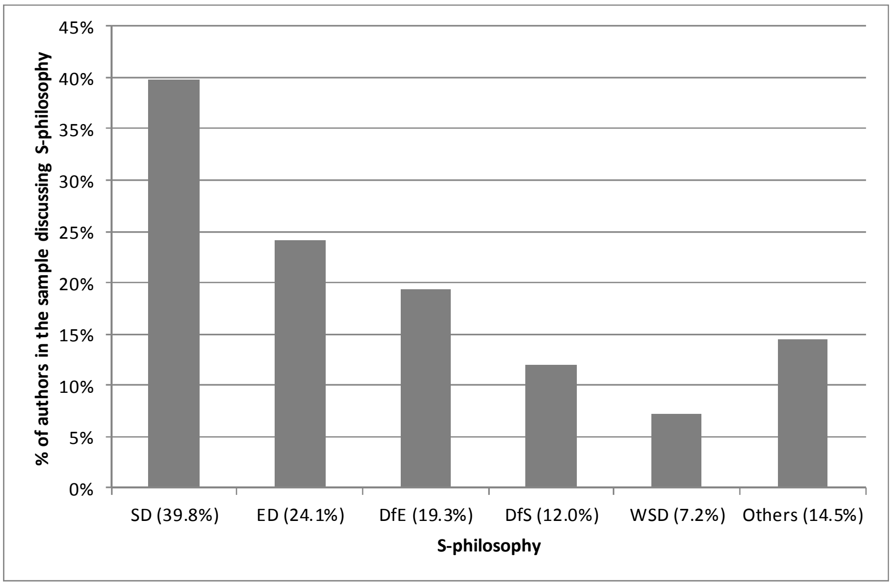


Figure 4-6: Percentages of sources from the design literature sample discussing different S-philosophies[6]

Table 4-2: Overview of all S-philosophies identified from the engineering design literature sample

No.	S-philosophy	Aim	Sources
1	Design for environment	To reduce the negative environmental impacts of a design throughout its life cycle, whilst simultaneously fulfilling traditional design requirements with respect to aspects such as performance, function, and quality.	Lindahl, 1999; Bhander et al., 2003; Boks and Stevels, 2007; Lindahl et al., 2007; Choi et al., 2008; Ramani et al., 2010; Wigum et al., 2011; Rosen and Kishawy, 2012
2	Design for sustainability	To improve (i.e. minimise negative or create positive) environmental, economic, and social impacts throughout the life cycle of a design.	Bhamra and Lofthouse, 2007; Wahl and Baxter, 2008; Clark et al., 2009; Alfaris et al., 2010; Spangenberg et al., 2010; Mayyas et al., 2012a
3	Discursive design	To nurture creative public discourse through the design of objects that communicate ideas and affect the thoughts and feelings of people.	Tharp and Tharp, n.d.; Edeholt, 2012
4	Ecodesign	To reduce the negative environmental impacts of a design throughout its life cycle, whilst simultaneously fulfilling traditional design requirements with respect to aspects such as performance, function, and quality.	Aschehoug et al., 2012; Bhamra et al., 1999; Bovea and Pérez-Belis, 2012; Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010; European Parliament and the

[6] Note that certain authors in the sample were observed to discuss more than one S-philosophy and therefore, the percentages presented in Figure 4-5 do not sum to 100%.

No.	S-philosophy	Aim	Sources
			Council of the European Union, 2005, in Unger et al., 2008; Ostad-Ahmad-Ghorabi and Collado-Ruiz, 2011; Park et al., 2005; Spangenberg et al., 2010; Wimmer, 1999
5	Ecological engineering	To design systems that integrate society and the environment.	Gagnon et al., 2012; Mitsch, 2012
6	Emotionally durable design	To reduce consumption and waste and increase resource productivity by increasing the durability of relationships between users and products.	Chapman, 2011
7	Empathic design	To reduce waste by fostering deeper emotional relationships between products and users.	Niinimäki and Koskinen, 2011
8	Environmentally conscious design	To address the environmental impacts of a design throughout its life cycle.	Poole et al., 1999
9	Evolutionary systems design	To create systemic, sustainable, and evolutionary solutions for the future, and to foster social change that parallels natural systems and processes.	Laszlo et al., 2009
10	Industrial ecology	To create ecologically sustainable production and consumption systems.	Wang and Côté, 2011
11	Life cycle design	To reduce the negative environmental impacts and maximise the benefits of a design throughout its life cycle, whilst simultaneously fulfilling traditional design requirements with respect to aspects such as performance, function, and quality.	Ernzer and Bey, 2003; McAloone and Andreasen, 2004
12	Restorative design	To design artefacts that restore natural systems by making positive contributions to the environment without sacrificing natural resources.	Gu and Frazer, 2009
13	Scale-linking design	To link spatial and temporal biophysical scales "across all scales of design from product design, architecture, construction ecology, community design, industrial ecology, to urban and bioregional planning."	Wahl, 2012
14	Sustainable design	To improve (i.e. minimise negative or create positive) environmental, economic, and social impacts throughout the life cycle of a design.	McDonough and Braungart, 2002a; Waage, 2007; Hossain et al., 2010; Azkarate et al., 2011; Bhamra et al., 2011; Chapman, 2011; Laitala et al., 2011; Zachrisson and Boks, 2011; Chen et al., 2012; Chiu and Chu, 2012;

No.	S-philosophy	Aim	Sources
			Keitsch, 2012; Lopes et al., 2012
15	Whole system design	To improve (i.e. minimise negative or create positive) environmental, economic, and social impacts throughout the life cycle of a system.	Blizzard and Klotz, 2012; Charnley et al., 2011; Coley and Lemon, 2009; Stasinopoulos et al., 2009

4.2.2.1 Design for environment (DfE) and ecodesign (ED)

Authors position DfE and ED as equivalent philosophies (Boks and Stevels, 2007; Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010; Ostad-Ahmad-Ghorabi and Collado-Ruiz, 2011). For instance, Unger et al. (2008, p.14) remark that, "Ecodesign is often also referred to as green design, ecological design, environmentally sound or environmentally sensitive design, Design for the Environment (DfE), environmentally responsible design or others." Similarly, Poole et al. (1999, p.334) consider "ecodesign as synonymous with Design for Environment" (DfE) and "Environmentally Conscious Design" (ECD)." They claim that "the field of study has developed such that all these names refer to the process of designing products and processes with attention to the environmental impact throughout their life-cycle."

The aim of DfE and ED may be viewed as: to reduce the negative environmental impacts of a technical artefact throughout its life cycle, whilst simultaneously fulfilling traditional design requirements with respect to aspects such as performance, function, and quality (Poole et al., 1999; Bhander et al., 2003; Boks and Stevels, 2007; Choi et al., 2008; Spangenberg et al., 2010; Bovea and Pérez-Belis, 2012). For example, Ramani et al. (2010, p.2) suggest that "DFE practices are meant to develop environmentally compatible products and processes while maintaining product, price, performance, and quality standards." Similarly, Park et al. (2005, p.254) remark that the "ultimate aim of ecodesign is to improve a product's environmental performance. Basic characteristics of a product, such as cost, functionality, performance, and reliability, must be considered simultaneously in the ecodesign process."

None of the authors discussing DfE and ED in the literature sample were seen to define sustainability in relation to the technical artefact. However, given the focus on environmental impacts and performance (Park et al., 2005; Ramani et al., 2010), it may be inferred that both DfE and ED are oriented towards environmental sustainability, i.e. the delivery of environmentally sustainable artefacts (Ramani et al., 2010; Rosen and Kishawy, 2012). Nonetheless, environmental sustainability should not be achieved at the expense of design and business success. That is, environmental sustainability should not be pursued at the expense of, for instance, design and business performance goals (Ramani et al., 2010).

DfE and ED share a number of perspectives on design and sustainability, which may be summarised as:

- the challenges involved in reducing the environmental impacts of design may be viewed as business opportunities (Boks and Stevels, 2007; Unger et al., 2008; Ramani et al., 2010);
- environmental considerations should be integrated into all stages of the design process (Ramani et al., 2010; Rosen and Kishawy, 2012), especially the early phases where the design is most flexible (Lindahl, 2001; Park et al., 2005; Bovea and Pérez-Belis, 2012), and viewed in a balanced manner alongside traditional design requirements for aspects such as cost, quality, and technical performance (Park et al., 2005; Ramani et al., 2010);
- the environmental impacts of technical artefacts are addressed at various stages throughout their life cycle (Lindahl, 2001; McAloone, 2001; Bhander et al., 2003; Choi et al., 2008; Bovea and Pérez-Belis, 2012), with a particular focus on the end-of-life stage (Huisman et al., 2000; Choi et al., 2008; Wigum et al., 2011);
- in certain cases, life cycle stages with the greatest potential for negative impacts may be targeted as opposed to the full life cycle, in order to maintain acceptable performance with respect to the time and resources consumed by design activities (Bovea and Vidal, 2004; Park et al., 2005; Choi et al., 2008); and
- reductions in the material and energy consumption of technical artefacts are sought (Choi et al., 2008; Wigum et al., 2011), often through efficiency improvements (Boks and Stevels, 2007; Choi et al., 2008; Spangenberg et al., 2010).

4.2.2.2 Design for sustainability (DfS) and sustainable design (SD)

Whilst not explicitly equated by authors, DfS and SD may be seen to share essentially the same aim, with both philosophies seeking to improve environmental, economic, and social impacts throughout the life cycle of a technical artefact (Hossain et al., 2010; Spangenberg et al., 2010; Bhamra et al., 2011; Chiu and Chu, 2012; Mayyas et al., 2012a). This improvement may involve either minimising negative (Bhamra and Lofthouse, 2007; Chapman, 2011) or creating positive (McDonough and Braungart, 2002a; Spangenberg et al., 2010) impacts. For instance, Bhamra et al. (2011, p.428) remark that sustainable design "takes into account environmental, economic and social impacts enacted throughout the product lifecycle," and that the "application of sustainable design can greatly reduce the environmental and social impacts of [...] products and services." With respect to the creation of positive impacts, McDonough and Braungart (2002a, p.254) write that the "goal of an effective company," in the context of SD, "is to stay in business as it transforms, providing shareholder value as it discovers ways to generate positive social and environmental effects." In the context of DfS, Bhamra and Lofthouse (2007, p.40) discuss the need for designers to "reduce the environmental and social impact [of design] across the life cycle." With respect to the creation of positive impacts in the context of DfS, Spangenberg et al. (2010, p.1490) write that DfS involves "minimising the negative and maximising the positive impacts on nature, humans and society." Therefore, it may be concluded that DfS and SD represent essentially the same design philosophy.

Like DfE and ED, none of the authors discussing DfS and SD in the literature sample were seen to explicitly define sustainability in relation to the technical artefact. However, given the focus on environmental, economic, and social impacts, it may be inferred that both DfS and SD are oriented towards environmental, economic, and social sustainability, i.e. the delivery of artefacts that are environmentally, economically, and socially sustainable (Spangenberg et al., 2010; Gagnon et al., 2012). In other words, artefacts that contribute to sustainable development (Keitsch, 2012), given that this type of sustainability has a triad of environmental, economic, and social sustainability objectives (encapsulated in the three pillars of sustainable development introduced in Chapter 3, Section 3.3.4).

In the case of DfE and ED as discussed in Section 4.2.2.1, it was shown that environmental considerations must be balanced against traditional design requirements (Park et al., 2005; Ramani et al., 2010). Certain authors in the context of DfS and SD may be seen to adopt a similar perspective. For instance, Mayyas et al. (2012a, p.1846) highlight the work of Curtis and Walker (2001), who suggest that "designing for sustainability involves balancing social, ethical and environmental issues alongside economic factors within the product or service development process." However, from other perspectives, sustainability considerations may be seen to drive evolution in what may be considered to be "traditional" design requirements. For instance, in the context of SD, McDonough and Braungart (2002a, p.252) argue that the creation of "a sustaining industrial system" requires "a new definition of quality in product, process and facility design." They write that "quality is embodied in designs that allow industry to enhance the well being of nature and culture while generating economic value." In other words, a traditional design requirement for "quality" has been redefined to account for sustainability considerations.

DfS and SD share a number of perspectives on design and sustainability, which may be summarised as follows:

- environmental, economic, and social considerations should be integrated into all stages of the design process (Bhamra and Lofthouse, 2007; Waage, 2007; Spangenberg et al., 2010; Gagnon et al., 2012), and considered in a balanced and holistic manner (McDonough and Braungart, 2002a; Spangenberg et al., 2010; Keitsch, 2012; Mayyas et al., 2012a);
- the environmental, economic, and social impacts of technical artefacts should be addressed throughout their full life cycle (Bhamra and Lofthouse, 2007; Spangenberg et al., 2010; Bhamra et al., 2011; Gagnon et al., 2012; Mayyas et al., 2012a) – however, in certain cases, a specific stage in the life cycle may be targeted, such as the use phase (Rodriguez and Boks, 2005; Bhamra et al., 2011);
- the complexity and multiple scales of the Earth's sub-systems and in turn, design problems, are acknowledged (Wahl and Baxter, 2008; Spangenberg et al., 2010; Gagnon et al., 2012; Gamage and Hyde, 2012);
- the ethical aspects of design should be considered (Spangenberg et al., 2010; Bhamra et al., 2011; Chapman, 2011; Mayyas et al., 2012a), and the designer should recognise their ethical responsibilities towards society (Bhamra and Lofthouse, 2007; Chapman, 2011);
- human values and behaviour are viewed as underpinning the sustainability of design, production, and consumption (Bhamra and Lofthouse, 2007; Spangenberg et al., 2010; Bhamra et al., 2011; Chapman, 2011);
- to ensure that multiple (and potentially competing) values and perspectives are considered during design, a greater number of stakeholders (e.g. the general public (Wahl and Baxter, 2008), and product users (Bhamra et al., 2011)) should participate in design than has conventionally been the case (Spangenberg et al., 2011; Gagnon et al., 2012; Keitsch, 2012); and
- to tackle multidisciplinary challenges, cross-disciplinary collaboration should occur during design (Wahl and Baxter, 2008; Spangenberg et al., 2010; Gagnon et al., 2012; Keitsch, 2012).

4.2.2.3 Whole system design (WSD)

In Sections 4.2.2.1 and 4.2.2.2, it was inferred that: (i) DfE and ED are oriented towards environmental sustainability (Ramani et al., 2010; Rosen and Kishawy, 2012), i.e. the delivery of environmentally sustainable artefacts; and (ii) DfS and SD are oriented towards environmental, economic, and social sustainability (Spangenberg et al., 2010; Gagnon et al., 2012), i.e. the delivery of artefacts that are environmentally, economically, and socially sustainable. In contrast, WSD may not necessarily be conducive to the delivery of sustainable artefacts. For instance, Blizzard and Klotz (2012, p.458) remark that WSD "does not guarantee sustainable design outcomes. It may, however, offer more opportunity than traditional design approaches for designers to create sustainable solutions to our most pressing issues." Further, WSD may be seen to be discussed in the wider design literature, with no relation to sustainability (e.g. M'Pherson, 1980; Levine and Mohr, 1998). However, the philosophy is positioned by a number of authors as effective in tackling sustainability challenges (Coley and Lemon, 2009; Stasinopoulos et al., 2009; Charnley et al., 2011; Blizzard and Klotz, 2012; Gagnon et al., 2012).

Considering the research output on WSD in a sustainability context, it may be seen that the aim is essentially the same as that of DfS/SD (Stasinopoulos et al., 2009). That is, to improve the life cycle environmental, economic, and social impacts of technical artefacts, as discussed in Section 4.2.2.2. However, a notable difference between DfS/SD and WSD appears to be that the latter is founded in a systems view of the world (Coley and Lemon, 2009; Charnley et al., 2011) – that is, a view where "the interconnections between sub-systems and systems are actively considered" (Stasinopoulos et al., 2009, p.3). Furthermore, certain authors discussing WSD were observed to make explicit reference to a focus on "technical engineered systems" (Stasinopoulos et al., 2009, p.3) and "product systems" (Fiksel, 2003, p.5331), as opposed to simply products, artefacts, or design solutions. Additionally, the process for sustainable whole system design prescribed by Stasinopoulos et al. (2009) is an expansion of the traditional systems engineering process outlined by Blanchard and Fabrycky (1981). As such, from the perspective of sustainability at least, the aim of WSD may be stated as: to improve (i.e. minimise negative or create positive) environmental, economic, and social impacts throughout the life cycle of a system (Stasinopoulos et al., 2009; Charnley et al., 2011; Blizzard and Klotz, 2012).

Unlike authors discussing DfE/ED and DfS/SD, one author discussing WSD in the literature sample was observed to explicitly define sustainability in relation to the technical artefact. Fiksel (2003, p.5331) outlines a set of definitions that clearly conveys the systems perspective referenced above, suggesting that they "offer a logical framework of "nested" systems that may be helpful to system designers." The final definition in this list may be viewed as a definition of sustainability of the technical artefact, i.e. in the words of Fiksel, a "product system":

i. "A sustainable society is one that continues to satisfy the current needs of its population without compromising quality of life for future generations.
ii. A sustainable enterprise is one that continues to grow and adapt in order to meet the needs and expectations of its shareholders and stakeholders. (The enterprise system is a component of the overall socio-economic system.)

iii. A sustainable product (or service) is one that continues, possibly with design modifications, to meet the needs of its producers, distributors, and customers. (The product system is a component of the overall enterprise system.)"

Additionally, although they do not define sustainability *per se*, Stasinopoulos et al. (2009, p.3) provide a "description of a sustainable [technical engineered] system." They argue that sustainable technical engineered systems:

- "Consume natural resources (energy, materials and water) within the capacity for them to be regenerated (thus favoring renewable resources), and preferably replace or reuse natural resources;
- Do not release hazardous or polluting substances into the biosphere beyond its assimilative capacity (thus zero release of hazardous persistent and/or bio-accumulative substances), and preferably are benign and restorative;
- Avoid contributing to irreversible adverse impacts on ecosystems (including services and biodiversity), biogeochemical cycles and hydrological cycles, and preferably protect and enrich ecosystems, biogeochemical cycles and hydrological cycles;
- Provide useful and socially accepted services long term, and enrich communities and businesses by providing multiple benefits; and
- Are cost effective and have a reasonable rate of return on total life-cycle investment, and preferably are immediately profitable."

On the basis of the above, it may be concluded that when applied as an S-philosophy, WSD is oriented towards system sustainability. That is, the delivery of sustainable systems. Comments from certain authors, coupled with the focus of WSD on improving the environmental, economic, and social impacts of systems as discussed above, may be seen to suggest that system sustainability entails environmental, economic, and social dimensions. For example, Blizzard and Klotz, (2012, p.475) remark that "whole systems design is an approach that offers designers the opportunity to holistically optimize solutions for social, environmental, and economic sustainability." The description of a sustainable system outlined by Stasinopoulos et al. (2009) above may also be seen to cover environmental, economic, and social aspects.

A number of key perspectives emerge from the literature on WSD in the context of sustainability, which may be summarised as follows:

- design problems are viewed as embedded within a wider system (Coley and Lemon, 2009), where design requirements are interrelated with solutions (Blizzard and Klotz, 2012) – as such, limits with respect to the sustainability of a particular design solution may be averted by redefining the problem (Coley and Lemon, 2009);

- the environmental, economic, and social performance of whole systems should be optimised during design, as opposed to isolated entities (Stasinopoulos et al., 2009);
- the environmental, economic, and social impacts of systems should be addressed throughout their full life cycle – in particular, synergies among sub-systems should be sought out to increase positive and reduce negative impacts throughout the life cycle of the overall system (Coley and Lemon, 2009; Stasinopoulos et al., 2009; Charnley et al., 2011; Blizzard and Klotz, 2012);
- throughout the design process, designers should adopt a systems view and rely more heavily upon ingenuity and intuition, as opposed to checklists and guidelines (Coley and Lemon, 2009; Blizzard and Klotz, 2012);
- the complexity and multiple scales of the Earth system, and in turn design problems, are acknowledged (Coley and Lemon, 2009; Stasinopoulos et al., 2009; Charnley et al., 2011) ;
- to tackle multidisciplinary challenges, cross-disciplinary collaboration should occur during design (Coley and Lemon, 2009; Stasinopoulos et al., 2009; Charnley et al., 2011; Blizzard and Klotz, 2012) ; and
- to ensure that multiple (and potentially competing) values and perspectives are considered during design, a greater number of stakeholders should participate in design than has conventionally been the case (Coley and Lemon, 2009; Charnley et al., 2011).

4.2.3 Design methods and tools

In addition to the S-philosophies discussed in Section 4.2.2, 170 distinct design methods and tools were identified from the literature sample. That is, methods and tools positioned by authors as useful or effective in sustainability-oriented engineering design. These methods and tools were categorised according to the kinds of activities they are intended to support during design: creating; decision making; evaluation and analysis; modelling and simulation; and optimisation. These categories are elaborated on in Section 5.1 of Paper A. Note that the categories are not intended to constitute an exhaustive representation of all types of design method/tool in existence. Rather, they may be viewed as the categories that emerged most prominently from the range of methods and tools identified from the literature sample. As discussed in Section 4.2.1, it is beyond the scope of Section 4.2 to provide detailed descriptions of each method/tool identified. However, an overview of the major examples is presented in Table 4-3. Additionally, a breakdown showing the fractions of each type of method/tool emerging from the sample as percentages of the total methods and tools identified is presented in Figure 4-7.

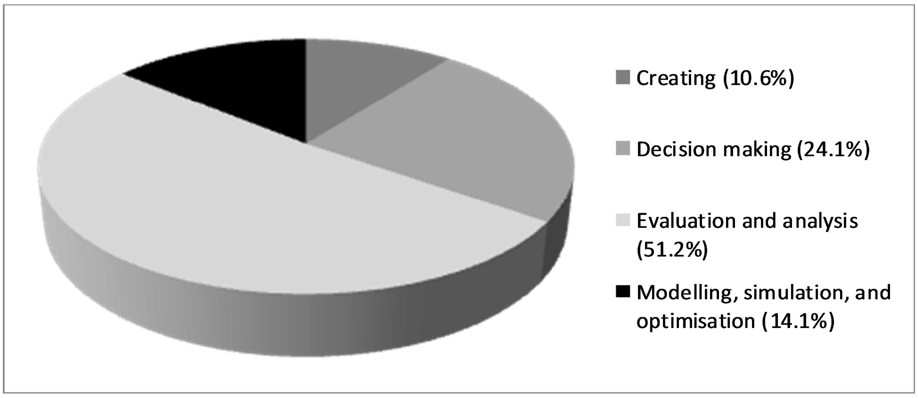


Figure 4-7: Percentages of each type of design method/tool emerging from the literature sample

Table 4-3: Overview of methods and tools discussed by authors in the literature sample

No.	Method/tool description	Sources
Creating:		
1	Backcasting	Bhamra & Lofthouse, 2007; Byggeth et al., 2007a,b; Gagnon et al., 2012
2	Concept generation	Karlsson and Luttropp, 2006; Bhamra and Lofthouse, 2007; Stasinopoulos et al., 2009; Gagnon et al., 2012
3	Design spiral	Gamage and Hyde, 2012
4	Layered games	Bhamra and Lofthouse, 2007
5	Mood boards	
6	Real People (T)	
7	Templates for Sustainable Development (T)	Byggeth et al., 2007a,b
8	Theory of Inventive Problem Solving (TRIZ) and TRIZ-based methods	Strasser and Wimmer, 2003; Trotta, 2010; Chiu and Chu, 2012; Gamage and Hyde, 2012
Decision making:		
9	A framework for ethical decision-making in design - the "culturally negotiated ethical triangle" (T)	Oram, 2010
10	Checklists	Lindahl, 2001; Bhamra and Lofthouse, 2007; Bovea and Pérez-Belis, 2012
11	Design for/to X	Huisman et al., 2000; Bhander et al., 2003; Byggeth et al., 2007b; Mayyas et al., 2012a
12	Design guidelines	Lindahl, 2001; Bovea and Pérez-Belis, 2012; Chiu and Chu, 2012; Mayyas et al., 2012a
13	Design principles	Boks and Stevels, 2007;

No.	Method/tool description	Sources
		Spangenberg et al., 2010; Blizzard and Klotz, 2012; Chiu and Chu, 2012
14	Fractal triangle (T)	McDonough and Braungart, 2002a
15	Multi criteria decision analysis	Choi et al., 2008; Gagnon et al., 2012
16	Typological analysis	Gamage and Hyde, 2012
17	User-centred design methods	Wigum et al., 2011
Evaluation and analysis:		
18	ABCD analysis	Byggeth et al., 2007a,b; Unger et al., 2008
19	Benchmarking	Boks and Stevels, 2003; Stasinopoulos et al., 2009
20	Economic and social performance evaluation	Bovea and Pérez-Belis, 2012; Gagnon et al., 2012; Mayyas et al., 2012b
21	Environmental performance evaluation	Lenau and Bey, 2001; Stasinopoulos et al., 2009; Bovea and Pérez-Belis, 2012; Gagnon et al., 2012; Mayyas et al., 2012a
22	Failure mode and effects analysis (FMEA) and FMEA-based methods/tools	Lindahl, 2001; Byggeth et al., 2007a,b; Bovea and Pérez-Belis, 2012
23	Functional analysis	Stasinopoulos et al., 2009
24	Hierarchical design decomposition	Alfaris et al., 2010
25	Impact assessment	Bovea and Pérez-Belis, 2012; Gagnon et al., 2012
26	Integrated environmental, economic, and/or social performance evaluation	Bovea and Pérez-Belis, 2012; Chiu and Chu, 2012
27	Morphological analysis	Gagnon et al., 2012
28	Nature studies analysis	Gamage and Hyde, 2012
29	Quality function deployment (QFD) and QFD-based methods	Vinodh and Rathod, 2010; Bovea and Pérez-Belis, 2012
30	Scenario analysis	Huisman et al., 2000
31	System analysis	Stasinopoulos et al., 2009
32	User-centred design methods	Bhamra and Lofthouse, 2007; Bhamra et al., 2011
Modelling, simulation, and optimisation:		
33	Formal optimisation methods	Papandreou and Shang, 2008; Gagnon et al., 2012; Taras and Woinaroschy, 2012
34	Life cycle optimisation	Mayyas et al., 2012b
35	Models and modelling	Byggeth et al., 2007b; Stasinopoulos et al., 2009; Alfaris et al., 2010
36	PILOT	Wimmer and Judmaier, 2003
37	Simulation	Hossain et al., 2010
38	System optimisation	Stasinopoulos et al., 2009

As discussed in the introduction to Section 4.2, a tool may be used to support the application of a particular method (Cross, 2008). As such, it was assumed during the investigation that a method and a tool that are seen to be used in direct conjunction will always belong to the same category from the list provided above. Therefore, in cases where a tool was found to be clearly associated with a method, only the method was recorded and included in Table 4-3. Conversely, in cases where a tool was seen to be discussed in isolation from any particular method, then the tool was recorded and included in the table. Tools are suffixed with the following in order to distinguish them from methods: (T). Furthermore, it should be noted that certain methods and tools presented in Table 4-3 represent generalisations of groups of specific methods discussed by authors in the literature sample. Namely, the following may all be decomposed into specific examples discussed and/or applied by different authors (the numbers associated with each method/tool in Table 4-3 are included in brackets below):

- benchmarking methods (19);
- checklists (10);
- concept generation methods/tools (2);
- design for/to X methods (11);
- design guidelines (12);
- design principles (13);
- economic and social performance evaluation methods/tools (20);
- environmental performance evaluation methods/tools (21);
- failure mode and effects analysis (FMEA) and FMEA-based methods/tools (22);
- formal optimisation methods (33);
- impact assessment methods/tools (25);
- integrated environmental, economic, and/or social performance evaluation methods/tools (26);
- multi criteria decision analysis methods/tools (15);
- quality function deployment (QFD) and QFD-based methods/tools (29);
- Theory of Inventive Problem Solving (TRIZ) and TRIZ-based methods/tools (8); and
- user-centred design methods (32).

The specific methods and tools comprising each of these general groups are outlined in both Appendix 6 and Tables 4–7 in Section 5.1 of Paper A.

Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010, p.479) suggest that in the development of means for tackling sustainability issues in design, “Many design methods were “environmentalized,” as well as new ones generated.” Along these lines, it should be noted that a mixture of the following are included in Table 4-3:

- new methods and tools, i.e. those newly developed with the explicit purpose of tackling sustainability issues (e.g. the Templates for Sustainable Development tool developed by Ny et al. (2008));
- modified methods and tools, i.e. those developed by modifying conventional methods and tools to be more effective in tackling sustainability issues (e.g. the Environmental Effect Analysis method developed by Lindahl (2001)); and
- conventional methods and tools, i.e. those that may be applied in design conventionally, but are presented as effective in tackling sustainability issues in their original, unmodified form (e.g. the brainstorming method presented by Stasinopoulos et al. (2009) and Gagnon et al. (2012)).

As indicated in Table 4-3, methods and tools identified from the literature sample were seen to be associated with particular S-philosophies. That is, authors were observed to discuss the use of different methods/tools in the context of different S-philosophies (although certain method/tools are shared by multiple philosophies). As such, the methods and tools identified from the sample may be positioned according to both: the design activities they are intended to support (as outlined above); and the S-philosophy (or S-philosophies) they were seen to be associated with in the literature sample. On this basis, the Design Sustainability Matrix (DSM) was developed to visually represent the state of the art with respect to philosophies, methods, and tools for sustainability-oriented engineering design. The DSM is presented in Figure 4-8. Items suffixed with (M) are methods, whilst those suffixed with (T) represent tools. It must be emphasised that the matrix is *descriptive* in nature and not prescriptive. That is, it is intended to describe what philosophies and methods/tools are currently discussed and applied in sustainability-oriented engineering design, based on the literature sample outlined in Appendix 6. It is not intended to prescribe what philosophies and methods/tools *should* be applied, both in general and with respect to specific S-philosophies.

As may be seen in Figure 4-7, one category of method/tool in particular stands out from the range detected in the sample, namely evaluation and analysis. 51.2% of all methods and tools identified were found to fall into this category (87 methods/tools in total), meaning that this type of method/tool is the most prevalent in the sample. To put this into context, decision making was the second largest category, including 24.1% of all methods/tools identified. The evaluation and analysis category may be broken down into:

- methods/tools for evaluating economic and social performance;
- methods/tools for evaluating environmental performance;

- methods/tools for integrated evaluation of environmental, economic, and/or social performance; and
- other evaluation and analysis methods/tools.

These sub-categories may be seen to reflect the aims of the major S-philosophies identified in Section 4.2.2, i.e. to improve (in various ways) the environmental, economic, and/or social performance of technical artefacts throughout their life cycle. The percentages of the identified evaluation and analysis methods/tools falling into each of these sub-categories are illustrated in Figure 4-9.

It may be seen in Figure 4-9 that 59.7% of the identified methods/tools for evaluation and analysis (51 methods/tools) were found to focus on evaluating the environmental, economic, and/or social performance of technical artefacts (either as separate dimensions, or in an integrated fashion as indicated in Figure 4-9). This represents 30.6% of the total methods and tools of all types identified from the sample. Specific examples of performance evaluation methods identified from the sample are presented in Table 4-4.

The above observations suggest that performance evaluation is an area receiving relatively significant attention in sustainability-oriented engineering design. Furthermore, several authors suggest that information on the environmental, economic, and/or social performance of artefacts is instrumental with respect to improving the sustainability of technical artefacts (Park et al., 2005; Waage, 2007; Gagnon et al., 2012). For instance, Azkarate et al. (2011, p.169) suggest that information on the environmental, economic, and social performance of technical artefacts can help designers to "select the most sustainable option from several alternatives." Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010, p.480) focus solely upon environmental performance, remarking that most design processes in the context of DfS and ED "share an initial stage of environmental evaluation, from which improvement strategies are developed." They highlight that it is "necessary for designers to know about the environmental impacts of their products in order for them to focus on the relevant aspects," suggesting that the "positive effect of having environmental information is generally taken for granted in design for sustainability and ecodesign." Indeed, as shown in Figure 4-10, a considerable fraction of the performance evaluation methods/tools identified from the sample were found to focus on environmental performance (75%), as opposed to economic and social performance (13.5%) and integrated environmental, economic, and/or social performance (11.5%).

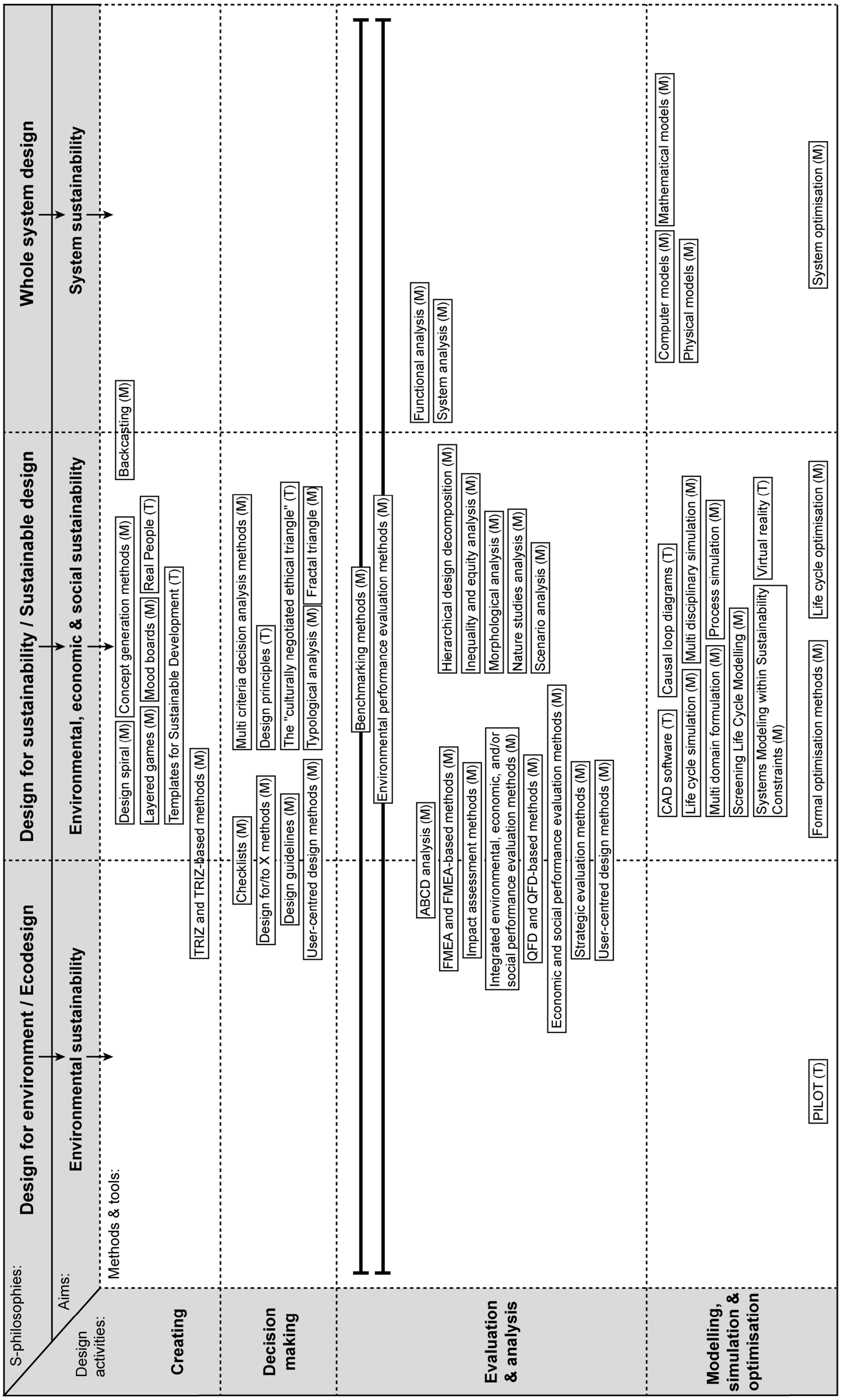


Figure 4-8: The Design Sustainability Matrix

Figure 4-8: The Design Sustainability Matrix

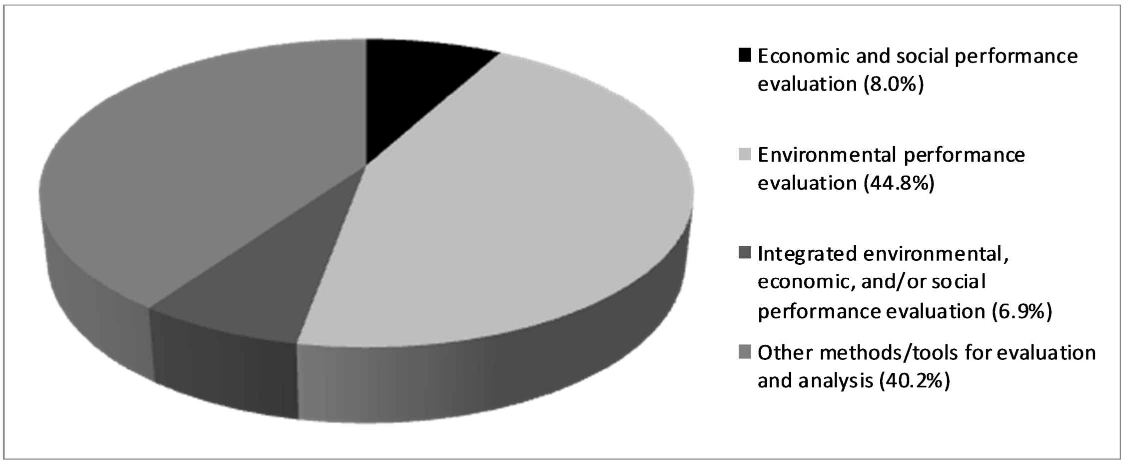


Figure 4-9: Distribution of different types of methods/tools in the evaluation and analysis category

Table 4-4: Examples of performance evaluation methods identified from the sample

No.	Method/tool description	Sources
Life cycle assessment (LCA) and LCA-based methods/tools:		
1	DfE matrix (T)	Bovea and Pérez-Belis, 2012
2	Eco-Indicator 95	Huisman et al., 2000; Lenau and Bey, 2001
3	Eco-Indicator 99	Huisman et al., 2003; Bhamra and Lofthouse, 2007
4	Environmental Priority Strategies	Lenau and Bey, 2001; Huisman et al., 2003
5	Environmental Product Life Cycle matrix (T)	Bovea and Pérez-Belis, 2012
6	Life cycle assessment	McAloone, 2001; Park et al., 2005; Bhamra and Lofthouse, 2007; Stasinopoulos et al., 2009; Hossain et al., 2010
7	Life cycle check	McAloone, 2001
8	Life Cycle Planning	Bovea and Pérez-Belis, 2012
9	Okala method	Chiu and Chu, 2012
10	Product life thinking	McAloone, 2001
11	Simplified life cycle assessment	Lu et al., 2011; Chiu and Chu, 2012
12	Strategic Life Cycle Management	Byggeth et al., 2007a
13	Streamlined life cycle assessment	Bovea and Pérez-Belis, 2012
Strategic methods/tools:		
14	Design abacus	Bhamra and Lofthouse, 2007
15	Ecodesign web	
16	Environmentally Responsible Product Assessment	Chiu and Chu, 2012
17	Environmentally Responsible Product/Process Assessment Matrix (T)	Bovea and Pérez-Belis, 2012
18	RAILS	Bovea and Pérez-Belis, 2012
19	Strategic environmental assessment	Gagnon et al., 2012
20	Strategic wheel (T)	Unger et al., 2008
Other:		

No.	Method/tool description	Sources
21	Assistant environmental assessment tool (T)	Wimmer and Judmaier, 2003
22	Cumulated Energy Demand	Unger et al., 2008; Ostad-Ahmad-Ghorabi and Collado-Ruiz, 2011
23	Eco effectiveness	Wang and Côté, 2011
24	Eco efficiency	Hong et al., 2012
25	Ecological footprinting	Unger et al., 2008; Gagnon et al., 2012
26	Ecological indicators (T)	Stasinopoulos et al., 2009
27	Emergy analysis	Gagnon et al., 2012
28	Energy analysis	Hossain et al., 2010
29	Environmental product declaration	Mayyas et al., 2012a
30	Environmental valuation	Gagnon et al., 2012
31	Exergy analysis	Hossain et al., 2010; Urban et al., 2010; Gagnon et al., 2012
32	Footprinting	Bovea and Pérez-Belis, 2012
33 34	Material Flow Analysis Material Intensity per Unit of Service	Unger et al., 2008
35	Material Recycling Efficiency calculations	Huisman et al., 2003
36	Materials, Energy & Toxicity matrix (T)	Bovea and Pérez-Belis, 2012; Chiu and Chu, 2012
37	Oil Point Method	Bovea and Pérez-Belis, 2012; Chiu and Chu, 2012
38	Recyclability assessment	Huisman et al., 2000
39	Toxicity assessment	Huisman et al., 2000

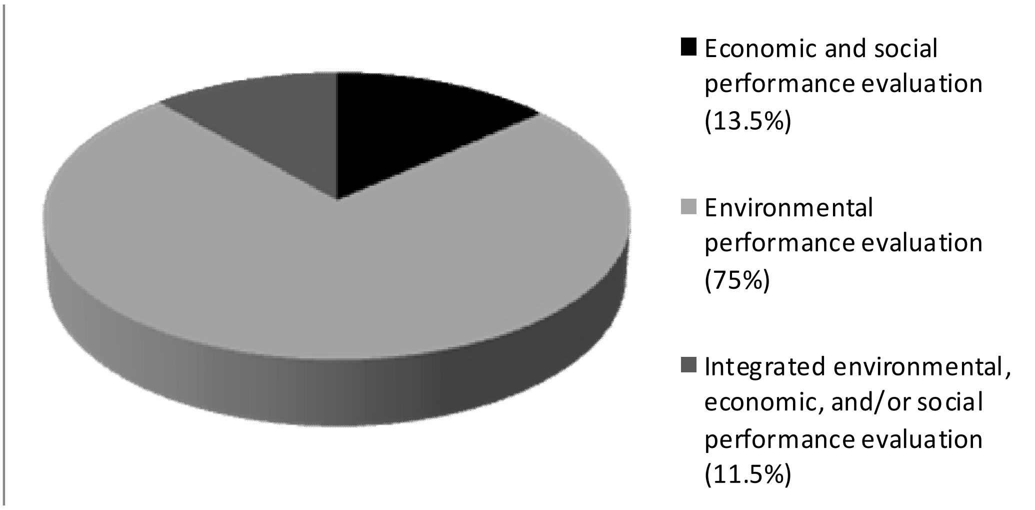


Figure 4-10: Distribution of different types of performance evaluation methods/tools emerging from the literature sample

In addition to sustainability-oriented engineering design, information on the sustainability performance of technical systems may also be required in other contexts. For instance, organisations are also increasingly participating in the voluntary activity of sustainability reporting (SR). SR entails the evaluation of an organisation's environmental, economic, and social performance, and the communication of this performance to stakeholders via a sustainability report (Lozano and Huisingh, 2011). As noted in the introduction to Chapter 4, organisations in the business of designing and manufacturing technical systems typically need to evaluate and report the performance of their technical products as part of a comprehensive sustainability report (ISO, 1999; Park et al., 2005). In an organisational context, information on the sustainability performance of technical products may be used by:

- the organisation *per se* to manage certain aspects of the business (Hussey et al., 2001; Global Reporting Initiative, 2013a), e.g. the design of technical products as discussed in this section (Park et al., 2005), and the implementation and monitoring of sustainability and corporate social responsibility policies (Marimon et al., 2012; Global Reporting Initiative, 2013a);
- the organisation's competitors (Tokos et al., 2011), e.g. for benchmarking the performance of their own technical products (Boks and Stevels, 2003); and
- consumers to make purchasing decisions on the basis of product sustainability (Chapman, 2011; Koller et al., 2011), e.g. which product to buy from an organisation or which organisation's products to buy.

It may be seen from the above that there is a need for information on the sustainability performance of technical systems to support decision making at various levels beyond the design process. To gain greater insight into the evaluation methods applied and the performance aspects measured outside of an engineering design context, the literature on sustainability performance evaluation of technical systems in a broader organisational context is reviewed in Section 4.3.

4.3 Sustainability performance evaluation of technical systems

Design has been cited as a critical activity with respect to improving the sustainability of technical products (Park et al., 2005; Stasinopoulos et al., 2009; Spangenberg et al., 2010). Accordingly, the key findings of a literature investigation on sustainability-oriented engineering design were presented in Section 4.2. Performance evaluation was highlighted as a key activity in this area, providing information on the environmental, economic, and/or social performance of technical artefacts that may be used to support design decisions (Park et al., 2005; Waage, 2007; Azkarate et al., 2011; Gagnon et al., 2012).

As noted in Section 4.2.3, information on the sustainability performance of technical systems may be required in a broader organisational context, as well as during the design process. For instance, it was highlighted that organisations may evaluate and report the performance of their technical products as part of a comprehensive sustainability report. A key set of guidelines supporting organisational sustainability reporting (SR) are those produced by the Global Reporting Initiative (Global Reporting Initiative, 2013a,b). These guidelines include a number of indicators that may be seen to require the evaluation of product performance during various stages of the life cycle (introduced in Section 4.1). This performance is then included in an aggregate measure of organisational performance for reporting, e.g.:

- the indicator "other indirect greenhouse gas (GHG) emissions" requires evaluation of "emissions [that] are a consequence of the activities of the organization, but occur from sources not owned or controlled by the organization" – among the relevant emissions categories is "the end use of products and services," i.e. emissions during a product's use phase/life in service (Global Reporting Initiative, 2013b, p.112);
- the indicator "energy consumption outside the organization" requires evaluation of energy consumption occurring "throughout [the] organization's upstream and downstream activities associated with its operations" – this may include "the use of sold products by consumers and the end-of-life treatment of sold products after consumer use," i.e. energy consumption during both a product's use phase/life in service and its end of life phase (Global Reporting Initiative, 2013b, p.91); and
- the indicator "extent of impact mitigation of environmental impacts of products and services" requires quantitative evaluation of "the extent to which environmental impacts of products and services have been mitigated during the reporting period" – this will entail some evaluation of trends in a product's environmental performance over the reporting period, but also across the product life cycle given that the "significance of such impacts is determined by both customer behavior and general product or service design" (Global Reporting Initiative, 2013b, p.128).

A number of performance evaluation methods applied to technical artefacts were identified during the literature investigation on sustainability-oriented design, as discussed in Section 4.2.3 (and listed in Table 4-4). However, to gain greater insight into the evaluation methods applied to technical systems in a broader organisational context, a literature investigation focusing on a sample of 43 sources from this area was carried out. The sample is outlined in Table 6 of Paper B in Appendix 2. The results of an analysis conducted on the sample are discussed at length in Chapter 8, and the findings of the investigation are presented in full in Paper B (Appendix 2). However, certain key points and findings from the literature review conducted as part of the investigation are presented in the following sub-sections. The intention is to provide an overview of the literature on sustainability performance evaluation of technical systems beyond the context of engineering design.

4.3.1 Sustainability performance evaluation and the technical system life cycle

In Section 4.1, the concept of the technical system life cycle was introduced (illustrated in Figure 4-2). To recap, it was shown that the life cycle is generally considered to involve four stages: (i) extraction and processing of raw materials required to manufacture the system; (ii) manufacturing (including design and development, and also transportation of components); (iii) system operation; and (iv) recycling and disposal. In Chapter 3 (Section 3.5), indicator-based approaches to sustainability assessment were positioned as among the most prolific of those discussed in the literature on the sustainability of society. Indeed, the sustainability of technical systems is typically assessed using sustainability performance indicators (SPIs), which measure various aspects of a system's performance throughout its life cycle. As discussed in Section 4.3.2 below, the majority of the authors in the sample outlined in Table 6 of Paper B were seen to evaluate SPIs focusing on material and energetic aspects of performance. However, certain authors were observed to also cover economic and social aspects to a limited extent. Furthermore, SPIs were seen to be defined and evaluated through either formal methods or *ad hoc* approaches[7], also discussed in Section 4.3.2.

Sustainability performance evaluation may be carried out across different portions of the technical system life cycle. For instance, certain authors focus upon performance during the operation phase only (e.g. Caliskan et al., 2012; Rotella et al., 2012; Aydin et al., 2013), whilst others apply methods such as life cycle assessment to evaluate performance across the full life cycle (e.g. Ulgiati et al., 2011; Adams and McManus, 2014; Ofori-Boateng and Lee, 2014). In Chapter 3 (Section 3.5.1), it was shown that sustainability indicators may be evaluated from different temporal perspectives, i.e. retrospective or prospective. This is true for

[7] *Ad hoc* approaches are considered here as those where authors appear to define and evaluate SPIs on the basis of their knowledge of the system and sustainability generally rather than any formal method.

SPIs in a technical systems context. Retrospective evaluation focuses on the actual performance of a system due to past life cycle activities (Moss et al., 2014), whilst prospective evaluation focuses on the potential performance of a system due to future life cycle activities (Russell-Smith et al., 2014). For example, as discussed in Section 4.2.3, the sustainability performance of technical artefacts may be evaluated prospectively during the design process to facilitate selection of the most sustainable concept, or to identify areas for sustainability improvements to products (Park et al., 2005; Azkarate et al., 2011).

In a technical systems context, Ulgiati et al. (2011) highlight that the life cycle stages outlined above are closely tied to the spatial scale at which material and energetic flows are evaluated. As discussed in Chapter 3 (Section 3.5.1), sustainability indicators may be evaluated at local, regional, and global scales. In a technical systems context, Ulgiati et al. (2011, p.177) suggest that each scale is "characterized by well-specified processes" occurring at different life cycle stages:

- the *local* (L) scale involves "final resource use," i.e. the operation of the technical system – here, only the direct material and energetic inputs to and outputs from the system need to be considered;
- the *regional* (R) scale involves "manufacturing and transport of components" – here, the indirect material and energetic inputs/outputs associated with manufacturing and transporting system components must be considered in addition to the direct inputs/outputs above; and
- the *global* (G) scale involves "resource extraction and refining" – here, the indirect inputs/outputs resulting from the extraction and processing of the raw materials consumed to manufacture the components must additionally be considered.

As discussed above, there is a final stage in the technical system life cycle that does not appear to be covered by Ulgiati et al. (2011) – that is, recycling and disposal. In essence, recycling and disposal mirror the manufacturing phase, only they focus on deconstructing the system as opposed to constructing it. Thus, like manufacturing processes, recycling and disposal processes may be considered to occur at the regional scale. However, for a number of technical systems, data on the material and energetic flows associated with recycling and disposal are rather limited. Thus, in certain cases this phase may be excluded from a regional or global scale evaluation of a technical system's sustainability performance (Gurzenich and Wagner, 2004; Hondo, 2005; Raugei et al., 2005).

The different spatio-temporal scales delineated above may be illustrated by considering the notion that all of the activities involved in the technical system life cycle, including the operation of the system *per se*, occur within a wider environment that provides inputs to activities and receives the outputs produced

(Blanchard and Fabrycky, 1981; Hubka and Eder, 1988; Tully, 1993; Stasinopoulos et al., 2009). Essentially, increasing the spatial scale over which sustainability performance is to be evaluated means that: (i) more of the Earth system is included in the technical system's environment; and (ii) the technical system's interactions with this environment must be considered across a broader portion of the system life cycle, as shown in Figure 4-11.

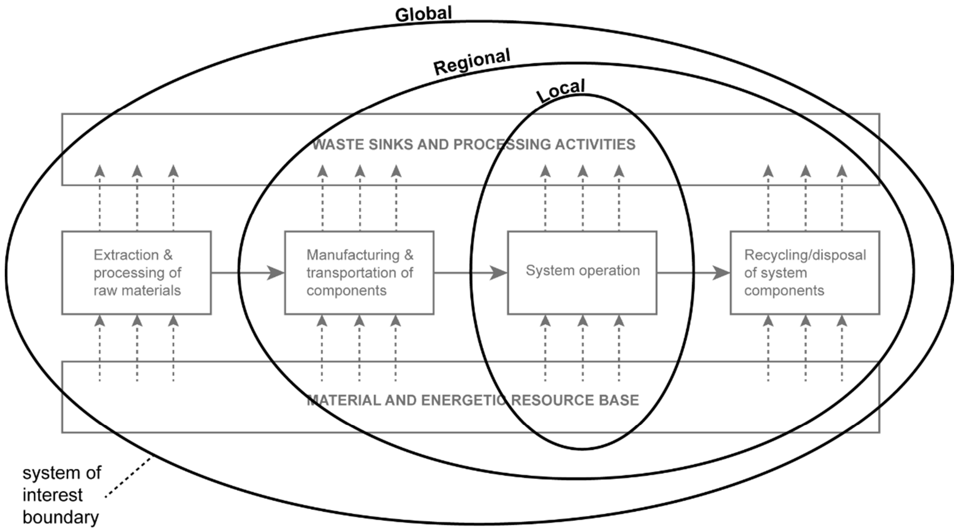


Figure 4-11: The spatio-temporal scales of sustainability performance evaluation

Ulgiati et al. (2011, p.177) highlight that the "value of a given indicator is only 'true' at the scale at which it is calculated." In other words, from the perspective of a decision maker, system performance that seems to be sustainable at one spatio-temporal scale may in fact appear to be unsustainable at others. To illustrate, consider the use of non-renewable resources by a solar panel. A solar panel may be viewed as a relatively simple technical system that converts solar energy into electrical energy. At the local scale, we may evaluate the solar panel's use of non-renewable resources and find that it uses none – the only energetic input to the system during its operation is renewable solar energy. As discussed in Chapter 3 (Section 3.4), for sustainability, the use of non-renewable resources by a technical system should be minimised, ideally to zero if possible. Thus, at the local scale, the panel's use of non-renewable resources appears to be sustainable. However, if we evaluated the same aspect of performance at the regional scale, we would likely obtain a rather different picture. The manufacture of solar panels involves non-renewable and scarce metals (Fthenakis, 2009) and is likely to be driven by fossil fuels (Kim et al., 2014), which are also non-renewable. Furthermore, solar panels require rather intensive processing in order to be recycled and/or disposed of at the end of their life cycle (Fthenakis, 2009). Again, this is likely to be driven by fossil fuels (Kim et al., 2014). Thus, whilst the panel's use of non-renewable resources appears to be sustainable at the local scale, it seems less so at the regional scale.

As noted in the introduction to Section 4.3, evaluations of a technical system's sustainability performance may be carried out to obtain information for different purposes. For example, consider a designer. As touched upon in Section 4.2.3, they may wish to identify areas where changes could potentially be made to a technical artefact to improve aspects such as energy efficiency and consumption during its life in service (Aydin et al., 2013). In this case, evaluation at the local scale is likely sufficient, given the relationship between temporal and spatial scale outlined above. In other cases, it may be desired to understand what phase in a system's life cycle is associated with the worst sustainability performance (Park et al., 2005). This is likely to entail evaluation at the regional and possibly also global scales. As such, it may not be necessary to evaluate SPIs at every scale outlined above in every case. Rather, it is necessary to consider performance at all scales that are relevant given the purposes of the evaluation.

4.3.2 Major sustainability performance evaluation methods applied to technical systems

As discussed in Section 4.3.1, sustainability performance evaluation of technical systems seeks to measure various aspects of a system's sustainability performance throughout its life cycle (to varying degrees). During the literature investigation, it was found that authors carrying out this kind of evaluation may be broadly split into two categories: (i) those applying *ad hoc* approaches; and (ii) those applying formal evaluation methods. Each category is briefly discussed below, and an overview of the major formal methods identified and their associated indicators is provided.

Category (i) refers to authors who appear to define and evaluate SPIs for technical systems based on their knowledge of the system and sustainability generally rather than any predefined method. A selection of several authors from the sample that were seen to apply this kind of approach is presented in Table 4-5. As touched upon in Section 4.3.1, the majority of authors in the sample (Table 6 of Paper B, Appendix 2) were seen to focus on evaluating material and energetic aspects of performance. In this respect, it may be seen in Table 4-5 that although the specific material and energetic aspects measured by authors adopting *ad hoc* approaches are different in a number of cases, similarities may be detected with respect to the broad areas being measured. For example:

- various types of emissions and waste products may be seen to be measured by all authors listed in Table 4-5 with the exception of Rotella et al. (2012);

- energy efficiency, focusing on various kinds of energy, may be seen to be measured by Denholm et al. (2005), Evans et al. (2009), Onat and Bayar (2010), Chandrasekaran and Guha (2012), Rahman et al. (2014), Singh et al. (2014); and
- material and energy consumption, again focusing on various kinds of materials and energy, may be seen to be measured by all authors listed in Table 4-5 with the exception of Hondo (2005) and Asif and Muneer (2014).

For those systems evaluated at the local scale, these include only direct inputs and outputs. For those systems evaluated at regional and global scales, they include both direct and indirect inputs and outputs, as discussed in Section 4.3.1.

Table 4-5: A selection of authors applying ad hoc approaches to evaluating the sustainability performance of technical systems

Source	Technical system	Indicators	Scale
Denholm et al., 2005	Baseload wind energy system, including turbines & storage)	• Fuel consumption rate • GHG emission rate • NOx emission rate • Primary energy efficiency • SO2 emission rate	R
Hondo, 2005	A range of different power production systems	• Life cycle GHG emission factor	R
Evans et al., 2009	Photovoltaic, wind, hydro, & geothermal energy production systems	• Efficiency of energy generation • Greenhouse gas emissions • Land use • Price of electricity generation • Social impacts • Water consumption	R
Onat and Bayar, 2010	Power production systems generally	• Carbon dioxide emissions • Efficiency • Fresh water consumption • Land use • Social effects • Unit energy cost	L
Rotella et al., 2012	Hard machining system	• Cutting force • Material removal rate • Mechanical power • Thrust force • Wear rate • White layer thickness	L
Coelho et al., 2012	Ten different waste-to-energy plants	• Area required by treated waste • Chemicals and additives consumption by treated waste • CO2 emissions by treated waste • Dust emissions by treated waste • Electricity consumption by treated waste • Electricity generation by treated waste • Fossil fuel consumption by treated waste • Greenhouse gas emissions by treated waste	L

Source	Technical system	Indicators	Scale
		• Liquid effluents generated by treated waste • Other gases emitted by treated waste • Other materials consumed by treated waste • Soil used by treated waste • Thermal energy generation by treated waste • Waste or sub products generated by treated waste • Water consumption by treated waste • Water vapour consumption by treated waste	
Chandrasekaran and Guha, 2012	Turbofan engine	• Emission index of carbon dioxide • Emission index of carbon monoxide • Emission index of hydrocarbons • Emission index of NOx • Inlet mass flow • Net thrust • Overall efficiency • Specific fuel consumption • Thermal efficiency	L
Abdel-Salam and Simonson, 2014	Membrane liquid desiccant air conditioning system	• CO emissions • CO2 emissions • NOx emissions • PM emissions • Primary energy consumption • SOx emissions	L
Asif and Muneer, 2014	Window (panel & frame)	• Annual CO2 emission – electricity • Annual CO2 emission – gas • Annual electricity cost • Annual gas cost • Annual heat loss • Life cycle CO2 emission – electricity • Life cycle CO2 emission – gas • Life cycle cost – electricity • Life cycle cost - gas • Life cycle heat loss	L
Rahman et al., 2014	Compression ignition engine	• Brake specific fuel consumption • Carbon monoxide (emission parameter) • Exhaust gas temperature • Hydrocarbons (emission parameter) • Nitrogen oxides (emission parameter) • Particulate matter (emission parameter) • Thermal efficiency	L
Singh et al., 2014	Biodiesel-fuelled HCCI engine	• CO2 emissions • Hydrocarbon emissions • Indicated specific fuel consumption • Indicated thermal efficiency • NO emissions • Smoke opacity	L

In addition to material and energetic aspects of performance, certain authors in the sample were also observed to cover economic and social aspects to a limited extent. For example, as shown in Table 4-5:

- Asif and Muneer (2014) evaluate the following indicators focusing on economic aspects of a window's performance alongside various material and energetic indicators: annual electricity cost; annual gas cost; life cycle cost of electricity; and life cycle cost of gas.
- Evans et al. (2009) consider SPIs for various renewable energy production systems. They discuss a range of material and energetic indicators, but also present the following economic and social indicators: price of electricity generation; and social impacts.
- Onat and Bayar (2010) consider SPIs for what they term alternative energy production systems. Again, they discuss a range of material and energetic indicators, but also present the following economic and social indicators: unit energy cost; and social effects.

This may be seen to mirror the application of evaluation methods focusing on economic and social performance in addition to environmental performance under the sustainability-oriented design philosophies discussed in Section 4.2 (illustrated in Figure 4-8, Section 4.2.3). All three of the above authors appear to adopt the concept of sustainable development as the basis for selecting SPIs. Thus, the assessment of environmental, economic, and social aspects may also be seen to reflect the three pillars of sustainable development introduced in Chapter 3 (Section 3.3.2) and the triple bottom line as discussed in Section 4.2. The inclusion of social and economic aspects in certain *ad hoc* approaches may be contrasted with the formal evaluation methods discussed below, which, as will be shown, focus almost exclusively upon material and energetic aspects of performance.

Considering the second category of authors delineated above, i.e. those applying formal evaluation methods, Ness et al. (2007) provide a review of methods and tools for assessing sustainability. Under the umbrella of product-related assessment, they highlight several methods that, as shown in Table 4-6 below, were found to be applied to technical systems by authors in the literature sample: life cycle assessment; material flow analysis; energy analysis; exergy analysis; and emergy accounting. None of these methods are claimed in the literature to be comprehensive with respect to sustainability performance. However, they all focus on the material and/or energetic flows associated with a technical system at varying spatio-temporal scales. Thus, they are considered to be useful for assessing the sustainability performance of technical systems (Ness et al., 2007; Gasparatos et al., 2008; Ulgiati et al., 2011; Gagnon et al., 2012). Each of these methods was also identified in the engineering design literature sample in Section 4.2.3 (Table 4-4). As shown in Table 4-6, the nature of the indicators associated with each method depends primarily upon its particular material and/or energetic perspective. These perspectives, and the basic procedures involved in each method, are briefly summarised below.

Table 4-6: Formal sustainability performance evaluation methods applied to technical systems, and associated SPIs

Evaluation method	Associated indicators	Scale	Sources
Embodied energy analysis	• CO2 release • Cumulative energy demand • Embodied energy per unit of output • Energy efficiency • EROI of material and/or energetic output • GER of outputs • Oil equivalent of outputs • Oil equivalent intensity per unit of output • Total oil equivalent applied • Total embodied energy applied	G	Raugei et al., 2005; Ulgiati et al., 2011; Buonocore et al., 2012; Cellura et al., 2013
Emergy accounting	• Adjusted yield ratio • Emergy efficiency index • Emergy from imported resources • Emergy from local non-renewable resources • Emergy from local renewable resources • Emergy Sustainability Index • Emergy Yield Ratio • Environmental Loading Ratio • Renewable fraction • Total emergy • Transformity of outputs	G	Raugei et al., 2005; Ulgiati et al., 2011; Buonocore et al., 2012; Moss et al., 2014
Energy analysis	• CO2 emissions • Coefficient of Performance • Cooling capacity • Energetic renewability ratio • Energy efficiency • Energy input rate • Energy losses • Energy storage rate • Wet bulb effectiveness • Work output	L	Balta et al., 2010; Caliskan et al., 2011b; Caliskan et al., 2012; Li et al., 2012; Söğüt et al., 2012; Waheed et al., 2014
Exergy analysis	• Entropy generation • Environmental effect factor • Exergetic renewability ratio • Exergetic sustainability index • Exergy destruction rate/factor • Exergy efficiency • Exergy input rate • Exergy losses • Exergy output rate	L	Raugei et al., 2005; Balta et al., 2010; Caliskan et al., 2011a; Caliskan et al., 2011b; Ulgiati et al., 2011; Caliskan et al., 2012; Li et al., 2012; Söğüt et al., 2012; Aydin et al., 2013;

Evaluation method	Associated indicators	Scale	Sources
	• Exergy storage rate • Recoverable exergy ratio • Sustainability index [exergetic] • Thermodynamic efficiency • Total exergy input • Waste exergy ratio		Waheed et al., 2014
Life cycle assessment	• Abiotic depletion potential [Im] • Acidification potential (overall & per unit of output) [Im] • Carbon footprint (overall & per unit of output) [Im] • CH4 emissions • Chemical oxygen demand [Im] • Climate change [Im] • CO emissions • CO2 emission intensity • CO2 emissions • CO2 payback time • Dissolved organic carbon • Ecotoxicity potential [Im] • Electricity generation • Energy gain ratio • Energy intensity • Energy payback time • Eutrophication potential [Im] • Fossil depletion [Im] • Global warming potential [Im] • Human toxicity (overall & per unit of output) [Im] • Land use [Im] • Life cycle embodied energy • Life cycle GHG emissions • Metal depletion [Im] • Net CO2 reduction • Net energy ratio • Non-radioactive waste creation [Im] • Non-renewable energy [Im] • NOx emissions • Odour • Ozone depletion potential [Im] • Particulate matter formation [Im] • Photochemical oxidation (overall & per unit of output) [Im] • PO4 emissions • Potable water consumption [Im] • Primary energy consumption [Im] • Radioactive waste creation [Im] • Respiratory inorganics [Im] • SOx emissions • Water consumption/resource depletion [Im]	R – G	Pacca et al., 2007; Shah et al., 2008; Ulgiati et al., 2011; Buonocore et al., 2012; Thiers and Peuportier, 2012; Adams and McManus, 2014; Antony et al., 2014; Kim et al., 2014; Ofori-Boateng and Lee, 2014; Russell-Smith et al., 2014; Shahabi et al., 2014; Uddin and Kumar, 2014
Material flow accounting	• Abiotic material intensity per unit of output	G	Raugei et al., 2005; Ulgiati et al., 2011;

Evaluation method	Associated indicators	Scale	Sources
	• Global to local ratio of abiotic material • Global to local ratio of water demand • Material intensity, air factor • Material intensity, biotic factor • Total abiotic material requirement • Total water demand • Water demand per unit of output		Buonocore et al., 2012

Life cycle assessment (LCA):

LCA was introduced in Chapter 3 (Section 3.5.2.1), where three different forms were discussed: (i) what is typically termed "life cycle assessment" in the literature, focusing on environmental aspects of performance; (ii) social life cycle assessment, focusing on social aspects of performance; and (iii) life cycle costing, focusing on costs, i.e. financial performance. It is (i) that was found to be applied to technical systems by authors in the literature sample, as shown in Table 4-6. However, it should be noted that both (ii) and (iii) were identified in the engineering design literature sample in Section 4.2.3 (Table 4-4). According to Russell-Smith et al. (2014, p.1), the purpose of LCA is "to quantify the energy and material flows associated with each life cycle stage from raw material extraction through material processing, manufacture, distribution, use and maintenance, and end-of-life for a given product or service." As noted in Chapter 3, LCA has been standardised by the International Standards Organisation in ISO 14040 and 14044 (Ulgiati et al., 2011), and involves four procedural steps: (i) goal and scope definition; (ii) life cycle inventory analysis; (iii) life cycle impact assessment; and (iv) interpretation of results (Ofori-Boateng and Lee, 2014).

Impact indicators are typically associated with LCA, although authors may be seen to evaluate other types of indicator under a life cycle perspective, i.e. considering performance throughout the full life cycle (e.g. Ulgiati et al., 2011). Impact indicators are appended with '[Im]' in Table 4-6. These indicators focus on various environmental aspects (e.g. climate change, acidification, eutrophication, ozone depletion, and so on), and are evaluated by assigning material/energetic flows to impact categories and converting them to equivalent units so that they may be compared and consolidated (SAIC, 2006). Impact indicators are typically evaluated at either: the global scale, considering the full life cycle from extraction and processing through to recycling and disposal (e.g. Antony et al., 2014); or the regional scale, considering the manufacturing, operation, and potentially recycling and disposal phases (e.g. Shahabi et al., 2014).

Material flow analysis:

According to Raugei et al. (2005, p.124), the purpose of material flow analysis (MFA) is "to evaluate the environmental disturbance associated with the withdrawal or diversion of resources from their natural ecosystemic pathways." Material intensity (MI) indicators are typically associated with MFA (Raugei et al., 2005; Ulgiati et al., 2011), and may be viewed as global scale indicators (Ulgiati et al., 2006). To evaluate MI indicators, data is first gathered to quantify the material flows into a system. Each flow is then multiplied by predefined material intensity factors to account for "the total amount of abiotic matter, water, air and biotic matter that is directly or indirectly required in order to provide that […] input to the system" (Raugei et al., 2005, p.124). Finally, for each material category the material intensity values calculated for the input flows are summed to yield total values for the categories (i.e. abiotic material, biotic material, air, and water). These indicators are intended to provide a "quantitative measure of [the system's] cumulative environmental burden" with respect to each category (Ulgiati et al., 2006, p.435). Additional indicators may also be defined and evaluated by authors applying MFA, e.g. global to local ratios of material intensities, and material intensities per unit of output (Ulgiati et al., 2011) as shown in Table 4-6.

Energy analysis:

Two types of energy analysis approach may be identified in the literature on sustainability performance evaluation. The first, simply termed "energy analysis" (EnA) in Table 4-6, is typically carried out at the local scale, focusing on the energy consumed directly by a system during its operation (Balta et al., 2010). EnA typically involves writing thermodynamic energy balances or developing quantitative models of the system (Balta et al., 2010; Caliskan et al., 2012; Waheed et al., 2014), and evaluating indicators focusing on aspects such as energy efficiency (Söğüt et al., 2012), energy input (Caliskan et al., 2011b), and energy losses (Waheed et al., 2014) as shown in Table 4-6. Indicators focusing on emissions, particularly CO2, may also be evaluated as part of EnA (Caliskan et al., 2012). In certain cases, indicators focusing on system-specific aspects may also be defined, e.g. wet bulb effectiveness for cooling systems (Caliskan et al., 2012). EnA is commonly combined with exergy analysis (e.g. Balta et al., 2010; Caliskan et al., 2012), another local scale method, which is discussed below.

Embodied energy analysis:

The second type of energy analysis approach identifiable in the literature is known as embodied energy analysis (EEA). According to Ulgiati et al. (2006, p.435), EEA "deals with the gross (direct and indirect) energy requirement of [an] analysed system." Unlike EnA, EEA is carried out at the global scale, considering the full life cycle (Ulgiati et al., 2006). The indicators typically associated with EEA include oil equivalents for the material and energy inputs to the system, total oil equivalent applied, and the Gross Energy Requirement (GER) (Buonocore et al., 2012) as shown in Table 4-6. To calculate oil equivalents, data is first gathered on the material and energetic inputs to the system. Each input is then multiplied by an oil equivalent factor to determine its equivalent magnitude in terms of grams of oil per unit of input. The cumulative oil equivalent is then the sum of the oil equivalents for individual inputs (Ulgiati et al., 2006; Buonocore et al., 2012). According to Ulgiati et al. (2006, p.435), the GER expresses "the total commercial energy requirement of one unit of output in terms of equivalent Joules of petroleum." Buonocore et al. (2012, p.74) suggest that only non-renewable inputs should be included in the evaluation of GER, as it is "concerned with the depletion of fossil energy." Energy efficiency indicators may also be associated with EEA, as shown in Table 4-6. In this respect, Ulgiati et al. (2006, p.435) suggest that the method "offers useful insight on the first-law energy efficiency of [an] analysed system on the global scale." This may be contrasted with EnA above, which evaluates energy efficiency at the local scale.

Exergy analysis:

Gasparatos et al. (2009b, p.957) define exergy, or "available energy," as "the maximum work that can be extracted from a system when this system moves towards thermodynamic equilibrium with a reference state." In short, exergy accounts for the "usefulness or quality or potential to cause change" inherent in a particular energy form. According to Balta et al. (2010, p.1320), exergy analysis (ExA) therefore enables "the locations, types, and true magnitudes of wastes and losses [in a system] to be determined," leading to "more efficient energy-resource use." ExA typically involves writing exergy balances or developing quantitative models of the system being evaluated (Caliskan et al., 2011b; Waheed et al., 2014), in a similar vein to EnA discussed above.

A key indicator associated with ExA is exergy efficiency (Rosen and Dincer, 2001; Balta et al., 2010) , also known as second law efficiency (Raugei et al., 2005; Hepbasli, 2008). Certain authors suggest a direct relationship between exergy efficiency and environmental impact (e.g. Rosen and Dincer, 2001; Gasparatos et al., 2009b), with increased exergy efficiency corresponding to reduced impact (although others are more cautious in this respect, e.g. Ulgiati et al. (2006)). As shown in Table 4-6, a range of other indicators may be evaluated through ExA, focusing on similar aspects to the energy indicators discussed above e.g. exergy input and exergy losses (Caliskan et al., 2012; Waheed et al., 2014).

As noted above, ExA may be applied in conjunction with EnA (e.g. Caliskan et al., 2012; Waheed et al., 2014), to obtain views on both the first and second law efficiencies of a system. Like energy analysis, ExA is typically viewed as a local scale method, focusing primarily on performance during the operation phase of the life cycle (Ulgiati et al., 2006). However, certain authors may be observed to carry out exergy analysis from a life cycle perspective, i.e. considering all life cycle stages (Ofori-Boateng and Lee, 2014).

Emergy accounting:

The final method commonly applied to evaluate the sustainability performance of technical systems is emergy accounting (EmA), sometimes called emergy analysis (Moss et al., 2014). Like EnA, EEA, and ExA above, EmA is an energy-based method (Ness et al., 2007). According to Ulgiati et al. (2006, p.435), EmA "looks at the environmental performance of the system on the global scale." However, in comparison to the other major global scale energy-based method, i.e. EEA, EmA is broader in scope, "taking into account all the free environmental inputs such as sunlight, wind, rain, as well as the indirect environmental support embodied in human labour and services."

Moss et al. (2014, p.392) state that EmA employs various environmental indices to quantify and compare "the contribution of renewable and non-renewable components of labor, materials, and feedstocks" to a system, in order to "determine the ability of a system or process to efficiently and sustainably produce products over time." Key indicators associated with EmA include a range of indices relating the renewable and non-renewable aspects touched upon above, including the Environmental Loading Ratio and the Emergy Yield Ratio (Buonocore et al., 2012; Moss et al., 2014) as shown in Table 4-6. Also associated with EmA is the Emergy Sustainability Index, which essentially relates the emergy yielded by a system to the system's environmental burden (Moss et al., 2014). To evaluate emergy indices, all flows of material and energy into a system must first be accounted for "in terms of their solar emergy, defined as the total amount of solar available energy (exergy) that was directly or indirectly required to make a given product or to support a given flow, and measured in solar equivalent Joules (seJ)**.**" Measuring the total emergy requirement of the system provides "an indication of the total appropriation of environmental services" by the system (Ulgiati et al., 2006, pp.435-436).

4.4 Summary

This chapter has presented a review of research on sustainability in a technical systems context, aiming to provide an overview of the key concepts involved, as well as perspectives on sustainability and its nature in this area. In Section 4.1, the nature of technical systems was explored:

- technical systems are developed through the processes of engineering design/systems engineering, in response to human needs;
- the technical system life cycle may be viewed as consisting of four key stages: (i) extraction and processing of raw materials, (ii) manufacturing (including design and development, and also transportation of components), (iii) system operation, and (iv) recycling and disposal;
- a technical system meets human needs during the operation stage of the life cycle, by fulfilling the function(s) it was designed for through purposeful behaviour that is manifested through the system's structure and its interactions with its environment;
- a technical system may be generally defined as a system comprised primarily of artificial components, where most of the structural parameters have been defined by humans so that the system will behave in a particular way; and
- design may be viewed as a key activity with respect to improving the sustainability of technical systems, with the early stages of design holding the greatest potential in this respect.

Given the potential significance of design with respect to the sustainability of technical systems, research on sustainability-oriented engineering design was reviewed in Section 4.2:

- as an element of product development processes that in turn form part of an organisation's business processes, design may be viewed as ultimately contributing to the socio-economic development process forming the focus of the sustainable development concept introduced in Chapter 3;
- sustainability considerations have been increasingly integrated into design with the intention of fostering a greater sense of ethical responsibility in designers, and improving the environmental, economic, and/or social impacts of design;
- there are two central means by which sustainability considerations may be integrated into engineering design: (i) the development of sustainability-oriented design philosophies; and (ii) the development of new design methods/tools to tackle sustainability challenges, and the modification of existing ones;
- five major S-philosophies were identified from a sample of 83 sources drawn from the engineering design literature, and then grouped and differentiated on the basis of their aims and perspectives: design for environment (DfE) and ecodesign (ED); design for sustainability (DfS) and sustainable design (SD); and whole system design (WSD);

- 170 design methods and tools positioned by authors as useful in sustainability-oriented engineering design were also identified from the above sample, and categorised according to the kinds of design activity they are intended to support: creating; decision making; evaluation and analysis; modelling and simulation; and optimisation;
- identified methods and tools were organised with respect to the design activities they are intended to support, and the S-philosophies they are associated with by authors in the literature, to produce the Design Sustainability Matrix (DSM), a visual representation of the state of the art in sustainability-oriented engineering design; and
- 30.6% of the total methods and tools identified from the sample were found to focus on evaluation of the environmental, economic, and/or social performance of technical artefacts, suggesting that performance evaluation is an area receiving relatively significant attention in sustainability-oriented design.

Finally, it was shown that information on the sustainability performance of technical systems may be required in a broader organisational context (e.g. to compile an organisational sustainability report), as well as during engineering design. Thus, in Section 4.3, the literature on sustainability performance evaluation of technical systems in this wider context was reviewed:

- the sustainability performance of technical systems is typically evaluated using sustainability performance indicators (SPIs) focusing primarily upon a system's material and energetic performance during the life cycle, although limited economic and social aspects may also be covered by certain authors;
- the sustainability performance of technical systems may be evaluated across different portions of the life cycle, and either retrospectively (evaluating actual system performance due to past life cycle activities) or prospectively (evaluating potential system performance due to future life cycle activities);
- the sustainability performance of technical systems may be carried out at different spatio-temporal scales, i.e. local (considering only direct material and energetic inputs/outputs due to system operation), regional (additionally considering indirect inputs/outputs due to manufacturing and recycling/disposal), and global (additionally considering indirect inputs/outputs due to extraction and processing of raw materials used to manufacture the system);
- performance that appears to be sustainable at one spatio-temporal scale may be deemed to be unsustainable at another, i.e. the spatio-temporal

scale of evaluation may be viewed as a key factor influencing the interpretation of a technical system's sustainability performance;
- SPIs for technical systems may be defined and evaluated through either *ad hoc* approaches (relying primarily on the assessors' knowledge of the system and sustainability generally), or formal evaluation methods (outlining procedures for the definition and evaluation of SPIs); and
- six formal evaluation methods were identified from a sample of 43 sources evaluating the sustainability performance of technical systems, and all were observed to focus exclusively on material and energetic performance: life cycle assessment; material flow analysis; energy analysis; embodied energy analysis; exergy analysis; and emergy accounting.

In Chapter 5, the literature on the sustainability of society reviewed in Chapter 3 is considered alongside the literature on sustainability in a technical systems context reviewed in this chapter, leading to identification of three key issues to be tackled by research in these areas. In turn, the focus of the research documented in this thesis is defined.

5 Definition of research focus

In Chapter 3, sustainability research spanning multiple sectors of society was reviewed. Three viewpoints on the sustainability concept were determined (Figure 3-2, Section 3.3.1), namely: V1 – lexical definitions of sustainability (Section 3.1.1); V2 – sustainability objectives, encompassing what is to be sustained and for how long (Section 3.1.2); and V3 – interpretations of the basic constitution of sustainability (Section 3.2). Sustainability goals were identified as the means by which humans shift activities and systems towards sustainability (Section 3.4), and an overview of approaches to sustainability assessment was provided (Section 3.5). Technical systems were introduced as ubiquitous elements of manufactured capital throughout the sectors reviewed, driving economic production and consumption and ultimately, the societal progress that may result from economic activity. It was shown that the sustainability of technical systems is increasingly under scrutiny, owing primarily to the realisation that they may potentially have significant impacts on the wider Earth system (Section 3.6).

In Chapter 4, research on sustainability in a technical systems context was reviewed, to provide an overview of the key concepts involved and perspectives on sustainability and its nature in this area. It was shown that a technical system may be viewed as a system comprised primarily of artificial components, where most of the structural parameters have been defined by humans so that the system will behave in a particular way (Section 4.1). Engineering design was highlighted as a key activity with respect to improving the sustainability of technical systems, and it was shown how sustainability considerations have been integrated into design via sustainability-oriented design philosophies (S-philosophies), methods, and tools (Section 4.2). Sustainability performance evaluation of technical systems was in turn revealed to be an important activity during engineering design, and also in a broader organisational context (Section 4.3).

In this chapter, the findings from Chapters 3 and 4 are discussed. Conclusions that may be drawn from the findings are elaborated, leading to the identification of three salient issues for sustainability research in Sections 5.1 – 5.3. Namely, these are the lack of a:

- I1. consistent view on how the sustainability of human activities and systems can be improved (Section 5.1);
- I2. common approach for identifying appropriate sustainability performance indicators (SPIs) for technical systems (Section 5.2); and
- I3. fundamental formalism to describe the constitution of sustainability generally and in turn, sustainability of technical systems (Section 5.3).

The research aim is subsequently defined on the basis of these issues in Section 5.4. A brief summary of the chapter is provided in Section 5.5.

5.1 Sustainability improvement of human activities and systems

The first issue for sustainability research to emerge from the initial literature reviews pertains to consistency in sustainability improvement efforts. As discussed in Chapter 3, different people in different contexts have different conceptions of sustainability, based on different perspectives regarding the meaning and constitution of sustainability, and pursue different sustainability objectives owing to differences in values. In this respect, Hannon and Callaghan (2011, p.877) remark that organisations "are faced with a high degree of uncertainty and competing interests in attempting to move towards sustainability." They suggest that "the lack of a unified and rigorous understanding of sustainability means that sustainability initiatives are often ineffectual." This point is made in a business context, but is readily translatable to society as a whole. As highlighted in Chapter 3, differences in perspectives on the meaning, value, and constitution of sustainability extend across different research categories focusing on different activities and systems within society (illustrated in Figure 3-3 and Table 3-1 in Chapter 3). As a result of these variations, Kajikawa (2008, p.218) remarks that "solutions tend to be sustainable within sectors rather than across the whole of society."

Lindsey (2011, p.561) provides what is arguably a succinct summary of the state of the art in sustainability research: "While there seems to be considerable consensus that a more sustainable society is in the best interest of everyone, opinions regarding what sustainability really means and how to achieve it are as diverse as the entities striving for it." Owing to the involvement of uncertainty, multiple interpretations, and discordant values, improving the sustainability of human activities and systems has been framed as a "wicked problem" by authors (Wahl and Baxter, 2008; Metcalf and Widener, 2011). That is, one of "a class of social system problems which are ill-formulated, where the information is confusing, where there are many clients and decision makers with conflicting values, and where the ramifications of the whole system are thoroughly confusing" (Churchman, 1967, p.141). Lindsey (2011, p.561) highlights the need for a common frame of reference among people with different perspectives and values in efforts to improve sustainability, calling for the development of "a consistent framework for human effectiveness in achieving sustainability."

The need for consistency in sustainability improvement efforts is also reflected in the literature on sustainability of technical systems reviewed in Chapter 4. For instance, Alfaris et al. (2010, p.1) state that a "multidomain design approach" is required in the design of large-scale, complex technical systems. Similarly, multidisciplinary working is a key feature of the conventional systems engineering process (Blanchard and Fabrycky, 1981) that forms the basis of an approach to sustainable whole system design proposed by Stasinopoulos et al. (2009). Thus, designing a sustainable technical system may involve designers from different disciplines, who may hold different values and perspectives on sustainability as discussed above in a societal context. Consequently, Alfaris et al. (2010, p.1) suggest that designing a sustainable "large-scale complex system" requires designers to adopt "a systematic approach toward integrated design of all subsystems" in order to avoid "suboptimality." That is, the achievement of sustainability in one part of the system at the expense of sustainability in other parts.

From the above, it may be concluded that the literature is lacking a consistent view on how the sustainability of human activities and systems can be improved. Given that the lack of a unified understanding among different people involved in a system (e.g. society, an organisation, or a large scale technical system) in turn reduces the effectiveness of efforts to improve sustainability at the whole system level, this may be viewed as a key issue to be addressed in sustainability research.

5.2 Identification of SPIs for technical systems

A second issue for sustainability research, relating to the identification of appropriate SPIs for technical systems, was found to emerge from the literature reviewed in Chapter 4. As discussed in Sections 4.2 and 4.3, information on the sustainability performance of technical systems is needed in the context of both the engineering design process and the wider organisation. In the former context, the information may be used to identify areas for product improvements or to select the most sustainable option from a range of concepts, i.e. to support decision making. In this respect, performance evaluation was identified as an activity receiving relatively significant attention in sustainability-oriented design in Section 4.2.3. In the latter context, the information may be used by: the organisation *per se* for management purposes; the organisation's competitors for benchmarking purposes; and consumers as a basis for purchasing decisions.

In Section 4.2.3, a breakdown of different types of performance evaluation methods identified from the engineering design literature sample was presented (Figure 4-10). That is, performance evaluation methods focusing on: economic and social performance; environmental performance; and integrated environmental, economic, and/or social performance. This may be seen to reflect the aims of the major S-philosophies identified in Section 4.2.2, i.e. to improve the environmental, economic, and/or social performance of technical artefacts. Nonetheless, a notable focus on environmental performance was observed in the sample: 75% of the performance evaluation methods identified were found to focus solely on environmental performance, as opposed to economic and social performance (13.5%) and integrated environmental, economic, and/or social performance (11.5%).

In Section 4.3, the literature on sustainability performance evaluation of technical systems in a broader organisational context was reviewed. Authors were observed to apply a combination of *ad hoc* approaches and formal evaluation methods to define and evaluate sustainability performance indicators (SPIs). With respect to the evaluation of environmental, economic, and social performance, a notable focus on environmental performance was once again observed. That is, the majority of authors were seen to evaluate environmental aspects of performance alone. Certain authors applying *ad hoc* approaches were observed to evaluate economic and social aspects to a limited extent. In contrast, formal evaluation methods were found to focus almost exclusively on environmental aspects. In cases where economic and social aspects were measured alongside environmental aspects, it appears that the three pillars of sustainable development (introduced in Chapter 3, Section 3.3.2) or the triple bottom line (introduced in Chapter 4, Section 4.2) is adopted as the basis for identifying SPIs. However, as noted in Section 5.3 below, sustainable development is not equivalent to the sustainability of technical systems. Sustainable development refers to the sustainability of socio-economic development, i.e. a higher-order process that engineering design ultimately contributes to. Thus, it is not apparent why environmental, economic, and social aspects of performance are considered to be relevant in sustainability performance evaluation of technical systems.

Considering environmental performance evaluation methods alone, a number of methods were found to be applied in both an engineering design context and a broader organisational context. Namely, these were: life cycle assessment; material flow analysis; energy analysis; exergy analysis; and emergy analysis. The nature of these methods and the SPIs they employ was examined more closely in Section 4.3, i.e. considering the literature sample focusing on sustainability performance evaluation in an organisational context. All of the methods were classified as evaluating the material and energetic performance of technical systems, and similarities may be detected across certain methods with respect to the broad areas being measured (e.g. material/energy consumption, and waste production). However, the specific indicators applied vary from method to method (as shown in Table 4-6 in Section 4.3.2). This raises the question of what material and energetic aspects should fundamentally be measured in sustainability performance evaluation of technical systems.

From the above, it may be concluded that there is a lack of clarity regarding which of the plethora of indicators reported in the literature, if any, constitute appropriate SPIs for technical systems. In their work on design performance, O'Donnell and Duffy (2005, p.10) argue that to ensure appropriateness, performance indicators "should be derived from a model of the activity/process under investigation." A notable observation in this respect is that none of the methods commonly applied to evaluate the sustainability performance of technical systems appear to be based on a model of technical system sustainability. Thus, it is not immediately clear why the indicators associated with these methods should be considered relevant in an evaluation of a technical system's sustainability performance. O'Donnell and Duffy (2005, p.10) further suggest that indicators defined for a particular system should reflect "aspects that are specific to the scope of investigation." The behaviour of technical systems may vary considerably depending on aspects such as system function, structure, and environment and as such, the specific SPIs considered to be relevant are likely to differ from system to system. This suggests that applying the same evaluation method and SPIs across different technical systems may not be an appropriate means to evaluate sustainability performance. In this respect, O'Donnell and Duffy (2005, p.10) argue that "the means by which the most appropriate metrics [indicators] may be defined for any particular situation is considered to be of most importance, rather than the actual metrics themselves." In other words, a common approach to indicator identification is needed, rather than common sets of indicators.

On the basis of the above, it is suggested that a common approach, grounded in a model of technical system sustainability, is needed to support the identification of appropriate SPIs for technical systems. Such an approach could potentially integrate existing methods and indicators that are not necessarily based on models of technical system sustainability, but may nonetheless hold relevance from a sustainability perspective. Thus, the lack of a common approach for identifying SPIs for technical systems may be viewed as a second salient issue for sustainability research.

5.3 The constitution of sustainability

A final research issue, focusing on the basic constitution of sustainability, was found to emerge from the literature on both the sustainability of society (Chapter

3) and sustainability of technical systems (Chapter 4). Firstly, in Section 3.2 of Chapter 3, it was shown that four different interpretations of the basic constitution of sustainability may be identified in the literature. That is, sustainability constituting: (i) an ability; (ii) a property of an entity; (iii) a process of change; and (iv) a state of an entity. As discussed in Section 3.3.1, different types of sustainability discussed by authors in different sectors seem to be based on different interpretations in this respect (illustrated in Table 3-1). Furthermore, there are conflicting views regarding the differentiation of *sustainability* from *sustainable development*. Commentary from certain authors suggests that the two concepts are equivalent, whilst others indicate that sustainable development is simply one application of the sustainability concept. Consequently, it may be concluded from the literature reviewed in Chapter 3 that there is a lack of clarity regarding the basic constitution of sustainability. This may be seen to be supported by Hannon and Callaghan (2011, p.877), who argue that "the diffusion and popularity of the term *sustainability* with relatively little corresponding rigorous and grounded conceptualization may have created confusion over the basic concepts of sustainability."

Whilst multiple interpretations of the basic constitution of sustainability may be identified in the literature on sustainability of society, it seems that this viewpoint has received little attention in the literature on sustainability of technical systems. Considerable research effort has been spent on trying to characterise the sustainability of the design *activity*, in the form of various sustainability-oriented philosophies laying out perspectives on what it means to, for instance, "design for sustainability" or carry out "sustainable design" (Chapter 4, Sections 4.2.1 and 4.2.2). In contrast, few authors detail the constitution of sustainability of the design *artefact*, i.e. technical systems as discussed below.

As shown in Sections 4.2.2.1 and 4.2.2.2, certain S-philosophies identified from the engineering design literature sample were inferred as being oriented towards different types of sustainability: DfE/ED towards environmental sustainability, i.e. the delivery of environmentally sustainable artefacts; and DfS/SD towards environmental, economic, and social sustainability, i.e. the delivery of environmentally, economically, and socially sustainable artefacts. In each case, these inferences were made on the basis of references to a focus on improving the environmental, economic, and/or social impacts of technical artefacts made by authors discussing the philosophies. However, whilst certain authors may be seen to state the terms "sustainability" or "sustainable," none of the authors discussing DfE/ED and DfS/SD in the literature sample were seen to explicitly detail the basic constitution of sustainability of technical systems, i.e. the design artefact. For example:

- In the context of DfS, Alfaris et al. (2010, p.1) present a design methodology "for addressing design problems of complex sustainable systems" – however, they do not define what a complex sustainable system is. They also remark that "an integrated cross-domain approach is needed to create overall sustainability in engineered systems," and refer to "sustainable design solutions." However, again, they do not detail the basic constitution of sustainability of engineered systems, or what constitutes a "sustainable design solution."
- In the context of DfS, Mayyas et al. (2012a, pp.1856-1859) make numerous references to the development of "sustainable products," and write of the demand for "more sustainable vehicles in terms of fuel efficiency and less environmental impacts." Nonetheless, although they may be seen to outline criteria that a vehicle should meet in order to be sustainable, they do not explicitly detail what constitutes a "sustainable vehicle" or "sustainable product."
- In the context of ED, Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010, p.494) remark that "[it] is critical to preserve creativity in the design team if truly sustainable solutions are expected to be attained," but they do not detail what constitutes a "sustainable solution."
- Finally, in the context of SD, Chiu and Chu (2012, p.1259) highlight that there is a "need to implement sustainability at early stages of a product's life cycle." They go on to make references to the sustainability of "products, processes, and systems," as well as "sustainable design concepts." Nonetheless, they do not detail the basic constitution of sustainability of products, processes, and systems, or what constitutes a "sustainable design concept."

Cited by numerous authors in the field, Charter and Tischner (2001, p.17) provide a broad definition of a sustainable design solution in the context of product design and development and the SD philosophy:

"Sustainable solutions are products, services, hybrids or system changes that minimise negative and maximise positive sustainability impacts – economic, environmental, social, and ethical – throughout and beyond the life-cycle of existing products or solutions, while fulfilling acceptable societal demands/needs."

However, they define a "sustainable solution" in terms of "sustainability impacts," without defining what is meant by "sustainability" in this context. Thus, it remains unclear what constitutes a sustainable solution, sustainability impacts, and sustainability *per se*. Later in the same publication, Tischner and Charter (2001, pp.118-120) discuss the contribution of "sustainable product design" and "sustainable products" to "sustainable development" (introduced in Chapter 3, Section 3.3.2), a "sustainable society," and "sustainable consumption and production." However, they do not detail what constitutes a "sustainable product." Furthermore, definitions of sustainable development and sustainable consumption and production are definitions of sustainability of development, consumption, and production i.e. the higher-order processes illustrated in relation to design in Figure 4-4 (Section 4.2.1), rather than definitions of sustainability of technical artefacts.

As discussed in Section 4.2.2.3, WSD was observed to be oriented towards system sustainability – that is, the delivery of sustainable systems. Authors were found to explicitly highlight "technical engineered systems" (Stasinopoulos et al., 2009, p.3) and "product systems" (Fiksel, 2003, p.5331) as the technical artefact in this context. Fiksel (2003, p. 5331) defines a sustainable "product system" as "one that continues, possibly with design modifications, to meet the needs of its producers, distributors, and customers." In Section 4.2.2.3, Stasinopoulos et al. (2009, p.3) were shown to outline a "description of a sustainable [technical engineered] system." To paraphrase the authors, they argue that sustainable systems: consume resources within ecological limits; produce waste within ecological limits; have minimal negative and maximum positive ecological impacts; provide long term benefits, and useful and socially accepted services for society; and are cost effective, have a reasonable return on investment over the life cycle, and are preferably immediately profitable. However, the definitions provided by both Fiksel (2003) and Stasinopoulos et al. (2009) may be viewed as detailing criteria a technical artefact's behaviour should meet in order to be sustainable, rather than the basic constitution of sustainability of technical systems *per se*. Also in the context of WSD, Blizzard and Klotz (2012, p.475) remark that "whole systems design is an approach that offers designers the opportunity to holistically optimize solutions for social, environmental, and economic sustainability." This suggests that system sustainability may have environmental, economic, and social dimensions, something which may be seen to be reflected in the list of criteria provided by Stasinopoulos et al. (2009) above. Nonetheless, Blizzard and Klotz (2012) do not explicitly detail the basic constitution of sustainability of a technical system.

Above, it was concluded that there is a lack of clarity regarding the basic constitution of sustainability in a general societal context. Multiple, seemingly conflicting interpretations may be identified in the literature. In the literature on sustainability of technical systems, interpretations of the constitution of sustainability are rarely explicated. On this basis, it may be concluded that there is also a lack of clarity regarding the basic constitution of sustainability of technical systems, although this arises for different reasons than in the broader literature.

This conclusion may be seen to be supported to a certain degree by Azkarate et al. (2011, p.165), who remark that "it is not clear in an operational way what sustainability means applied to different industries and products." According to Sim (2000, p.17), researchers typically "understand and explain natural phenomena or human behaviour phenomena" using abstract formalisms such as theories and models. Thus, a general theory or model describing the basic constitution of sustainability could potentially provide clarity in this area. However, as highlighted by Hannon and Callaghan (2011, p.877) above, the literature is lacking any "rigorous and grounded conceptualization" of this nature. Thus, the lack of a fundamental formalism to describe the constitution of sustainability, both generally and in a technical systems context, may be viewed as a third key issue for sustainability research.

5.4 Research focus

Three issues for sustainability research that were found to emerge from the literature reviewed in Chapters 3 and 4 were discussed in Sections 5.1 – 5.3. In summary, these are the lack of a:

- I1. consistent view on how the sustainability of human activities and systems can be improved (Section 5.1);
- I2. common approach for identifying appropriate SPIs for technical systems (Section 5.2); and
- I3. fundamental formalism to describe the constitution of sustainability generally and in turn, the sustainability of technical systems (Section 5.3).

The research aim is defined on the basis of these issues in the following paragraphs.

With respect to issue I3, it was highlighted in Section 5.3 that two kinds of formalism are typically used by researchers to explain natural and human behaviour phenomena: theories and models. As stated by Sim (2000, p.17), theories may be viewed as "general statements which make no reference to and do not depend upon particular instances of the phenomenon they are supposed to be theories about." Models are considered to be "abstract organisational ideas derived from inferences based on observations." A key purpose of building models "is to make observations more comprehensible." Sim distinguishes between theories and models, stating that whilst "models do not actually constitute a theory, a theory can emerge when there are feasible explanations as to why a model behaves as it does." Thus, a model of a particular phenomenon may be viewed as a precursor to the development of theories about that phenomenon. As such, a general model describing the basic constitution of sustainability of technical systems could provide a basis for the future development of theories about the phenomenon of sustainability in this context.

In addition to increasing knowledge of the basic constitution of sustainability as discussed above, a generic model of technical system sustainability could also contribute to addressing issues I1 and I2 stated above. Firstly, with respect to issue I1, it has been suggested that "the transition towards a sustainable human presence in the world is *the* wicked problem for design in the twenty-first century" (Wahl and Baxter, 2008, p.75). Buchanan (1992, p.16) highlights ten properties of wicked problems as defined by Rittel and Webber (1973). Among these is the notion that for "every wicked problem there is always more than one possible explanation, with explanations depending on the *Weltanschauung* [worldview] of the designer." Meadows (1998, p.6-8) states that worldviews are "mental models about the very nature of reality," which vary "enormously" from person to person. She highlights that this is "one reason why we have trouble agreeing upon common indicators with which to inform our decisions" in efforts towards sustainability. It may also be viewed as a reason for the multiple conceptions of sustainability identifiable in the literature, and the differences in sustainability objectives pursued across society. Thus, to foster a consistent view on sustainability improvement among different people, there is a need to reconcile potentially misaligned or conflicting perceptions resulting from differences in worldviews. Meadows (1998, p.9) suggests that common models "can be a tool for expanding, correcting, and integrating worldviews." In this respect a generic model of sustainability, that can be applied in different contexts and to different systems, could provide the basis for a more consistent view on sustainability improvement.

Finally, with respect to issue I2, it was highlighted in Section 5.2 that to ensure appropriateness, performance indicators "should be derived from a model of the activity/process under investigation" (O'Donnell and Duffy, 2005, p.10). Thus, an approach for identifying appropriate SPIs for technical systems should be based on a model of technical system sustainability. Furthermore, given the need for a *common* approach to this activity, it is necessary that this model is broadly applicable across different technical systems. Thus, in addition to supporting a more consistent view on sustainability improvement, a generic model of technical system sustainability could also provide the basis for a common approach to the identification of appropriate SPIs for technical systems.

Following on from the above discussion, it may be stated that the research reported in this thesis aims *to develop a generic model of technical system sustainability*, to address the lack of a: (i) consistent view on sustainability improvement, (ii) common approach to identifying appropriate SPIs, and (iii) fundamental formalism of sustainability.

5.5 Summary

In this chapter, the findings from Chapters 3 and 4 have been discussed in order to define the focus of the research documented in this thesis. Conclusions drawn from the findings were elaborated in Sections 5.1, 5.2, and 5.3, leading to the identification of three salient issues for sustainability research. In summary, these are the lack of a:

- I1. consistent view on how the sustainability of human activities and systems can be improved (Section 5.1);
- I2. common approach for identifying appropriate SPIs for technical systems (Section 5.2); and
- I3. fundamental formalism to describe the constitution of sustainability generally and in turn, the sustainability of technical systems (Section 5.3).

In Section 5.4, it was shown that the development of general theories and models provides a means for researchers to explain natural and human behaviour phenomena, with models providing the foundation for theories. As such, it was suggested that the development of a general model provides a means to describe the basic constitution of sustainability in order to address issue I3, and a foundation for the future development of theories about the sustainability of technical systems. Furthermore, it was demonstrated how a generic model of technical system sustainability could also address issues I1 and I2. Firstly, with respect to I1, it was shown that to foster a consistent view on sustainability improvement, potentially misaligned or conflicting perceptions resulting from differences in worldviews may be reconciled through the use of a common (i.e. generic) model of sustainability. Secondly, with respect to I2, it was shown that to ensure appropriateness, SPIs for technical systems should be derived from a model of technical system sustainability. A generic model of this nature, i.e. one that can be applied to different technical systems, could therefore provide the basis for a common approach for identifying SPIs for technical systems.

Duffy and O'Donnell, (1998, p.39) outline a framework for conducting research within the design domain. They argue that models are "built and influenced by findings in literature, experiments, known theories and reality." Furthermore, Sim (2000, p.17) suggests that models are "derived from inferences based on observations." These views highlight two objectives to be carried out in order to achieve the research aim:

1. Inductive literature research to identify model elements and the relationships among them.
2. Evaluation of the model through application to technical systems in industry and expert appraisal.

These objectives form the focus of Chapters 6, 7, and 8 of this thesis.

6 The Sustainability Cycle/Loop (S-Cycle/S-Loop) models

In Chapter 5, the findings of the literature review presented in Chapters 3 and 4 were discussed in order to define the research focus. The research aims *to develop a generic model of technical system sustainability*, to address the lack of a: (i) consistent view on sustainability improvement, (ii) common approach to identifying appropriate SPIs, and (iii) fundamental formalism of sustainability. To achieve this aim, the Sustainability Cycle (S-Cycle) and Sustainability Loop (S-Loop) models were developed. This chapter outlines inductive literature research carried out to build the models, based on literature spanning the same sectors considered in Chapter 3. That is, sectors identified as major contributors to sustainability research. This includes design, as well as the following: agriculture; business; economics; fisheries; forestry; socio-economic development; sustainability science; and urban studies. Literature from a broad range of sectors was studied to facilitate the development of generic models.

The development of the S-Cycle and S-Loop models is reported in full in Paper C (Appendix 3). The following sections summarise the key points of the work discussed in the paper – readers are referred to Appendix 3 for additional details. It was not possible to carry out extensive evaluation of the S-Loop model during the course of the research. This was due to the time constraints of PhD research, particularly the length of time available to negotiate access to and conduct studies in industry (discussed in Chapter 7). As such, Chapters 7 and 8 discuss evaluation of the S-Cycle model, with further evaluation of the S-Loop model potentially forming the focus of future research as discussed in Chapter 9.

The findings of the literature investigation conducted as the basis for developing the S-Cycle and S-Loop models are presented in Sections 6.1 to 6.4. In Chapter 3, four interpretations of the basic constitution of sustainability were identified from the literature. In Section 6.1, it is shown how these different interpretations can be made more coherent by considering the constitution of “ability” generally. Sections 6.2, 6.3, and 6.4 focus on three concepts that were found to emerge from the literature as significant in relation to the aim of the research: (i) *systems*, which may be considered to provide the context for human action towards sustainability (Section 6.2); (ii) *activities*, which produce entities that humans value and wish to sustain and thus, may themselves be viewed as fundamental entities to be sustained (Section 6.3); and (iii) *knowledge*, which is typically presented as a driver of human action both generally, and in the context of sustainability specifically (Section 6.4). The S-Cycle and S-Loop models are introduced in Section

6.5, and it is shown how they were constructed through a process of induction from the findings of the literature investigation. A summary of the chapter is provided in Section 6.6.

6.1 The constitution of ability

As noted above, four interpretations of the constitution of sustainability were identified in Chapter 3 (Section 3.2). That is, sustainability interpreted as: (i) an ability; (ii) a process of change; (iii) a property or attribute of an entity; and (iv) a state of an entity. Each of these interpretations appears to describe sustainability differently. However, as shown in Section 2 of Paper C, examining the constitution of "ability" in a general sense suggests that the interpretations are likely to be complementary rather than conflicting:

- In general terms, an *ability* may be described as a *property of an entity*, that is manifested to humans as behaviour that produces certain effects (Hubka and Eder, 1988; Wang et al., 2008). From this perspective, it may be stated that the sustainability of an entity is manifested to humans as behaviour that produces the effect of maintenance/continuation, either of the entity in question or some other entity. Sustainability *per se* may be viewed as a *property of an entity* that exhibits this behaviour. Human cognisance of this property results from an assessment of an entity's behaviour, showing that the entity can actually produce the effect of maintenance/continuation (Wang et al., 2008). That is, sustainability assessment as discussed in Chapters 3 and 4.
- As discussed in Chapter 3, the notion of a "sustainability transition" is discussed in the literature. That is, the process involved in practically shifting human activities and systems towards sustainability, typically through the formulation and implementation of sustainability goals. It may be seen from the above that this represents a behavioural shift – humans are trying to shift the current behaviour of entities towards the behaviour required for sustainability. Thus, in efforts towards sustainability, some kind of *process of change* is occurring with respect to the behaviour of certain entities.
- Finally, as discussed above, sustainability is manifested to humans as behaviour that produces the effect of sustenance/maintenance/ continuation (Wang et al., 2008). This manifestation may be viewed as a kind of *state of an entity*. That is, the entity is perceived to be behaving in a particular manner (Oxford English Dictionary, 2014).

From the above, it may be seen that sustainability can be interpreted as an ability, which is a property of an entity and manifested to humans as behaviour that produces the effect of maintenance/continuation, either of the entity in question or some other entity. Therefore, it may be concluded that the interpretations identified from the literature in Chapter 3 are closely related, with each providing a view on a different aspect of the constitution of sustainability.

6.2 The systems context for sustainability

Voinov (2007, p.488) suggests that sustainability may be viewed as “a human intervention that is imposed on a system as part of human activity and is totally controlled and managed by humans.” Humans are primarily concerned with the sustainability of their society within the Earth system (Komiyama and Takeuchi, 2006; Voinov, 2007; Beddoe et al., 2009), although they tend to focus on different sub-systems of this overall system in order to reduce complexity. For example, technical systems form the focus of this thesis. To provide insight into the context for human action towards sustainability, the Earth system and its sub-systems are characterised in Section 3 of Paper C. An overview of the key points is provided in Sections 6.2.1 and 6.2.2 below.

6.2.1 The nature of systems

Like definitions of sustainability, definitions of “system” abound (Bell and Morse, 2008). However, on a basic level and in a generic sense, a system may be defined as “a collection of elements, also called parts [or components by certain authors], that are each interrelated with at least one other, and which possesses properties different from the collection of properties of the individual parts” (Thomé, 1993, p.4). Thomé (1993, p.5) remarks that systems “are in the eye of the beholder.” In other words, systems exist in the “real” world, but must be defined by humans in order to be studied. The author explains that “an observer, through a conscious act of her/his own, chooses to delimit something, that is a system, from its environment.”

The concepts of function, behaviour, and structure were introduced in Chapter 4 in relation to technical systems. It is suggested that the nature of all systems may be understood in terms of these three aspects. As discussed in Chapter 4, function refers to ‘what a system is for’ (Hubka and Eder, 1988; Gero and Kannengiesser, 2004; Meadows, 2008). A system fulfils its function through certain purposeful behaviour, with behaviour referring to ‘what a system does’ (Gero and Kannengiesser, 2004; Wang et al., 2008). According to Meadows (2008, pp.1-2), a “central insight of systems theory” is the notion that a “system, to a large extent, causes its own behaviour.” She writes that a “system may be buffeted, constricted, triggered, or driven by outside forces. But the system’s response to these forces is characteristic of itself." Along these lines, Tully (1993, p.46) remarks that the behaviour of a system is "determined by its structure and the stimuli it actually receives." Essentially, system behaviour may be viewed as an emergent property (Tully, 1993). That is, a property that "is not determined solely from the properties of the system's parts, but which is additionally determined by the system's structure" (Thomé, 1993, p.7). As discussed in Chapter 4, the structure of a system refers to "what its components are, how they are connected, and what passes across those connections" (Tully, 1993, p.46). A system's behaviour is manifested through its structure and its interactions with its surroundings (Gero and Kannengiesser, 2004; Wang et al., 2008). That is, humans can interpret the behaviour of a system by observing what its interrelated components do in a particular environment.

An example of a technical system (a car) is provided in Section 4.1 of Chapter 4, illustrating the concepts of function, behaviour, and structure discussed above. The relationships between these three concepts are illustrated in Figure 4-3.

6.2.2 The Earth system

As discussed above, the Earth system may be considered to provide the context for human action towards sustainability (UNEP, 2012). The Earth system may be viewed as a socio-ecological system (Beddoe et al., 2009). In other words, a system where "society and nature are innately coupled" (Dawson et al., 2010, p.2844). As such, it may be seen that humans are integral components of the system. However, they may also intervene in the system and its subsystems (Beddoe et al., 2009; Dawson et al., 2010). Further, given certain assumptions regarding the negligibility of material inputs and outputs (e.g. owing to space travel and asteroids), the Earth system may be approximated as thermodynamically closed (Daly 1992; Wackernagel and Rees 1997; Cabezas et al. 2005). That is, no mass crosses the system boundary. Only energy crosses the boundary, in the form of heat and work interactions (Çengel and Turner, 2004). A basic function of the Earth system and its sub-systems is processing materials, energy, and information (MEI) (Skyttner, 1996). Blanchard and Fabrycky (1981, p.4) highlight that some "motive force must be present to provide the alteration." In the context of the whole Earth system, it may be seen that ultimately, this motive force is provided by incoming electromagnetic radiation from the Sun (Stremke et al., 2011).

The Earth system may be broken down into a variety of "open, coupled, complex, interactive and non-linear dynamic [sub-]systems" (Dawson et al., 2010, p.2843). Major sub-systems of the Earth system considered in sustainability research were covered in Chapter 3 and include: agricultural systems; complex systems generally; economies; ecosystems; organisms; urban areas; and societies. Technical systems, forming the focus of this thesis, may also be viewed as sub-systems of the Earth system. Sub-systems of the Earth system may be seen to exist at various hierarchical levels. For instance, a human (i.e. organism) may be viewed as a sub-system of a society, which in turn may be viewed as a sub-system of an ecosystem (Köhn, 1998). Likewise, an ignition system may be viewed as a sub-system of an internal combustion engine, which may in turn be viewed as a sub-system of a car. Systems may also be considered to occupy the same hierarchical level within the Earth system. For example, a car, a bus, and a lorry driving on a road do not share a hierarchical relationship, but may interact with one another at the same hierarchical level.

6.3 Sustainable activities

In a system, activities may be viewed as "the fundamental elements that transform input to output" (O'Donnell and Duffy, 2005, p.56). For example, humans need production activities to transform raw materials into technical artefacts (Chapman, 2011), and socio-economic development activities to transform these artefacts into intangible entities such as living standards and wellbeing (UNDP, 2011). We need certain natural activities to transform our waste products back into useful resources (Lindsey, 2011) such as water and minerals. At the most fundamental level, we need biological activities to transform food into energy, and air into the oxygen we need to live. Thus, in order to sustain the entities that humans value, it is necessary to ensure the continued operation of the activities that produce those entities in the first place. Like "system," "activity" is a general concept that may be translated to any context (as shown in the following sections). Therefore, discussing sustainability in terms of systems and activities provides a general language that may be broadly applied and understood.

The concept of an activity is introduced and explained in the context of the Earth system in Section 4 of Paper C. The key points discussed are outlined in Sections 6.3.1 to 6.3.3 below.

6.3.1 The nature of activities

An activity may be defined as a goal-directed physical or cognitive action, where a set of passive resources are used by active resources to produce an output that should satisfy the goal of the activity, as shown in Figure 6-1 (Boyle et al., 2009). Active resources may be viewed as resources that use other resources in activities, and passive resources as resources used by active resources (Boyle et al., 2009). In a system, passive and active resources, and activity outputs, may be viewed as system components. The label of "passive resource," "active resource," or "output" that is attached to a particular system component depends upon the activities that it is involved in.

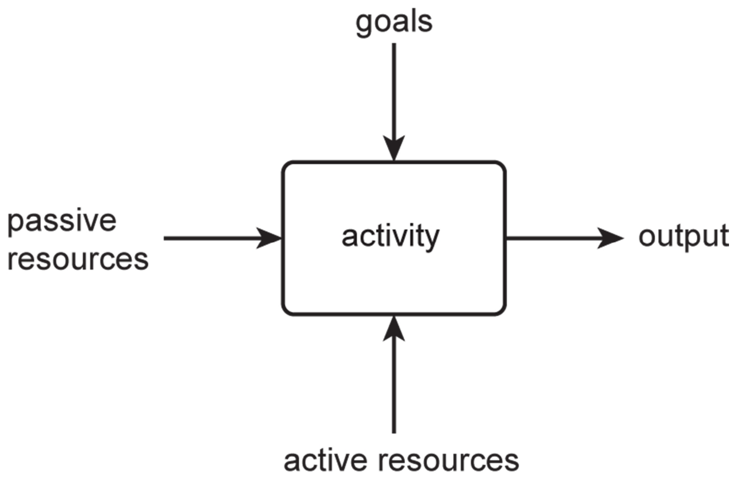


Figure 6-1: Activity formalism (adapted from Boyle et al. (2012))

As discussed previously, a system's behaviour is manifested through its structure and its interactions with its surroundings. That is, humans can interpret the behaviour of a system by observing what its interrelated components do in a particular environment. Similarly, humans may focus on the behaviour of activities operating in a particular system of interest (SoI), i.e. what the activities do within the system (Wang et al., 2008). This behaviour may be considered to be manifested through the particular set of system components (i.e. passive and active resources, and outputs) involved in the activity, and the activity's interactions with the wider SoI. As discussed above, in order to sustain the entities that humans value, it is necessary to ensure the continued operation of the activities that produce the entity in the first place. From this perspective, activity sustainability may be considered to be manifested as behaviour that is conducive to the continued operation of the activity within some wider SoI. That is, behaviour that produces the effect of continuation of the activity *per se*.

From the work detailed in Duffy (2005, p. 65), it can be inferred that an active resource may be considered as "the means to carry out the activity," and a passive resource as providing "the conditions or elements upon which the means act." As such, it may be seen that the ability of an activity to continue to operate within a particular SoI, i.e. its sustainability, depends fundamentally upon the availability of passive and active resources in the system. Major activities considered in sustainability research were covered in Chapter 3 and include: agricultural activities; business activities; design activities; the overarching process of socio-economic development; the activity of fishing; activities undertaken in the use of forests; and activities involved in the production of yield generally. The operation of a technical system may also be represented as an activity (Hubka and Eder, 1988), where the technical system is an active resource that transforms inputs into outputs.

6.3.2 Activity behaviour

In order to effectively influence the behaviour of activities towards what is required for sustainability, it is necessary for humans to understand the basic nature of this behaviour. As shown in Section 4.2 of Paper C, the behaviour of activities operating within the Earth system may be described in terms of four fundamental dimensions: (i) use of renewable and non-renewable resources; (ii) production of intended yield; (iii) production of waste; and (iv) production and use of intended resources. Each of these dimensions is illustrated in Figure 6-2 and summarised below.

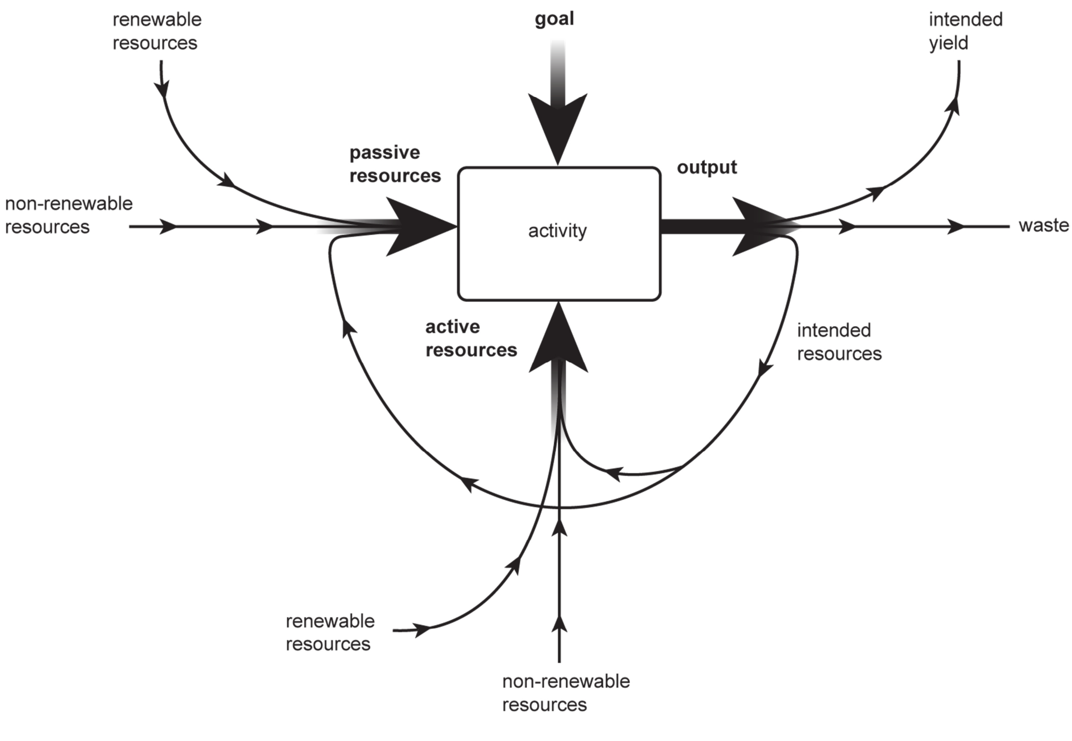


Figure 6-2: The behaviour of an activity operating within the Earth system

- *Use of renewable and non-renewable resources.* The Earth system is typically viewed as containing various stocks of resources. These may be classed as either: natural or artificial (Costanza and Daly, 1992; Williams and Millington, 2004; Ekins, 2011); and renewable or non-renewable (Daly, 1990a; Brown and Ulgiati, 1997; Campbell and Garmestani, 2012), i.e.

stocks that either regenerate over time, or do not regenerate significantly along anthropological timescales, respectively (Daly, 1992). As shown in Figure 6-2, an activity in the Earth system may use components from the above stocks as passive and active resources, to meet a need for resources as indicated by the goal of the activity. The term "resource" is defined thus: "A means of supplying a deficiency or need" (Oxford English Dictionary, 2014).

- *Production of intended yield.* An activity may produce components that are intended to be yielded to the wider system. These components may either contribute to resource stocks in the system, or they may be used directly as passive and/or active resources in other activities within the system (Brown and Ulgiati, 1997; Ekins, 2011; Liao, et al. 2011; Campbell and Garmestani, 2012). They are represented in Figure 6-2 as intended yield. For example, an air conditioning system may produce a flow of cool air as yield to be used as a cooling medium by human beings and/or technical systems that generate excess heat during their operation.

- *Production of waste.* In addition to intended yield, an activity may produce components that can be considered to be waste in relation to the activity (Brown and Ulgiati, 1997; Marchettini et al., 2007; Rosen et al., 2008; Barles, 2010; Zhang et al., 2011), as shown in Figure 6-2. That is, the fraction of the activity's output that is intended neither as yield nor resources and as such, has no utility in relation to the activity (Oxford English Dictionary, 2014). However, the terms "resource" and "waste" are defined here in relation to the activity under study. As such, components that may be classed as waste in relation to one activity may in fact represent resources to a different activity operating within the Earth system (Marchettini et al., 2007; Raut et al., 2011; Zhang et al., 2011). For example, spent filters produced by the air filtration unit in an air conditioning system may be considered as waste in relation to the activity of producing a flow of cool air, but a passive resource in relation to the activity of recycling filter materials.

- *Production of intended resources.* Finally, in addition to intended yield and waste, an activity may also produce components intended to be used as passive and/or active resources in the activity itself (Costanza and Daly, 1992; Ekins, 2011). These are represented in Figure 6-2 as intended resources. For example, economic activity generates goods and services as an output, a portion of which are intended for use as resources in economic activity itself to produce further goods and services (Eurostat, 2010; Ekins, 2011; Eurostat, 2011a). In certain cases, parts of the activity output that are conventionally be considered to constitute waste may be utilised as an intended resource (Yang et al., 2003; Marchettini et al., 2007; Zhang et al., 2011). For example, excess heat produced by the compressor in an air conditioning system may conventionally be viewed as waste in relation to the activity of producing cool air. However, this heat may instead be used to provide a portion of the energy required to drive the air conditioning system. That is, the heat may be used as a passive resource in the activity of producing cool air.

6.3.3 Sustainability as an emergent property

In Section 6.3.1, it was shown that the sustainability of an activity in the Earth system may be considered to be manifested as behaviour that is conducive to the activity's continued operation within the system. From this perspective, sustainability may be viewed as a property of an activity operating within the Earth system. However, as shown in Section 4.3 of Paper C, sustainability may also be viewed as an emergent property of a particular system of interest (SoI) supporting multiple activities.

In Section 6.3.2, the basic behaviour of activities operating within the Earth system was illustrated by focusing on the behaviour of a single activity in isolation. However, as discussed, the intended yield and waste outputs produced by one activity in the system may be used as resources by other activities in the system. In other words, activities in the Earth system may be coupled (Hubka and Eder, 1988; Yin and Xiang, 2009; Turner, 2010). Hubka and Eder (1988) suggest that activities may be coupled in at least three ways, as shown in Figure 6-3 below:

- An activity may produce its own passive and active resources. That is, intended resources as discussed in Section 6.3.2. In this case, it may be said that the activity displays feedback – that is, part of its output (i.e. intended resources) is used as part of its input (i.e. passive and active resources). For example, in Figure 6-3, it may be seen that activity 1 displays feedback, represented by the flow of intended resources.
- The yield or waste produced by one activity may be used as a passive or active resource by another activity in the system. In such a case, it may be said that the two activities are connected in series. For instance, in Figure 6-3, it may be seen that the intended yield produced by activity 1 is used as a passive resource by activities 2 and 3. Thus, activity 1 is connected in series with both activities 2 and 3. Additionally, the waste produced by activity 1 is used as a passive resource by activity 4. Therefore, activity 1 is also connected in series with activity 4.

- An activity in the Earth system may share its input of passive or active resources with another activity in the system. In this case, it may be said that the activities are connected in parallel. For example, in Figure 6-3, it may be seen that activities 2 and 3 share an input of passive resources originating from the output of activity 1 and thus, are connected in parallel.

The "goal-directed" nature of activities means that humans can influence their behaviour towards what is required for sustainability by formulating and implementing sustainability goals. Examples of sustainability goals focusing on the use of renewable and non-renewable resources, and the production of waste, were presented in Chapter 3 (Section 3.4). Owing to the coupling relationships outlined above, sustainability goals implemented to influence the behaviour of one activity may have an indirect impact on the behaviour of other activities to which the activity in question is connected. This impact may not necessarily be a positive one – the kind of behaviour that is conducive to the continued operation of one activity in the Earth system may in fact be detrimental to the sustainability of other activities in the system (Voinov, 2007; Alfaris et al., 2010). For example, consider activities 1 and 4 in Figure 6-3. A sustainability goal focused on reducing the waste production may be set for activity 1. However, it may be seen that activity 4 relies upon the waste output from activity 1 as a passive resource. As discussed in Section 6.3.1, an activity fundamentally depends upon resources for its continued operation. Thus, reducing the waste output of activity 1 may compromise the sustainability of activity 4, by reducing the availability of the passive resources it is dependent upon.

From the above, it may be seen that when seeking the sustainability of multiple activities in the Earth system, formulating and implementing sustainability goals for each activity in isolation is unlikely to be effective in bringing about the required behaviour. That is, behaviour that is conducive to the continued operation of the activities collectively. The *relationships* among the activities must also be taken into account when formulating the goals. Hubka and Eder (1988, pp.255-257) suggest that we may view the structure of a system from two different perspectives: (i) its *component* structure, i.e. "structure consisting of components and their relationships" as described above; and (ii) its *function* structure, i.e. "structure consisting of functions and their relationships, […] structure of activities." If we consider that a particular set of interconnected activities within the Earth system can be partitioned as a sub-system, then it may be seen that sustainability can be described as an emergent property of a particular SoI (Wahl and Baxter, 2008; Godfrey, 2010; Bodini, 2012). That is, a property that is "not determined solely from the properties of the system's parts, but which is additionally determined by the system's structure (i.e., by the way the parts are connected to form the system)" (Thomé, 1993, p.7). Even if all activities in a SoI may be said to have the property of sustainability individually, there is no guarantee that the system as a whole also has this property. In order for the system as a whole to be sustainable, the behaviour of individual activities must contribute to the system behaviour required for sustainability. That is, behaviour that is conducive to the continued operation of the system within its wider environment. In other words, from a performance perspective, the sustainability performance of individual system activities must contribute to the sustainability performance of the system as a whole.

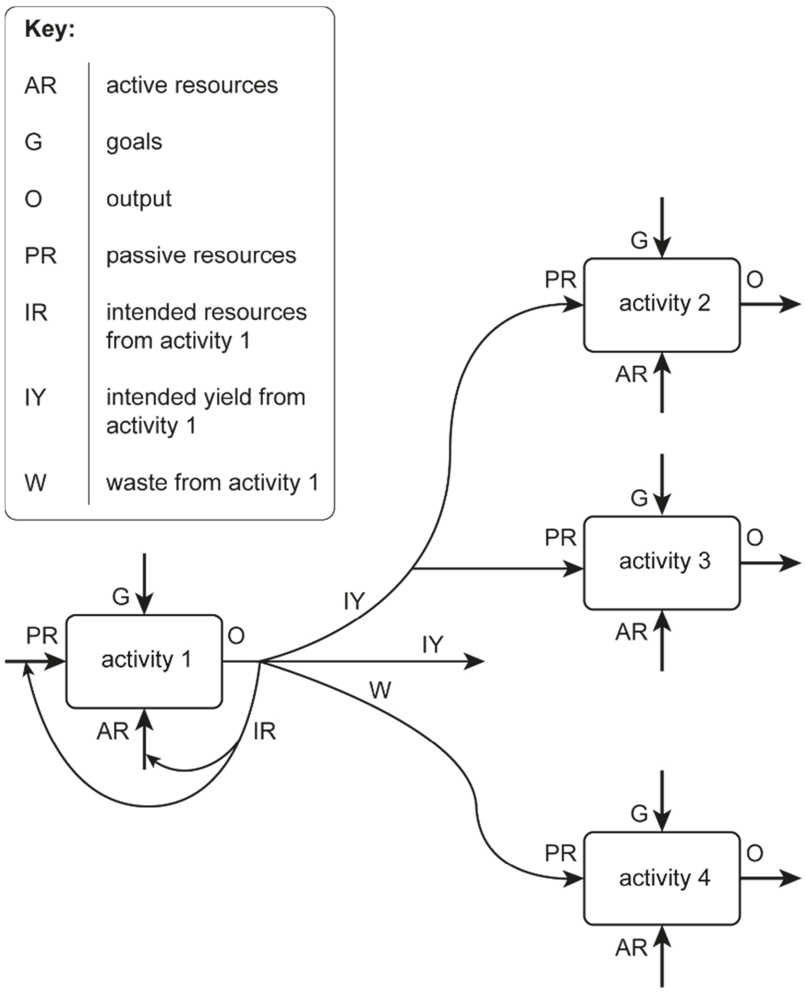


Figure 6-3: Coupling relationships between activities

6.4 Sustainability knowledge

As discussed in the introduction to Chapter 6, knowledge may be viewed as a driver of human action both generally (Newell, 1982), and in efforts towards sustainability. Three notable components of knowledge involved in human action towards sustainability are identified and discussed in Section 5 of Paper C. That is, knowledge of: (i) current activity behaviour; (ii) sustainability goals and indicators; and (iii) activity behaviour in relation to goals. An overview of these is provided in the following paragraphs. Note that throughout this thesis, the term "knowledge" is applied in a broad sense to include "expert knowledge," but also less concrete elements such as "implicit theories on how the physical world behaves," "outcome foci," "experiences," (Reber, 2011) and perceptions (Gero and Kannengiesser, 2004).

Firstly, as discussed in Section 6.3.3, humans may influence the behaviour of activities in the Earth system towards what is required for sustainability through the implementation of goals. Like all goals, sustainability goals refer to a future situation that is considered to be more desirable than the current one (O'Donnell and Duffy, 2005). They may be viewed as components of knowledge describing how an activity *should* behave in order to achieve sustainability in a particular SoI (O'Donnell and Duffy, 2005; Ness et al., 2007). In Section 6.3.2, it was shown that the use of renewable and non-renewable resources, the production of yield, the production of waste, and the production and use of intended resources may be viewed as basic aspects of the behaviour of activities operating in the Earth system. Humans may interpret these aspects of a particular activity's behaviour, to produce knowledge on current behaviour (Walter and Stützel, 2009; Jordan et al., 2010) that provides a basis for defining sustainability goals for the activity (Meadows, 1998; Parris and Kates, 2003; Eurostat, 2011a; Walter and Stützel, 2009).

On the basis of what they know about the activity's behaviour, humans can suggest actions to be taken with respect to the system components involved in the activity that are expected to result in the activity fulfilling its sustainability goals. To actually implement the goals, humans then carry out these actions (Parris and Kates, 2003; Eurostat, 2011a). As noted previously, examples of physical sustainability goals focusing on the use of renewable and non-renewable resources, and the production of waste, were presented in Chapter 3 (Section 3.4). To recap, these were: (i) non-renewable resources should not be used; (ii) renewable resources should not be used faster than stocks can regenerate; and (iii) waste should not be produced faster than it can be processed. To implement these goals, humans may take action to: (i) allocate renewable resources to their activities to replace any non-renewable resources that are currently used; (ii) reduce the rate at which their activities consume renewable resources; and (iii) reduce the rate at which their activities produce waste.

Secondly, as discussed in Chapter 3, following implementation it is necessary to ascertain whether or not an activity is fulfilling its sustainability goals. Sustainability assessment, as it is commonly termed in the literature (Ness et al., 2007; Bodini, 2012), provides humans with information on the behaviour and performance of entities from a sustainability perspective (Meadows, 1998; Bell and Morse, 2008; Singh et al., 2012). This information may in turn be used to make decisions relating to the sustainability of an entity (Ness et al., 2007; De Smedt, 2010; Heijungs et al., 2010; Ramos and Caeiro, 2010; Rametsteiner et al., 2011). As highlighted in Chapter 3, among the most prolific approaches to sustainability assessment are those based around the use of sustainability indicators (SIs) (Scerri and James, 2009; Ramos and Caeiro, 2010; Hak et al., 2012). A classification of SIs and evaluation approaches applied to human activities and systems generally is provided in Figure 3-7. More specifically, the range of sustainability performance indicators (SPIs) commonly applied to assess the sustainability of technical systems is outlined in Chapter 4, along with evaluation methods. Both the indicators *per se*, and the information they provide on activity behaviour and performance in relation to sustainability goals, may be viewed as components of knowledge employed in human efforts towards sustainability. Issues associated with the definition and selection of indicators are discussed in Section 3.5.1 of Chapter 3. Additionally, the elements involved in indicator-based sustainability assessment are illustrated in Figure 3-10.

6.5 The S-Cycle and S-Loop models

As noted in the introduction to Chapter 6, the S-Cycle and S-Loop models were developed through a process of induction from the findings presented in Sections 6.1 to 6.4. This is discussed fully in Section 6 of Paper C. A summary of the key aspects of the development of the two models is provided in Sections 6.5.1 (the S-Cycle model) and 6.5.2 (the S-Loop model) below.

6.5.1 The S-Cycle model

As discussed in Section 6.3, in order to sustain a particular entity, we need to sustain the activities that produce that entity within the Earth system. Like all systems, the Earth system can be viewed as “an organized system of matter, energy, and information” (Skyttner, 1996, p.32). In Section 6.2.2, it was shown that this system may be approximated as a thermodynamically closed system (Daly 1992; Wackernagel and Rees 1997; Cabezas et al. 2005), whose primary external energy source is the Sun (Stremke et al., 2011) as illustrated in Figure 6-4 below. Processing MEI may be viewed as a basic function of the system (Ulanowicz, 1980; Brown et al., 2004; Cabezas et al., 2005; Bodini, 2012). The Earth system may also be described as a socio-ecological system, i.e. one where "society and nature are innately coupled" (Dawson et al., 2010, p.2844). Therefore, human beings themselves may be viewed as components of the system (Beddoe et al., 2009). As discussed in Section 6.3.2, the Earth system contains stocks of natural and artificial components (Costanza and Daly, 1992; Ekins, 2011; Williams and Millington, 2004), that may be classed as either renewable or non-renewable in nature (Daly, 1990a; Brown and Ulgiati, 1997; Campbell and Garmestani, 2012), again illustrated in Figure 6-4.

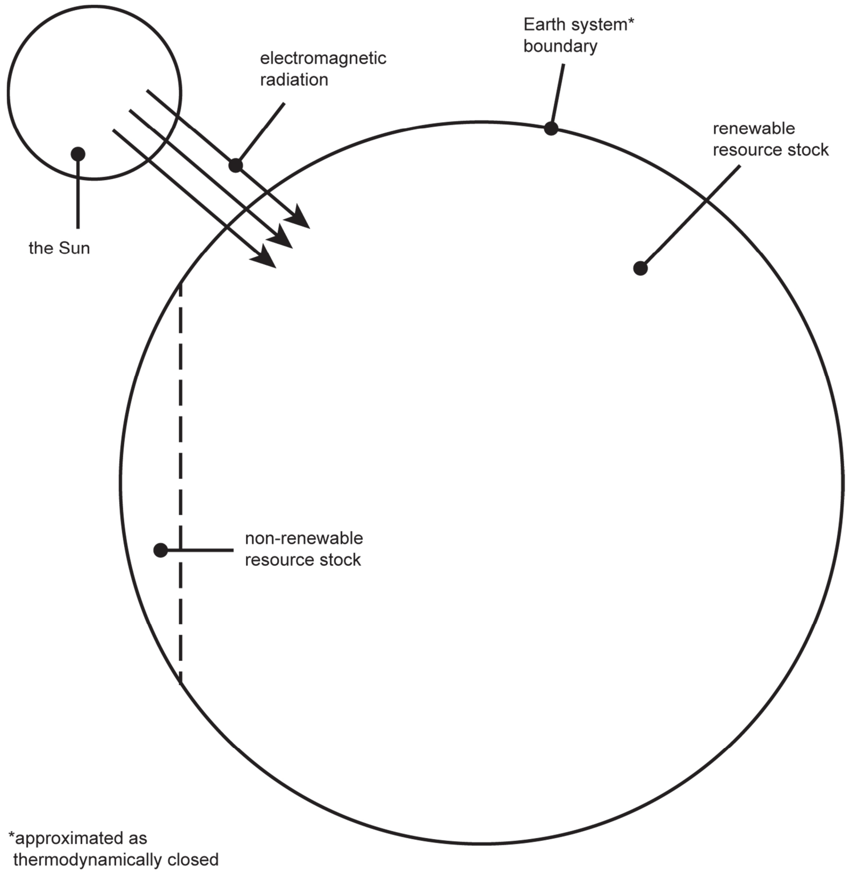


Figure 6-4: The Earth system

The S-Cycle model formalises the behaviour of activities in the Earth system from the perspective of sustainability. The model is presented in Figure 6-5, and is described here in relation to the literature that it was induced from. In Section 6.3.1, an activity was described as a goal-directed physical or cognitive action, where a set of passive resources are used by active resources to produce an output that should satisfy the goal of the activity (Boyle et al., 2009). Activities may use components from the renewable and non-renewable resource stocks in the system as passive and active resources, to produce an output consisting of three kinds of components, again shown in Figure 6-5:

- intended yield, i.e. components intended to be yielded to the wider system, that may be used directly as resources in other activities in the system, or may contribute to resource stocks in the system (Brown and Ulgiati, 1997; Ekins, 2011; Liao et al., 2011; Campbell and Garmestani, 2012);
- intended resources, i.e. components intended to be used in the activity itself as passive and active resources (Costanza and Daly, 1992; Ekins, 2011); and
- waste, i.e. components that are intended neither as yield nor resources and thus, have no utility in relation to the activity (Brown and Ulgiati, 1997; Marchettini et al., 2007; Rosen et al., 2008; Barles, 2010; Zhang et al., 2011).

As highlighted in Section 6.3.1, it may be seen that the sustainability of activities in the Earth system, i.e. their ability to continue to operate, depends fundamentally upon the availability of passive and active resources. In turn, the availability of resources in the system depends upon the rate at which activities in the system consume and produce them. As illustrated in Figure 3-4 in Chapter 3, consuming renewable resources faster than stocks are regenerated will lead to depletion of the stocks, and consuming non-renewable resources at any rate will deplete stocks since they are not regenerated significantly along anthropological timescales (Daly, 1990a).

In Section 6.3.3, it was shown that in addition to being viewed as a property of an individual activity in a system, sustainability may also be viewed as an emergent property of a system (Wahl and Baxter, 2008; Godfrey, 2010; Bodini, 2012). For sustainability to emerge in a system, the behaviour of all activities operating in the system must contribute to the continued operation of the system as a whole within its environment (given that system behaviour *per se* may be viewed as an emergent property (Tully, 1993), as discussed in Section 6.2.1). These activities are likely to be coupled with one another, potentially in complex ways (Hubka and Eder, 1988; Yin and Xiang, 2009; Turner, 2010) as shown in Section 6.3.3. We may represent the total activity operating in a system in precisely the same way as we represent an individual activity (O'Donnell and Duffy, 2005), i.e. using the formalism first provided in Figure 6-1 in Section 6.3.1. Thus, the S-Cycle model presented in Figure 6-5 may be interpreted as describing the operation of an individual activity in the Earth system, or the total system activity, i.e. the aggregate of all natural and anthropogenic activities operating in the system at a given time.

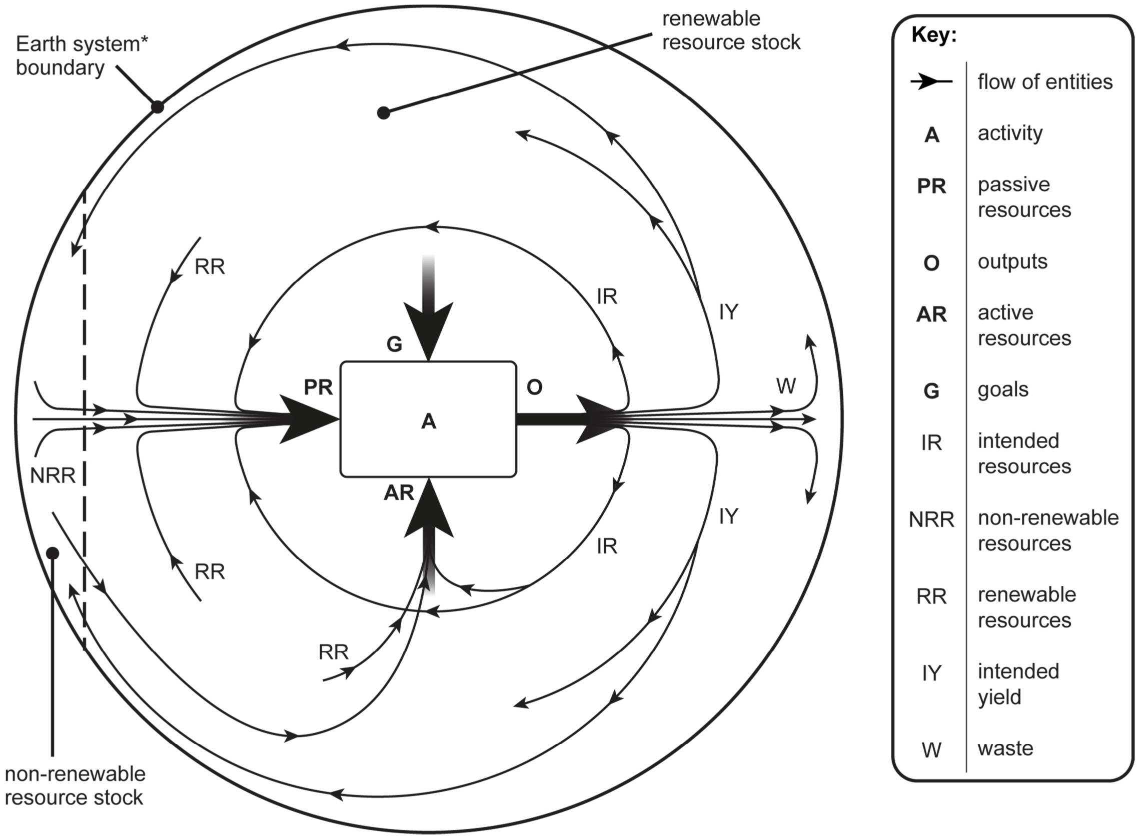


Figure 6-5: The S-Cycle model

In Figure 6-5 the system boundary is represented as that of the whole Earth system. However, the S-Cycle model is generic – it describes the operation of activities in a system in completely general terms (e.g. it does not make reference to specific kinds of resources, yield, and waste, only the stocks and flows of these kinds of entities generally). Thus, the system boundary in Figure 6-5 may be altered to represent that of any SoI within the Earth system. The nature of the system boundary will determine the specific stocks and flows to be considered when applying the model to interpret a particular activity. This is demonstrated in Chapters 7 and 8, which detail the evaluation of the model. The S-Cycle describes both the intended yield and waste produced by an activity as ultimately contributing to stocks within the wider system, where they become available for use as resources. Thus, the model may be seen to reflect the cradle-to-cradle view of the technical system life cycle and the notion of a circular economy as discussed in Chapter 3 (Section 3.3.3). That is, the view that the waste produced by economic activities should be directly usable as a resource by further technical and/or biological activities. Nonetheless, as stated above, the S-Cycle model is generic and is therefore not limited to any specific type of activity – it describes this behaviour for any activity, artificial or natural, operating within any SoI boundary.

6.5.2 The S-Loop model

The S-Cycle model illustrates that the sustainability of activities in the Earth system depends fundamentally upon the availability of resources in the system. In turn, the availability of resources in the system depends upon the rate at which activities in the system consume and produce them. In Section 6.4, it was shown that humans may intervene in these dynamics by implementing sustainability goals to influence the behaviour of activities, and then assessing the resulting behaviour. Considering the literature on sustainability goals and indicators covered in both Chapter 3 (Sections 3.4 and 3.5) and Section 6.4 holistically reveals a general process undertaken by humans striving for sustainability, consisting of the following basic activities:

- interpret the behaviour of activities in a particular SoI within the Earth system (Walter and Stützel, 2009; Jordan et al., 2010), to produce knowledge on their current behaviour, and how the activities *should* behave with respect to sustainability (Derissen et al., 2011) – that is, knowledge on sustainability goals (O'Donnell and Duffy, 2005);
- implement sustainability goals by suggesting and taking actions that produce effects on the system components involved in the activities, and are expected to result in the activities fulfilling their goals (Parris and Kates, 2003; Eurostat, 2011a);
- determine if activities have fulfilled, or are on track to fulfil sustainability goals by assessing their behaviour after the goals have been implemented, to produce knowledge on that behaviour (Ness et al., 2007; Jordan et al., 2010; van Zeijl-Rozema and Martens, 2010); and
- on the basis of this knowledge, suggest and take actions regarding the sustainability of the activities and/or the SoI as a whole (Ness et al. 2007; De Smedt 2010; Heijungs et al. 2010; Ramos and Caeiro 2010; Rametsteiner et al. 2011; Singh et al. 2012), e.g. if activities are not on track to fulfil their sustainability goals, humans may suggest and take actions to ensure that they are fulfilled in future, or they may begin the whole process again in the context of a different SoI, having learned from experience.

It may be seen that this process is essentially iterative: humans interpret the behaviour of activities in a SoI to produce knowledge, and then on the basis of this knowledge, take action to alter the behaviour of the activities and the overall system (given that system behaviour may be viewed as an emergent property, as discussed in Section 6.2.1). They then interpret the resulting behaviour to produce further knowledge and on the basis of this, suggest further actions to be taken. In other words: knowledge on behaviour determines the actions taken by humans striving for sustainability, and the actions taken by humans striving for sustainability result in the production of new knowledge on behaviour that determines further actions to be taken by humans, and so on and so forth.

According to Gero and Kannengiesser (2004, p.378), interpretation "transforms variables, which are sensed in the external world into the interpretations of sensory experiences, percepts and concepts that compose the interpreted world." They suggest that action may be viewed as "a transformation of an expected concept into an external representation." The result of action is "an effect, which brings about a change in the external world." Thus, it may be argued that humans striving for sustainability, via the iterative process of interpretation and action delineated above, operate between two different "worlds": (i) the external world, which may be viewed as the world "composed of representations outside" of a human i.e. the world that is extrinsic to the human mind; and (ii) the interpreted world, which may be viewed as the world composed of "sensory experiences, percepts and concepts" i.e. the inner mental world of a human (Gero and Kannengiesser, 2004, p.377). Different people may interpret representations in the external world in different ways and thus, the interpreted worlds of different people may be quite dissimilar in nature. As Meadows (1998, p.8) highlights, "people of different worldviews live literally in different worlds." This is arguably one of the reasons for the considerable variety in sustainability targets, interpretations of the basic constitution of sustainability, sustainability goals, and sustainability indicators as illustrated in Chapter 3. Furthermore, the work reported in this thesis represents the authors' interpretation of certain external representations, i.e. the sustainability literature. Other authors may have different interpretations of the same literature.

Above, Gero and Kannengiesser (2004) refer to both interpretation and action as the transforming of one thing into another. As highlighted previously, activities may be viewed as "the fundamental elements that transform input to output" (O'Donnell and Duffy, 2005, p.56). Therefore, it may be seen that both interpretation and action, as carried out in human efforts towards sustainability, may be viewed as activities, in the same sense as the activities we are trying to maintain. Subsequently, it can be concluded that in human efforts towards sustainability, two sets of activities are involved: (i) the activities whose operation we are trying to maintain; and (ii) the activities we undertake in order to manage the behaviour of (i). To characterise the external and interpreted worlds introduced above from a sustainability perspective, the concepts of systems, activities, and knowledge can be mapped to each world based on the activity of interpretation:

- As discussed in Section 6.2.1, a system is delimited from its environment by a human observer who draws a boundary. Thus, systems may be considered to exist in the external world, but are defined for study by humans in the interpreted world. That is, humans interpret the world around them to produce knowledge on the nature of a particular system of interest, as shown in Figure 6-6. This knowledge may be viewed as existing in the interpreted world.

- Like systems, activities may be considered to operate in the external world, but are defined for study by humans in the interpreted world (e.g. by applying the activity formalism adopted in the S-Cycle model). In other words, humans interpret the world around them to produce knowledge on the nature of activities in a particular system of interest, as illustrated in Figure 6-6. Again, this knowledge may be considered to exist in the interpreted world.
- Finally, humans interpret the behaviour of activities and systems in the external world to produce additional elements of knowledge discussed in Section 6.4, i.e.: sustainability goals and SIs; knowledge on current activity behaviour; and knowledge of the behaviour of activities in relation to sustainability goals after they have been implemented (Figure 6-6). Whilst the behaviour under study may be viewed as occurring in the external world, knowledge resulting from its interpretation may be seen to exist in the interpreted world. However, knowledge may be *represented* in the external world (Newell, 1982). For example, in this thesis, knowledge on the behaviour of activities from a sustainability perspective has been formalised in the external world via the development of the S-Cycle model. Furthermore, knowledge existing in the interpreted world may be transformed into effects in the external world via action, as highlighted by Gero and Kannengiesser (2004) above.

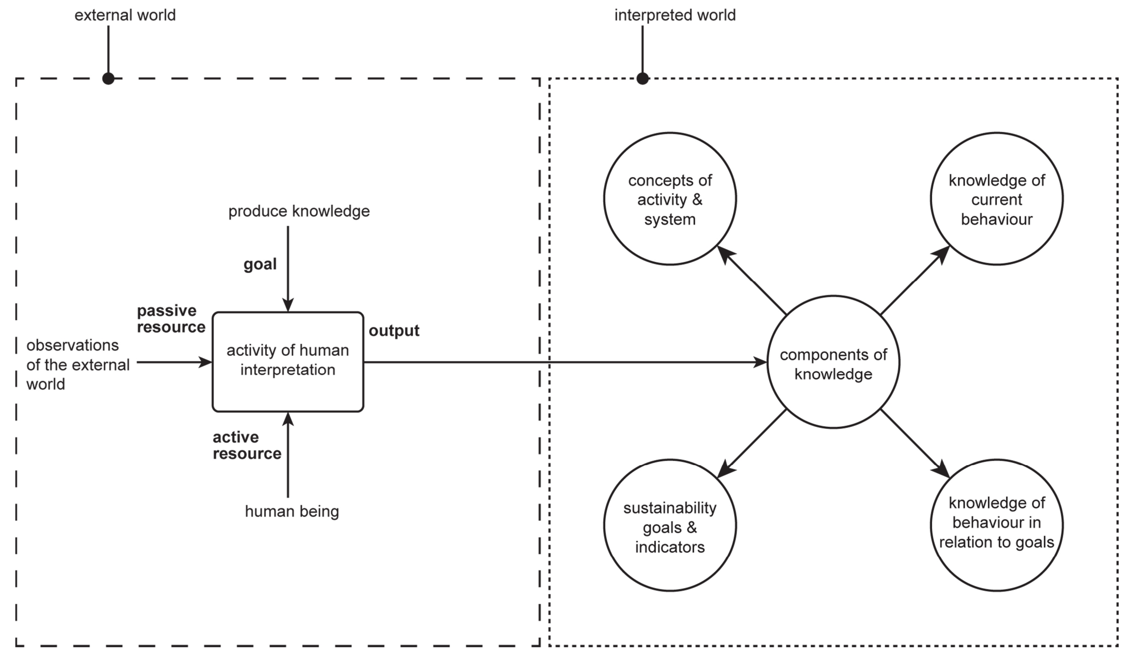


Figure 6-6: The activity of interpretation

In the S-Loop model, systems (Figure 6-4) and activities (Figure 6-5) are represented in the external world, whilst key components of knowledge employed in human action towards sustainability (Figure 6-6) are represented in the interpreted world. These three entities, i.e. systems, activities, and knowledge, are linked via the iterative process of interpretation and action outlined previously. The entities are presented at different levels so that they may be positioned relative to one another, according to their roles in the iterative process. The model is presented in Figure 6-7, and is described in relation to the literature it was induced from below.

As discussed in Section 6.2 and illustrated in the S-Loop model, the Earth system, like all systems, exhibits behaviour, i.e. it "does something". This behaviour is exhibited by the structure of the system (Gero and Kannengiesser, 2004; Wang et al., 2008), i.e. by its components and relationships (Tully, 1993). In turn, humans may focus on the behaviour of activities operating in the system. The behaviour of an activity may be viewed as the behaviour exhibited by the particular set of system components (i.e. passive and active resources, and outputs) involved in the activity (discussed in Section 6.3). In Section 6.2.2, it was shown that humans per se may be viewed as integral components of the Earth system (Beddoe et al., 2009; Dawson et al., 2010). Thus, humans may be considered to exist as components of the Earth system at the system level in the S-Loop model. In turn, given that interpretation and action may be viewed as activities as discussed above (Gero and Kannengiesser, 2004), it may be seen that humans carry out interpretation and actions at the activity level in the S-Loop. Humans may be viewed as active resources in these activities.

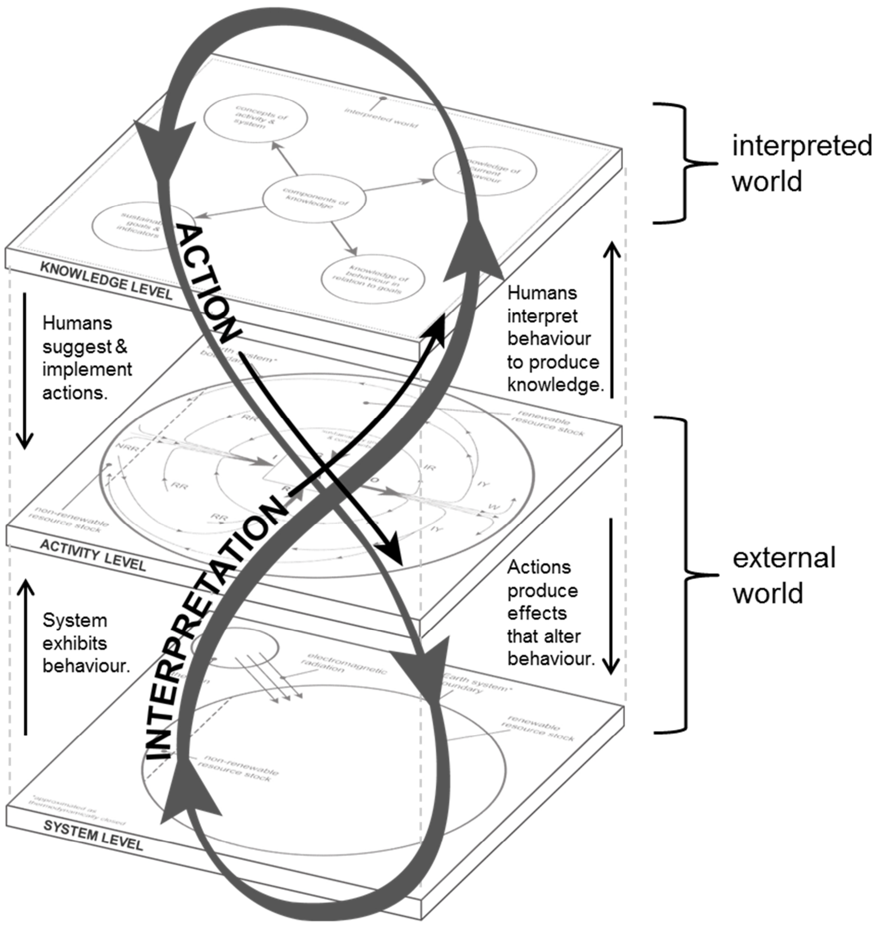


Figure 6-7: The S-Loop model

In the S-Loop model, the iterative process that emerges from the literature (outlined above) is described as follows. Humans interpret the behaviour of activities in a particular SoI (i.e. sub-system of the Earth system) in the external world (Jordan et al., 2010; Walter and Stützel, 2009), to produce knowledge on current behaviour and how the activities should behave with respect to sustainability, i.e. knowledge on sustainability goals (Ness et al., 2007; O'Donnell and Duffy, 2005). Both of these knowledge elements exist at the knowledge level in the interpreted world. On the basis of this knowledge, humans may suggest actions to be taken, that are expected to result in the activities fulfilling their goals. They may then implement actions at the activity level of the external world (Eurostat, 2011a; Parris and Kates, 2003), to produce effects on the system components involved in the activities (existing at the system level of the external world). These effects bring about a change in the behaviour of the activities at the activity level of the external world (discussed in Section 6.4). To determine if activities have fulfilled, or are on track to fulfil their sustainability goals, humans interpret activity behaviour after the goals have been implemented by defining and evaluating SIs (Ness et al. 2007; Jordan et al. 2010; Ramos and Caeiro 2010; Rametsteiner et al. 2011; van Zeijl-Rozema and Martens 2010; Singh et al. 2012). In other words, they carry out sustainability assessment (Bodini, 2012; Ness et al., 2007) at the activity level of the external world (discussed in Section 6.4, and also Chapter 3). Like knowledge on current behaviour and sustainability goals, knowledge on post-action activity behaviour exists at the knowledge level in the interpreted world. On the basis of the latter component of knowledge, humans may again suggest actions to be taken regarding the sustainability of the activities and/or the SoI as a whole (given that sustainability may be viewed as an emergent property of a system (Bodini, 2012; Godfrey, 2010; Wahl and Baxter, 2008), as discussed in Section 6.3.3). For example, if activities are found not to be on track to fulfil their sustainability goals, humans may suggest actions that are expected to result in the goals being fulfilled in future.

6.6 Summary

As discussed in Chapter 5, the research reported in this thesis aims *to develop a generic model of technical system sustainability*, to address the lack of a: (i) consistent view on sustainability improvement, (ii) common approach to identifying appropriate SPIs, and (iii) fundamental formalism of sustainability. This chapter has outlined inductive literature research carried out to build two generic models, namely the Sustainability Cycle (S-Cycle) and Sustainability Loop (S-Loop).

In Section 6.1, it was shown that in general terms, an ability may be viewed as a property of an entity that is manifested to humans as behaviour that produces certain effects. From this perspective, sustainability may be considered to be a property of an entity that is manifested to humans as behaviour that produces the effect of maintenance/continuation, either of the entity in question or some other entity. In Sections 6.2, 6.3, and 6.4, three concepts emerging from the literature as significant in relation to the aim of the research were defined and discussed:

- *Systems*, which may be considered to provide the context for human action towards sustainability. The Earth system was characterised as providing the context, and it was shown how this overall system may be decomposed into a multitude of different sub-systems forming the foci of efforts to achieve sustainability.
- *Activities*, which produce entities that humans value and wish to sustain and thus, may themselves be viewed as fundamental entities to be sustained.

Humans may influence the behaviour of activities towards what is required for sustainability by implementing sustainability goals. It was shown that the behaviour of activities operating within the Earth system may be described in terms of four fundamental dimensions: (i) use of renewable and non-renewable resources; (ii) production of intended yield; (iii) production of waste; and (iv) production and use of intended resources.

- *Knowledge*, which may be viewed as a driver of human action both generally, and in efforts towards sustainability. Four components of knowledge involved in human action towards sustainability were identified, i.e. knowledge of: (i) the concepts of activity and system; (ii) current activity behaviour; (iii) sustainability goals and indicators; and (iv) activity behaviour in relation to goals.

In Section 6.5, the S-Cycle and S-Loop models were introduced and discussed in relation to the literature they were induced from. The S-Cycle model describes the Earth system and its sub-systems as being comprised of renewable and non-renewable resource stocks that are consumed and replenished by both natural and human activities. These activities transform input flows of renewable and non-renewable resources into output flows of intended resources, intended yield, and waste. The ability of activities in the system to continue to operate fundamentally depends upon the availability of resources in the system. In turn, the availability of resources in the system fundamentally depends upon the rate at which they are consumed and produced by activities. Humans may intervene in these dynamics by implementing sustainability goals and indicators for activities, as described in the S-Loop model.

The S-Loop model describes human efforts towards sustainability as an iterative process of interpretation and action involving systems, activities, and knowledge. According to the model, humans interpret the behaviour of activities in a system to produce knowledge on: (i) their current behaviour; and (ii) how the activities *should* behave for sustainability, i.e. sustainability goal knowledge. This knowledge serves as a basis for suggesting and implementing actions that are expected to result in the activities fulfilling their sustainability goals. Humans then interpret the behaviour of activities after actions have been taken, by evaluating sustainability indicators to produce knowledge on resulting activity behaviour in relation to sustainability goals. This knowledge may then be used as a basis for suggesting and implementing further actions as needed, until a satisfactory outcome is achieved.

As discussed previously, it was not possible to carry out extensive evaluation of the S-Loop model owing to time constraints on the research. As such, Chapters 7 and 8 discuss evaluation of the S-Cycle model, with further evaluation of the S-Loop model potentially forming the focus of future research as discussed in Chapter 9.

Part 2: Model evaluation

7 Evaluation approach

The S-Cycle model developed in Chapter 6 consists of an activity formalism representing the operation of a technical system within a wider system of interest (SoI), with two stock elements and a number of flow elements representing the interactions between the technical system and the SoI from a sustainability perspective. Part 2 of this thesis discusses the work conducted to evaluate the model. As discussed in Chapter 5, the S-Cycle was developed in order to address three sustainability research issues, namely: I1 – the lack of a consistent view of sustainability improvement; I2 – the lack of a common approach for identifying appropriate SPIs for technical systems; and I3 – the lack of a fundamental formalism to describe sustainability. The major purpose of evaluation was to assess the extent to which the model can be considered to address these issues. In this respect, evaluation focused on three aspects of the model and its use aligning with the research issues. Namely, validity, utility, and applicability:

- *Validity*. According to Duffy and O'Donnell (1998, p.38), the activity of validation "focuses upon ascertaining a degree of truth for a particular hypothesis or result." In turn, they argue that "if a hypothesis or result is proven to be true then it is regarded as being validated." In order to address issue I3, the S-Cycle must be validated as a formal representation of sustainability of technical systems. It was shown in Chapter 6 that sustainability may be viewed as an ability, which is a property of a system and manifested as behaviour that produces the effect of maintenance/continuation of the system *per se*, or some other entity. With respect to the S-Cycle model, validity therefore refers to the degree to which its elements and relationships can be considered to model a technical system's behaviour from a sustainability perspective. The model may be considered to be validated if it can be demonstrated that it comprehensively describes this behaviour.

- *Utility*. Pidd (2010, p.14) highlights that models are "built with some intended use(s) in mind," and suggests that "careful consideration of how a model may be used is clearly an important part of any modelling project." In order to address issue I2, it must be demonstrated that the S-Cycle model can be used to identify appropriate SPIs for technical systems. The term "utility" is used in this thesis to refer to the S-Cycle model's usefulness and fitness for purpose (Oxford English Dictionary, 2014) in this respect. Utility encompasses not only the effectiveness of the model in supporting SPI identification, but also the degree to which the model can be understood and applied by those who would be using the model for this purpose in practice, e.g. engineering designers. Thus, in order to address issue I2, it must also be demonstrated that the model can be understood and applied by its intended users.

- *Applicability*. In the context of design research, Sim (2000, p.22) states that the applicability of a model refers to "the extent to which it has been applied to design of different artifacts or different types of design processes." A model may be described as "artifact independent or domain independent." In this thesis, applicability refers to the extent to which the S-Cycle model has been applied to different technical systems in different sectors. That is, the degree to which it can be considered to be generic. The model must be demonstrated to be applicable to at least two distinct technical systems in order to address all three of the above issues. Firstly, to address issue I1, it must be demonstrated that the model can be applied to different systems by different people, thereby providing the basis for a consistent view. Secondly, to address issue I2, it must be demonstrated that the model can be applied to identify SPIs for different technical systems. Finally, to address issue I3, it must be demonstrated that the S-Cycle's elements and relationships are reflected in the behaviour of different technical systems, and are not specific to any single system.

To evaluate the S-Cycle model, four research methods were applied to gather evidence relating to the three aspects outlined above. The evidence gathered was then interpreted, allowing conclusions to be drawn about the model's validity, utility, and applicability. In this chapter, the evaluation approach adopted is elaborated. That is, the methods applied to gather evidence, and the data sources from which this evidence was gathered. In turn, Chapter 8 presents the findings of the evaluation. In other words, the evidence gathered and its interpretation with respect to the above three aspects. The conclusions that may be drawn from the evaluation findings are discussed and reflected upon in Part 3 of this thesis (Chapters 9 and 10).

As discussed in Chapter 2, the evaluation approach consisted of the following methods:

- Two worked examples (WE1 and WE2) to provide initial evaluation of the model and its use. The technical systems forming the foci of these were a bioethanol production system and a car engine, respectively. Both of these can be considered as technical systems with notable sustainability challenges as discussed further in Section 7.1.2.

- Three case studies (CS1, CS2, and CS3) exploring the use of the model in greater depth through application to technical systems in industry. The systems studied were: a heating, ventilation, and air conditioning (HVAC) system in CS1; a chilled water (CW) system in CS2; and a CW plant in CS3, i.e. a sub-system of the CW system. All of these systems are sub-systems of a warship, which can be viewed as a technical system with significant sustainability challenges (elaborated in Section 7.1.3 below). A guideline focusing on performance assessment and improvement was developed to support the application of the model to the systems studied (known as the S-Cycle guideline).
- Appraisal of the model by engineering designers at two interactive workshops (WS1 and WS2) involving a practical exercise and self-report questionnaire. These workshops were preceded by a pilot study involving engineering design researchers as participants.
- An analytical study of indicators applied to evaluate the sustainability performance of technical systems, using the S-Cycle model and a performance model known as E^2, developed by O'Donnell and Duffy (2005) (discussed further in Section 7.1).

As discussed further in Chapter 8, all parts of the evaluation provided insights into the validity of the model. Utility was primarily evaluated through the case studies, expert appraisal, and analytical study, with the worked examples providing initial evaluation in this respect. Finally, applicability was evaluated through the worked examples, case studies, and the practical exercise delivered to experts at the two workshops. Each part of the evaluation approach is discussed in detail in the following sections. However, firstly, an overview of the chronology of the approach and the relationships between the different elements is provided below and illustrated in Figure 7-1.

As shown in Figure 7-1, the aforementioned guideline to support application of the model to technical systems was developed prior to the case studies. CS1 was then carried out first, followed by CS2. WE1 was developed concurrently with the early stages of CS2 to provide initial evaluation of the model and its use for dissemination in Paper C (Appendix 3). WE2 was developed during CS3, to support discussions on the S-Cycle model with engineering designers in industry. CS2 was conducted by the author within an engineering company, facilitating the development of a network of engineering designers and managers who also participated in the first workshop, i.e. WS1. The pilot study for the workshops was carried out concurrently with the final stages of CS2. Following the pilot study, WS1 was carried out at the end of CS2, which allowed dissemination of the study findings alongside the delivery of the practical exercise and questionnaire. During WS1, participants provided feedback on the use of the S-Cycle model to support the quantification of sustainability performance (discussed in Chapter 8). Briefly, this centred on the lack of performance quantification carried out in CS2 and specifically, the desire for a quantitative model to simulate CW system sustainability performance. A second group of engineering designers and managers from an energy company provided similar feedback regarding the lack of quantification at WS2, which was held concurrently with the early stages of CS3. This feedback was partially addressed by CS1, which involved the definition and evaluation of a set of SPIs for the HVAC system. Additionally, the feedback informed the aims and objectives of CS3, which yielded a set of SPIs for the CW plant system and a quantitative model to evaluate them. The SPI analysis also addressed the feedback through the development of a matrix to support technical system SPI definition and/or selection based on the S-Cycle. This analysis formed the final part of the evaluation.

In the following sections, each element of the approach is explained individually. Section 7.1 details the work conducted during the three case studies, and briefly describes the worked examples. In Section 7.2, the pilot study carried out prior to the two workshops is discussed, along with the format of the workshops and the practical exercise and questionnaire designed to facilitate appraisal of the model by engineering designers. Section 7.3 delineates the analytical study conducted to rationalise SPIs, and Section 7.4 provides a summary of the chapter. Note that certain sections draw from papers appended to the thesis. Part of Section 7.1.2 presents a summary of Section 6.3 of Paper C. Section 7.1.3.2 draws partially from Paper D. Finally, Section 7.3 presents a summary of elements of Paper B.

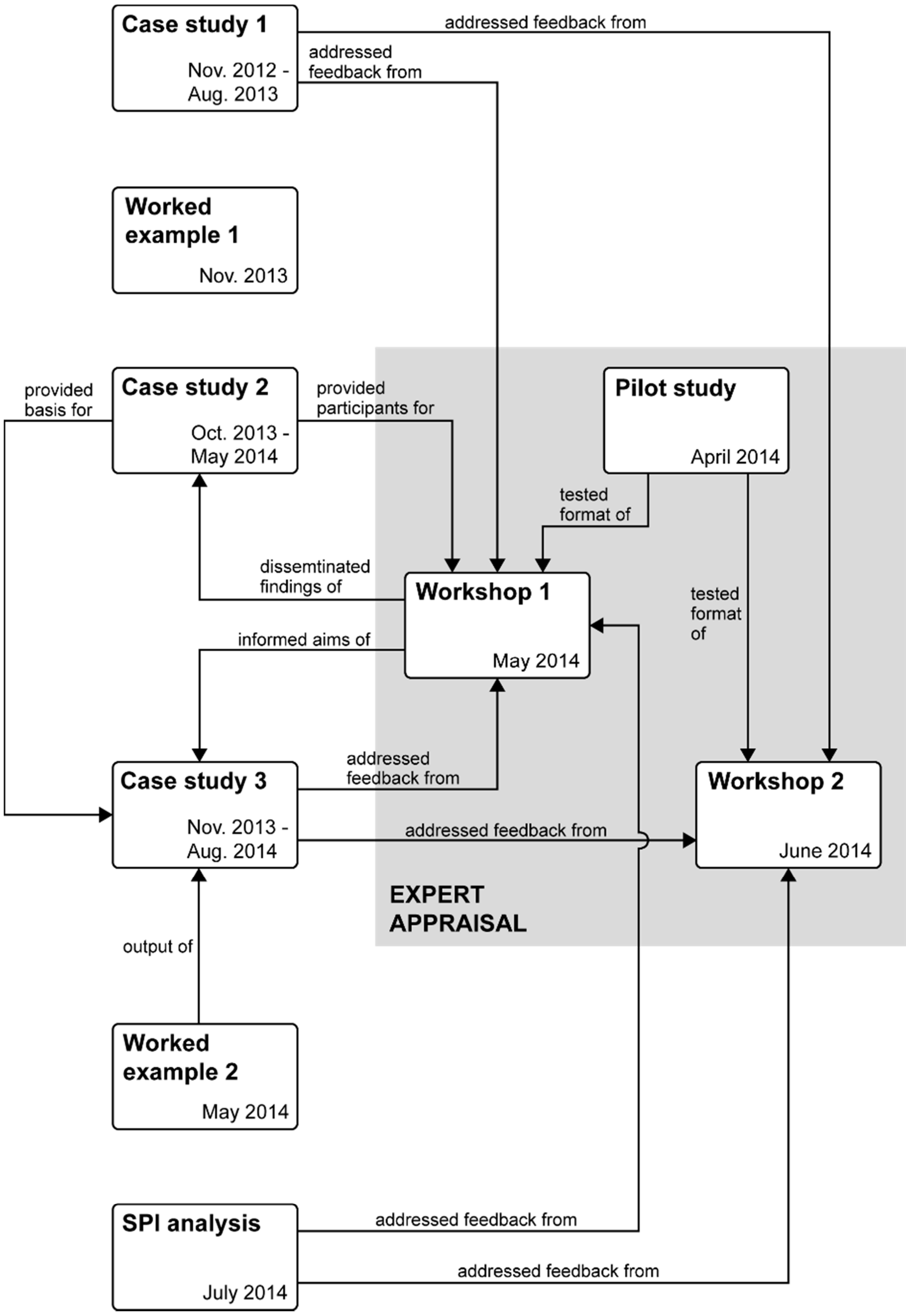


Figure 7-1: Chronology and structure of the evaluation approach

7.1 Case studies and worked examples

Each of the three case studies conducted was carried out by a different researcher, facilitating triangulation of the findings as discussed in Chapter 2. CS2 was conducted by the author, whilst CS1 and CS3 were carried out by two postgraduate students (Student A and Student B, respectively) as part of a Master's degree in sustainable engineering. The students were part of different course cohorts – Student A from 2012/2013, and Student B from 2013/2014. Thus, they worked independently of one another. All of the studies involved the application of the model to a technical system in industry, although the specific objectives varied depending on the context as shown in Section 7.1.3 below. As noted in the introduction to Chapter 7, a guideline was developed to support the application of the model to the systems studied. This is discussed in Section 7.1.1. Before the case studies were conducted, the worked examples were produced to provide initial evaluation of the model and the guideline. These are briefly outlined in Section 7.1.2. The three case studies are detailed in Section 7.1.3. Finally, an analysis of documentation produced during the case studies conducted in order to draw conclusions regarding the evaluation of the S-Cycle model is outlined in Section 7.1.4.

7.1.1 The S-Cycle guideline

As highlighted in Chapter 4, organisations are under increasing consumer and regulatory pressure to improve the sustainability of their technical products/ systems. Additionally, one of the issues to be addressed by the research is the lack of a common approach for determining SPIs for technical systems (I2), as discussed in Chapter 5. On this basis, it was decided to orient the S-Cycle guideline towards assessing and improving a technical system's sustainability performance. As noted above, this guideline supported the application of the model to systems during the case studies, and helped to foster a consistent approach among the three researchers conducting the studies. An overview of the guideline and its development is provided in this section – the full guideline is included in Appendix 8A.

The format of the guideline is based on a guide for measuring and managing organisational performance developed by Neely et al. (2002b). This guide is split into several parts, beginning with an overview and then moving on to a "workbook" laying out a stepwise procedure for measuring and managing performance. For each step in the procedure, aims, tasks, expected outcomes, and suggested documentation are outlined. A similar structure is adopted in the S-Cycle guideline, which consists of four parts:

- Part 1, Overview – provides background on sustainability and the S-Cycle model;
- Part 2, Using the S-Cycle model – details a stepwise procedure for improving the sustainability performance of a system (Figure 7-3), using the model as a tool to support the interpretation of behaviour and identification of SPIs;
- Part 3, Glossary of terms – lists definitions of key terms employed throughout the guideline; and

- Part 4, References – provides a list of work cited throughout the guideline.

Suggested documentation was also developed to support various steps in the guideline. This documentation is partially based on documentation developed by Duffy (2006) to support performance measurement in design. Although suggestions are made regarding documentation and methods to support various tasks in the guideline, these are recommendations and may be substituted for others to suit the particular preferences and expertise of those carrying out the process.

The content of Part 1 of the guideline is drawn from the literature covered in Chapters 3 and 6 of this thesis, and is intended to introduce sustainability and the S-Cycle model to a practitioner with limited knowledge of the topic. The core of the guideline is the aforementioned procedure for improving system sustainability performance (Part 2), named the S-Cycle Performance Improvement Process (S-CPIP). As illustrated in Figure 7-3, the S-CPIP consists of six steps. These are based on the activities described in a model of the performance improvement process outlined by O'Donnell and Duffy (2005, p.9) as part of their work on design performance measurement and management (Figure 7-2). Whilst the model refers to the performance of business processes such as design, the activities it describes are generic and thus, may also be applied to the design artefact i.e. technical systems. The following key activities are involved, and the process overall is presented as "cyclic" in nature:

- *Assessment,* aimed at "establishing values for different aspects of performance through the application of particular performance metrics/measures [indicators]." The focus is on "key elements of the particular business process(es), i.e. the inputs, outputs, goals and resources."
- *Analysis*, "aimed at providing information on the causes of high or low performance to support decision making for improvement." Analysing performance provides "a more comprehensive understanding of the performance in the process."
- *Action*, where the "output from analysis provides the necessary information to support decision making in relation to the necessary actions to achieve improved performance." Decisions may "may result in actions such as the allocation of resources, definition of goal priorities, implementation of controls, etc."

The S-CPIP is illustrated in Figure 7-3. Readers are referred to the guideline in Appendix 8A for a full description of the process; however, a brief overview is provided here. Steps 1 and 2 focus on the definition of sustainability objectives for the chosen system, and the interpretation of system behaviour with the S-Cycle to define system sustainability goals. Steps 3 and 4 provide guidance on how to assess and analyse sustainability performance through the identification and evaluation of appropriate SPIs. This guidance is largely drawn from the E^2 model defined by O'Donnell and Duffy (2005), which describes performance in terms of its two fundamental components – that is, efficiency and effectiveness. The E^2 model is generic and as such, O'Donnell and Duffy (2005, p.10) suggest that it "supports the modelling of design performance within any situation." A detailed discussion on the E^2 model and an example application to a manufacturing system are provided in Sections 2.1 and 2.2 of Paper B (Appendix 2). Step 5 involves taking action to influence performance. Performance is then assessed and analysed post-action, following the same guidance provided in Steps 3 and 4, to determine if any improvement has been attained. Finally, Step 6 centres on the implementation of a continuous improvement process for the technical system in question, reflecting the cyclic nature of performance improvement as highlighted by O'Donnell and Duffy (2005). However, it is acknowledged that this may not be appropriate for all technical systems and applications of the guideline. For instance, it may simply be desired to assess sustainability performance without taking any action to improve it, in which case it is not necessary to implement continuous improvement.

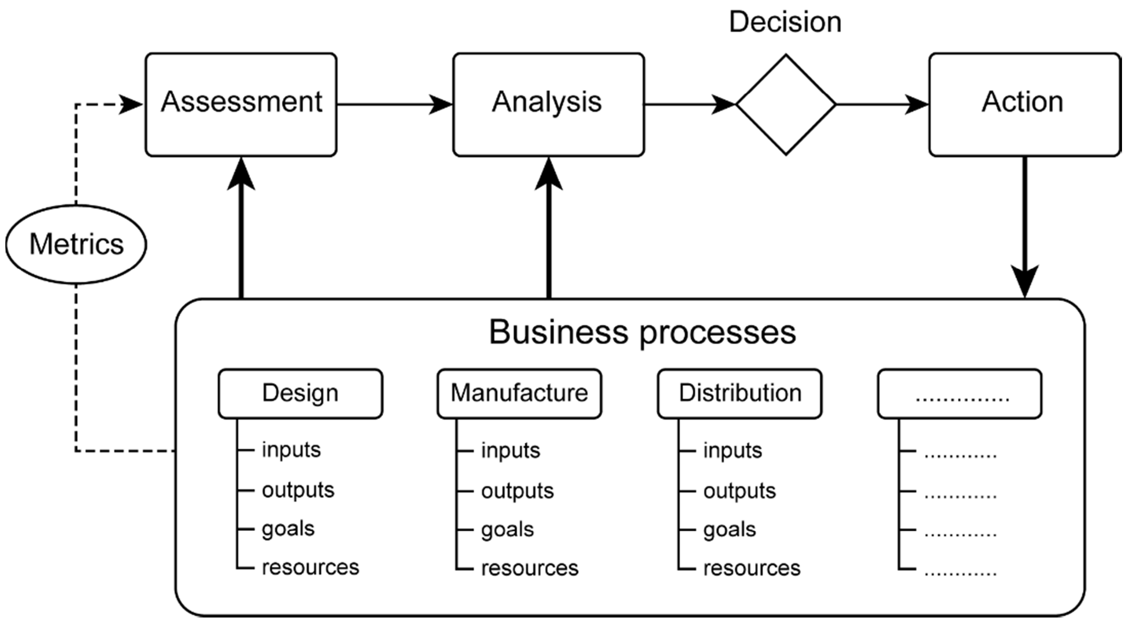


Figure 7-2: A model of the performance improvement process (reproduced from O'Donnell and Duffy 2005, p.9)

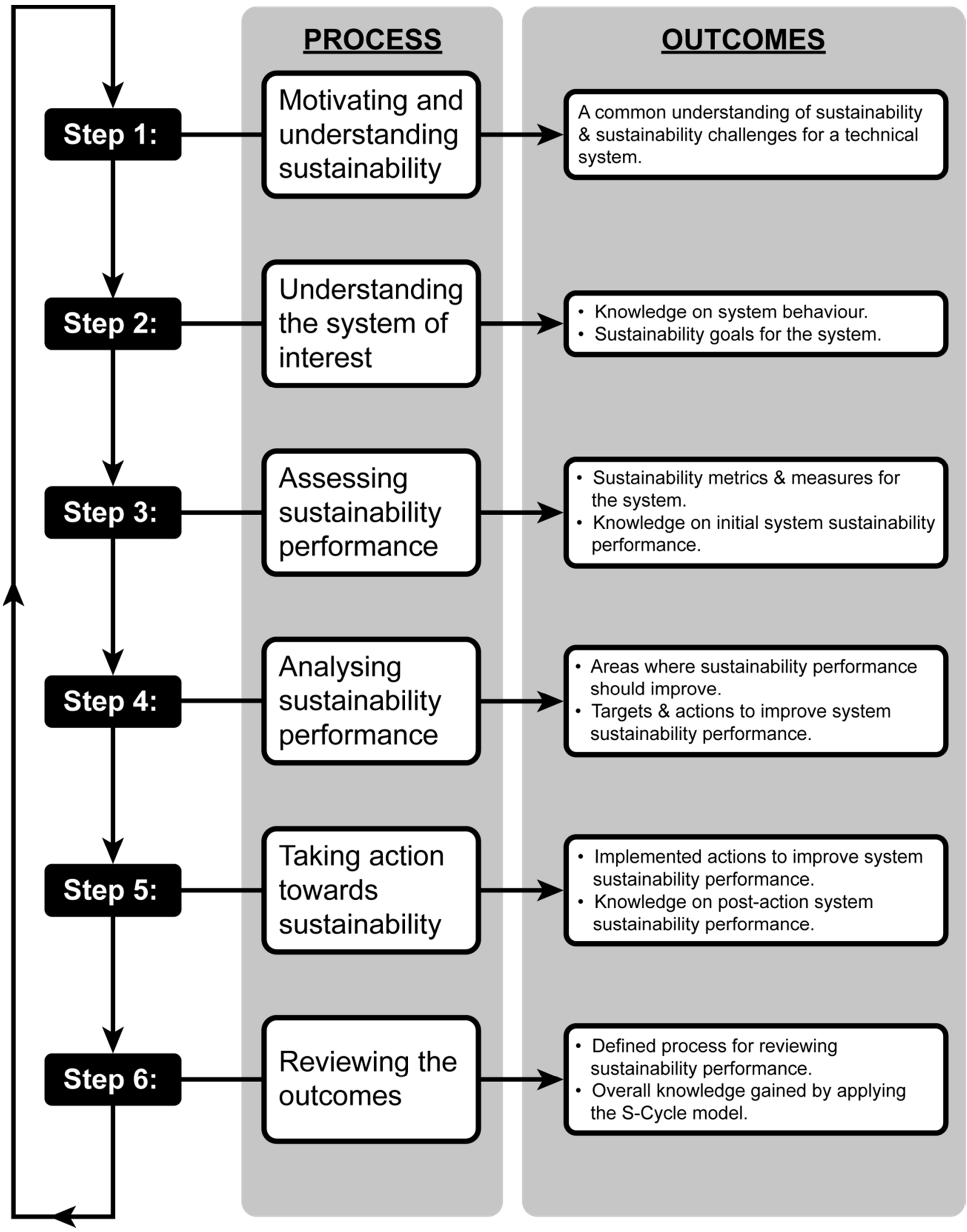


Figure 7-3: The S-Cycle Performance Improvement Process (S-CPIP)

7.1.2 Worked examples

As noted above, two worked examples were produced to provide initial evaluation of the S-Cycle model and its use. For WE1, the model was applied to a bioethanol production system according to the process described in the S-Loop model (introduced in Chapter 6). The major function of this system is to convert corn into bioethanol and dried grains, both intended for eventual use as biofuels. The system is described in the literature by Ulgiati et al. (2011), who represent its behaviour in an energy systems diagram illustrating the major system activities and supporting resource stocks. This diagram is presented in Figure 7-4. The system was chosen as the focus for WE1 for two reasons:

- It is an instance of a technical system, involving a number of sub-systems that closely interact with one another and the surrounding environment. Therefore, it aligns with the context of the research.
- The sustainability of biofuel production is increasingly under scrutiny, owing to its utilisation of land and other resources ordinarily used for food production. This leads to a potential trade-off between the two production processes in terms of their sustainability. Thus, it was felt that the system would form an appropriate challenge for evaluating the S-Cycle model.

The various sub-systems comprising the system carry out a range of activities, including: the production of steam and electricity to drive the production process; the preparation, cooking, fermentation, and distillation of corn to produce ethanol and distillery grains; drying of distillery grains; and storage of the dried grains and ethanol before they are transported for sale and use. Owing to the necessary space limitations of a journal article, the S-Cycle model was applied to the aggregate of these sub-activities rather than each one individually. That is, the activity of "bioethanol production." The SoI boundary was defined as including the bioethanol plant, as well as the resource stocks providing its direct inputs as described in the energy systems diagram in Figure 7-4. Applying the model yielded a visual interpretation of the system activity (Figure 7-5), a set of sustainability goals and corresponding metrics of efficiency and effectiveness for the system, and a list of actions that could potentially improve system sustainability performance. The worked example was published in Paper C (Section 6.3 – Appendix 3).

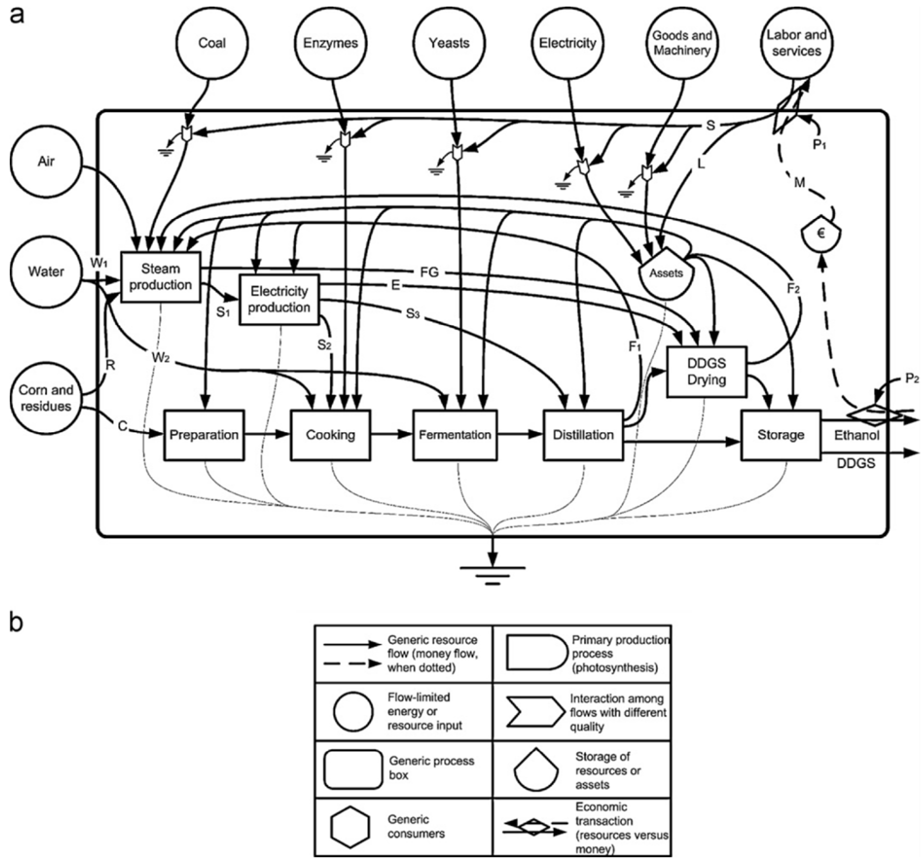


Figure 7-4: Energy systems diagram describing the bioethanol production system studied in WE1 (from Ulgiati et al. (2011, p.182))

WE2 was produced by Student B during the early stages of CS3, as a means to support explanation of the S-Cycle model and guideline to engineering designers in industry. For this example, the model was applied to a petrol car engine according to the S-CPIP detailed in the guideline. The major function of this system is to convert petrol and air into mechanical power. It was chosen as the focus of WE2 by Student B for the following reasons:

- It is an example of a technical system that whilst still relatively complex, is commonplace and would therefore likely be familiar to the engineering designers involved in discussions with the student.
- Petrol engines produce greenhouse gases as a byproduct of their internal combustion process. Accumulations of anthropogenic greenhouse gases in the atmosphere are believed to be a major driver of global warming, which in turn may compromise the sustainability of human activity in the Earth system. It is therefore desirable to reduce emissions of greenhouse gases by human activities and systems. Thus, as with the bioethanol production system in WE1, it was felt that the petrol engine would form an appropriate challenge for evaluating the S-Cycle model.

Applying the model once again yielded a visual interpretation of the system activity (Figure 7-6), and a set of sustainability goals and corresponding metrics of efficiency and effectiveness for the system. Although not explicitly stated, it is inferred from Student B's dissertation (Student B, 2014) that the SoI boundary was defined as including the engine and the natural resource stocks ultimately providing its direct inputs. For instance, as shown in Figure 7-6, the input of petrol was interpreted as non-renewable, which suggests that the SoI included the non-renewable stock of crude oil from which petrol ultimately originates. The goals and metrics defined by Student B were recorded in two tables developed to support Steps 3 and 4 of the S-CPIP. Several actions to improve the sustainability performance of the engine were also suggested, which are reported in the student's dissertation (Student B, 2014).

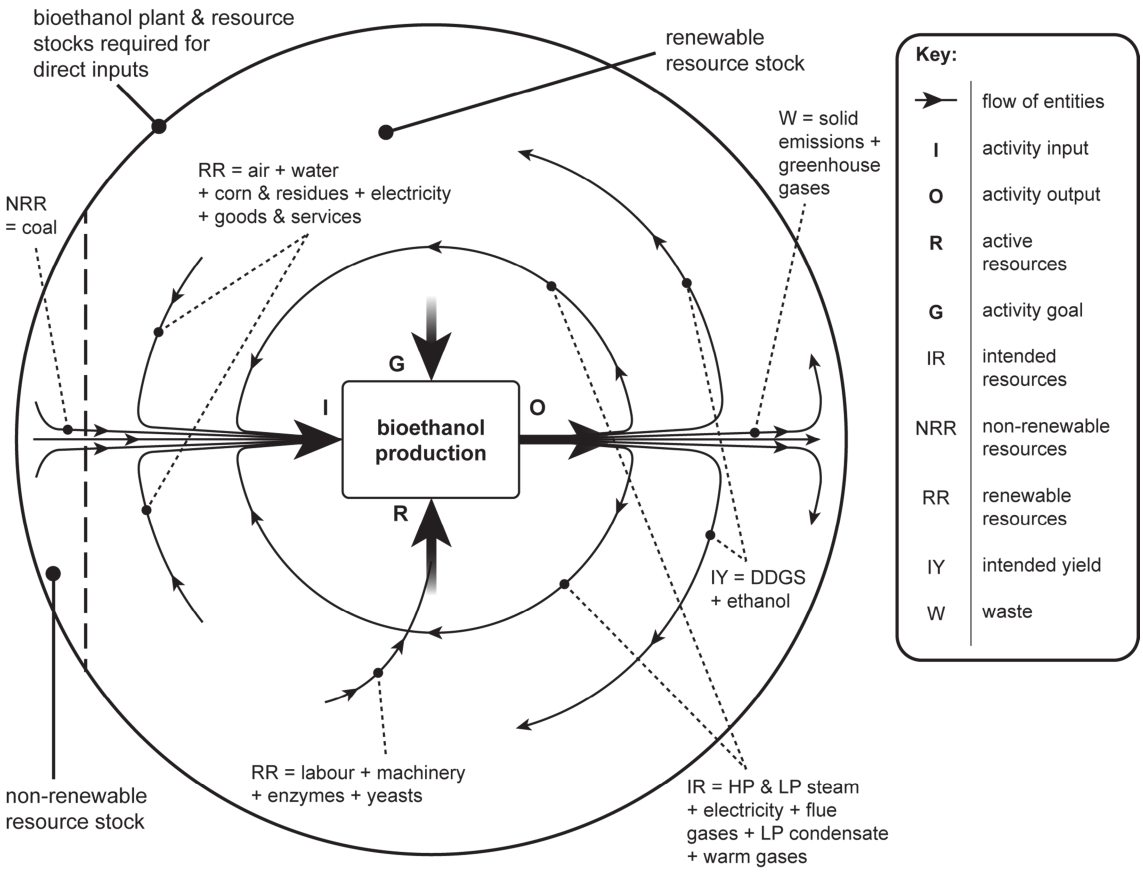


Figure 7-5: S-Cycle interpretation of the bioethanol production system activity

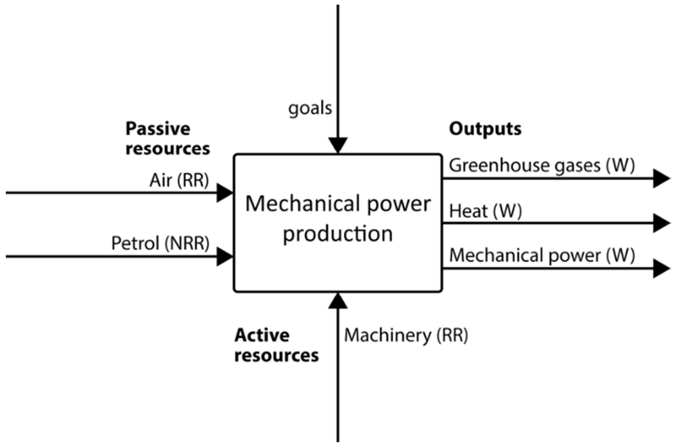


Figure 7-6: S-Cycle interpretation of a petrol car engine activity (adapted from Student B (2014))

7.1.3 Case studies

Given that the S-Cycle model was developed through inductive literature research, industrial practice formed an appropriate basis for evaluation. Accordingly, the three case studies introduced in the introduction to Chapter 7 focused on application of the model to technical systems in industry. Before the studies could be carried out, it was necessary to negotiate access to information on suitable systems. To expedite this process, it was decided to approach two companies already holding longstanding research partnerships with the University of Strathclyde – namely, Babcock Marine (hereafter Babcock) and BAE Systems Maritime (hereafter BAE Systems). Both organisations are in the business of designing, manufacturing, and maintaining complex technical systems for the defence sector in the United Kingdom (Babcock International Group PLC, 2014; BAE Systems Maritime, 2014). The companies each expressed a desire to apply the model to systems on a warship, in turn providing an opportunity to carry out the case studies. A warship may be considered to provide a suitable context for evaluation of the model for two reasons:

- A warship is an instance of a large-scale technical system, comprised of numerous interdependent sub-systems that closely interact with one another and the ship's working environment, e.g. the sea, the atmosphere, and other ships. Therefore, it aligns with the context of the research.
- Whilst at sea, and particularly in between replenishment efforts by supply ships, a warship and its human population (i.e. the ship's staff) are required to operate as a self-sustaining system. This requirement must be considered during the design of the ship's sub-systems. For instance, the ship must have the capability to produce its own electrical power, heating and cooling, and fresh water, and to process its own waste. Essentially,

from a sustainability perspective, a warship may be viewed as a microcosm of the Earth system, exhibiting limited interactions with its surrounding environment such as the consumption of sea water from the sea. Thus, it was felt that this system would form an appropriate challenge for evaluating the S-Cycle model.

As noted in the introduction to Chapter 7, the systems studied were an HVAC system (CS1), and a CW system (CS2) and its CW plant sub-system (CS3). The HVAC system was developed by Babcock Marine, whilst the CW system and its CW plant sub-system formed part of a generic system layout used by BAE Systems Maritime to design CW systems for different warships. As such, the systems studied did not physically form part of the same warship. Nonetheless, they may be viewed as elements of a general warship design. Figure 7-7 presents a schematic showing a simplified layout of the systems. This figure is based on a schematic found in Defence Standard 02-102, which defines design requirements and standards for ventilation, air conditioning, and cooling equipment aboard naval ships (Ministry of Defence, 2000). Note that the original schematic from the defence standard has been extended to better illustrate the CW system – this extension is based on descriptions of the CW system provided in Paper D (Appendix 4).

The primary functions of the HVAC system are the delivery of a heating or cooling effect to an input of air, and the distribution of the warm/cool air around the ship to provide ventilation. The major functions of the CW system are the production and circulation of a flow of chilled water throughout the ship, where it is used as a cooling medium by other systems (including the HVAC system). The CW plant sub-system of the CW system carries out the function of producing chilled water, by removing heat from the flow of used cooling medium returning from equipment aboard the ship and rejecting it to the sea via a flow of sea water overboard. The CW system contains multiple CW plants to serve different parts of the ship. It may be seen in Figure 7-7 that the HVAC system interfaces with the CW system, using a portion of the CW system's chilled water flow to cool a flow of air via a heat exchanger.

An overview of the context and work conducted for each case study is provided in the following sub-sections.

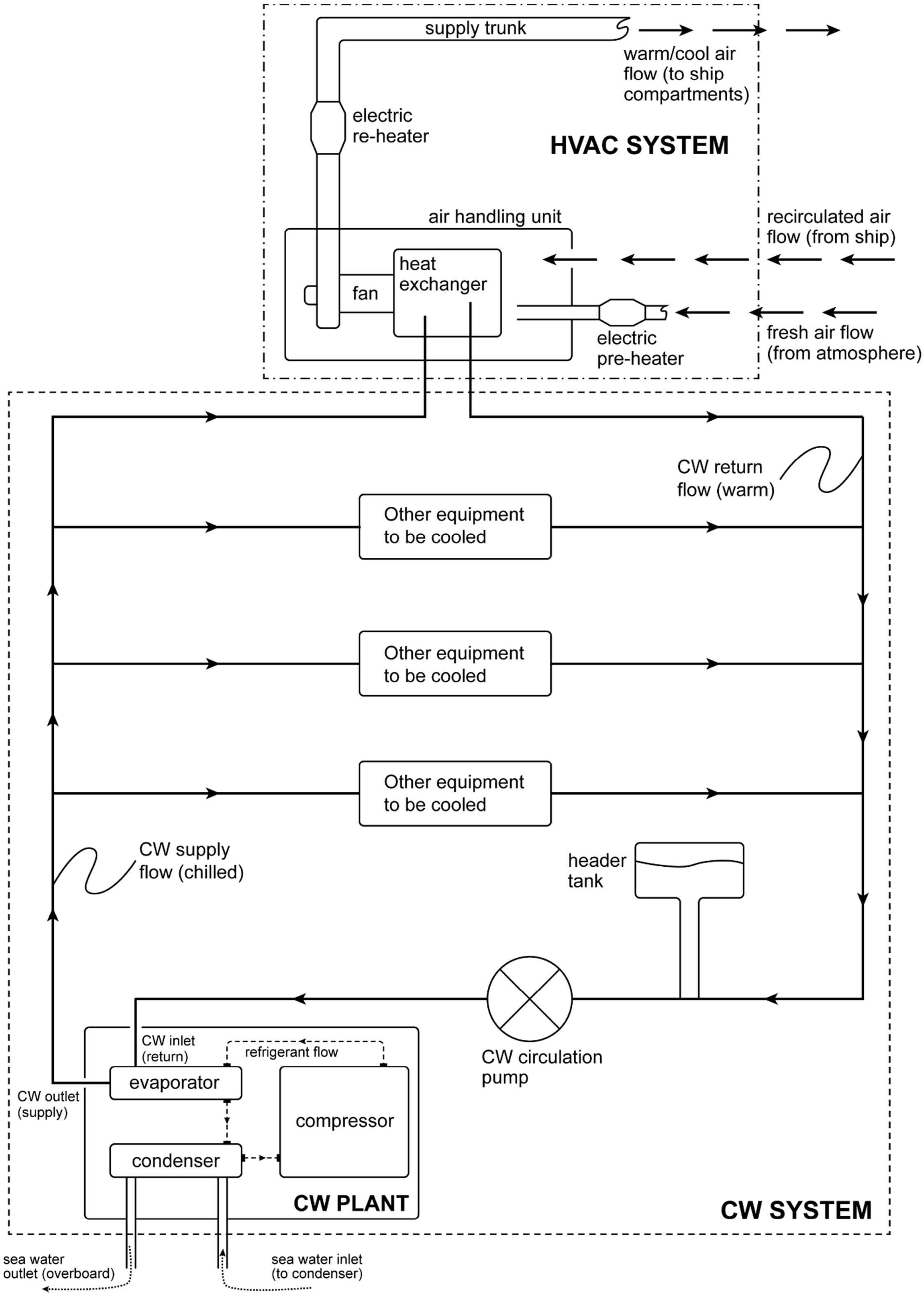


Figure 7-7: Schematic of a simplified HVAC and CW system layout on a warship

7.1.3.1 Case 1 (CS1)

CS1 was carried out by Student A in collaboration with Babcock. The student was based within the University of Strathclyde for the duration of the study, which was carried out between November 2012 and August 2013. However, they had regular contact with representatives from the company via face to face meetings and email exchanges.

CS1 consisted of Student A's postgraduate Masters dissertation project. The aim of Student A's investigation was to "assess the characteristics, environmental sustainability and impacts of air-cycle based HVAC systems in comparison to HCFC [hydrofluorochlorocarbon]-based HVAC systems" (Student A, 2013), to determine whether the former type of system is suitable for use on naval ships. To achieve this aim, the student applied the S-Cycle model and guideline to assess and compare the sustainability performance of the two types of HVAC system. The part of the student's investigation focusing on the technical characteristics of the systems is not discussed in this thesis as it is irrelevant with respect to evaluation of the S-Cycle model.

Steps 1 to 4 of the S-CPIP were executed during CS1. The major outcomes of applying the model to the air cycle- and HCFC-based HVAC systems were:

- a textual description of HVAC system behaviour from a sustainability perspective;
- a set of ranked sustainability goals for the systems;
- a set of metrics of efficiency and effectiveness relating to the defined goals;
- metric values for both types of HVAC system studied, facilitating a comparison of the systems on the basis of their sustainability performance;
- a set of targets to improve the performance of the air cycle-based HVAC system benchmarked against the performance of the HCFC-based HVAC system; and
- a set of suggested actions to achieve the performance improvement targets.

The guideline documentation filled out by Student A to record sustainability goals and metrics, improvement targets, and actions to achieve improved performance is included in Appendix 8B.

It should be noted that a difficulty faced by Student A throughout CS1 was a lack of available data on the behaviour and performance of HVAC systems currently installed on Babcock's ships. Additionally, the aim of the student's project was to determine the suitability of air cycle-based HVAC systems for use on naval ships. This type of system is *not* currently used in this context and thus, it is reasonable to assume that data on behaviour and performance is limited. Given the time constraints of Master's research, the student decided to utilise data on similar HVAC systems used on trains. In this context, "air-cycle HVAC systems have already been implemented for several years" (Student A, 2013, p.49). This data was used as the basis for applying the S-Cycle model to the systems studied.

7.1.3.2 Case 2 (CS2)

CS2 was carried out by the author in collaboration with BAE Systems. The author was based within the company for the full duration of the study, which was carried out between October 2013 and May 2014.

As noted previously, the system studied in CS2 was the CW system on a warship. BAE Systems desired a formal model of the system that could provide insight into its behaviour, potentially leading to improved system design. To address this need, a project aiming to develop a model of the CW system for future use by the company was undertaken by the author. As part of this project, Step 1 and part of Step 2 of the S-CPIP were executed, with the developed CW system model providing the basis for applying the S-Cycle model to the CW system. The definition of system sustainability goals, which forms part of Step 2, was not carried out owing to time constraints. The IDEF0 modelling language was chosen to represent the CW system. According to the standard that defines the language, it may be used "for systems composed of people, machines, materials, computers and information of all varieties" (NIST, 1993, p.7). Therefore, it provides a suitable means to model a technical system. Additionally, engineering designers at the company were familiar with the language. As such, its use facilitated the development of a model that would be understandable by its intended users.

Using the IDEF0 language, a system is modelled in terms of the major activities it performs, the inputs and mechanisms required for successful execution of these activities, the outputs produced as a result of the activities, and the controls that govern these outputs. Mechanisms carry out processing to produce outputs, whilst inputs are the materials, energy, and information processed by the mechanisms. Controls are conditions that govern the production of outputs from inputs by mechanisms. Activities may also be referred to as functions within the language. In turn, a model built with the language may be referred to as a function model – this terminology is adopted throughout the thesis. The two key elements of the language are: (i) *boxes*, which represent activities; and (ii) *arrows*, which represent the inputs, mechanisms, outputs, and controls associated with each activity. The IDEF0 activity representation is presented in Figure 7-8. It may be seen that this representation closely resembles the activity formalism used in the S-Cycle model. Thus, an advantage of the IDEF0 language in the context of this research is that it aligns with the S-Cycle model. For the purposes of CS2, IDEF0 inputs were equated with passive resources and mechanisms with active resources as shown in Figure 7-8.

The complete CW system function model is comprised of a hierarchical set of diagrams, describing the activities carried out by the CW system at different levels of decomposition. That is, the activities carried out by the CW system as a whole and its constituent sub-systems, as illustrated in Figure 7-9. The full set of diagrams is included at the end of Paper D in Appendix 4. Each diagram details the sub-activities of a parent activity described in a higher level diagram. The only exception is the A-0 diagram – this details the overall activity carried out by the CW system as a whole, for which no parent activity is modelled. Each activity in the model is assigned a code identifier, which corresponds with the diagram detailing the decomposed activity. This kind of structure is common to all function models built using IDEF0, and is illustrated in Figure 7-10 using an electric screwdriver as a simple example for the purposes of clarity. The code identifiers in Figure 7-9 correspond with the diagrams included in Appendix 4.

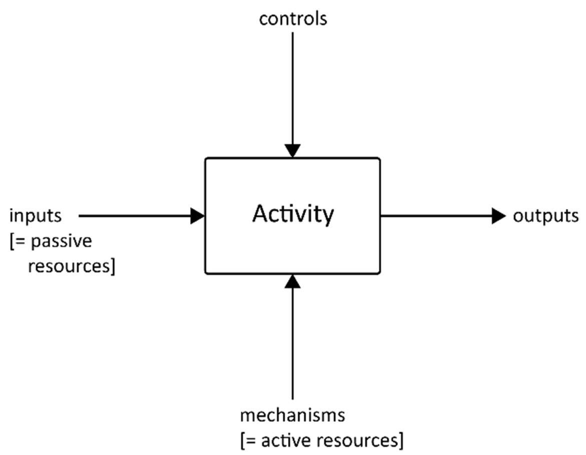


Figure 7-8: The IDEF0 activity representation as it is interpreted in this thesis

The function model was validated through a series of individual and group interviews with five engineering designers at BAE Systems, collectively holding over 120 years of experience in engineering. Included in this group were two engineers each holding over 35 years of experience. The process undertaken to develop the CW system function model, including validation of the model, is discussed in detail in Section 2 of Paper D (Appendix 4). The full function model is also included at the end of the paper.

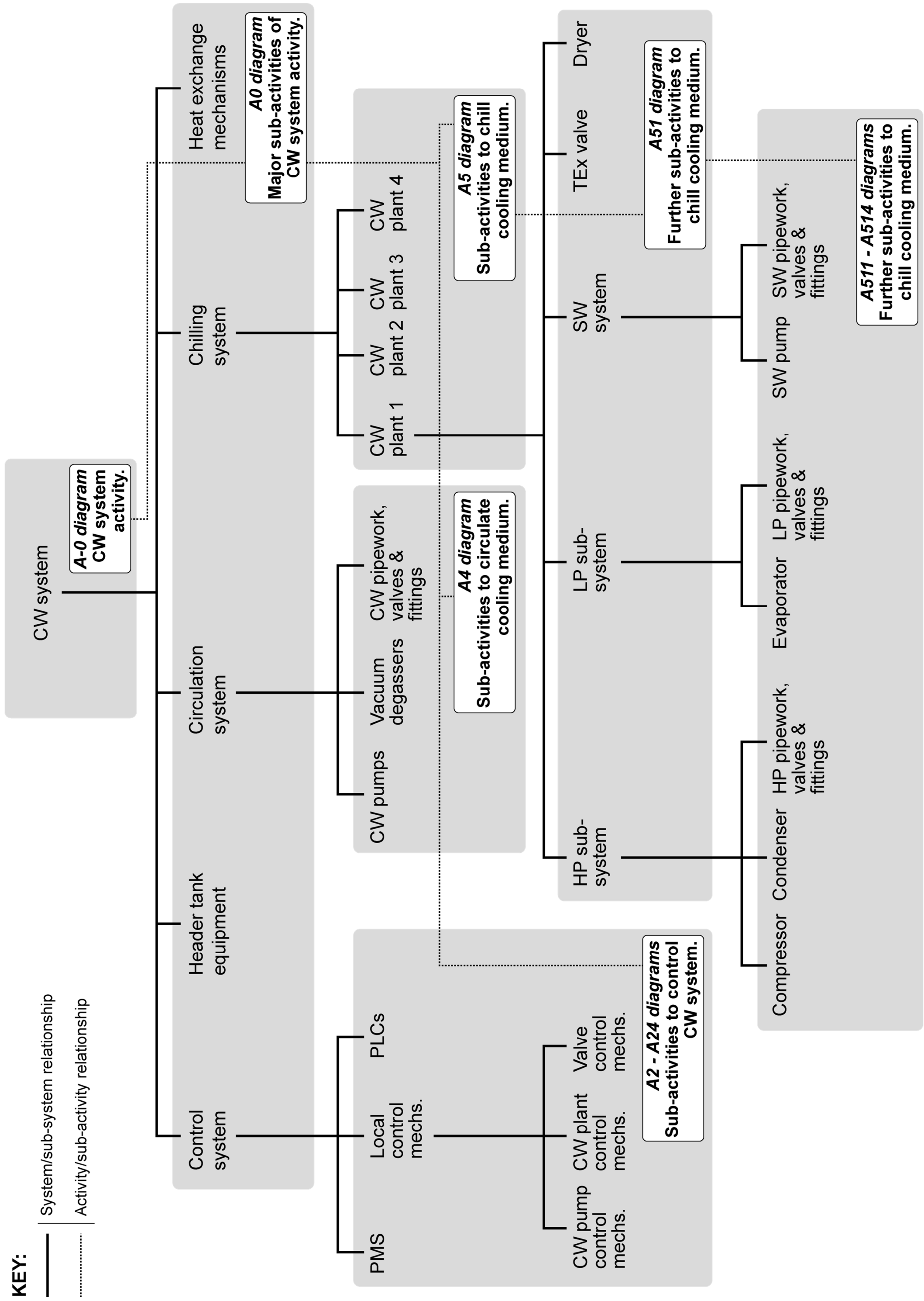


Figure 7-8: Structure of the physical CW system and the function model[5]

Figure 7-9: Structure of the physical CW system and the function model[8]

[8] Abbreviations: CW = chilled water; HP = high pressure; LP = low pressure; mechs. = mechanisms; PLCs = programmable logic centres; PMS = platform management system; SW = sea water; TEx valve = thermostatic expansion valve

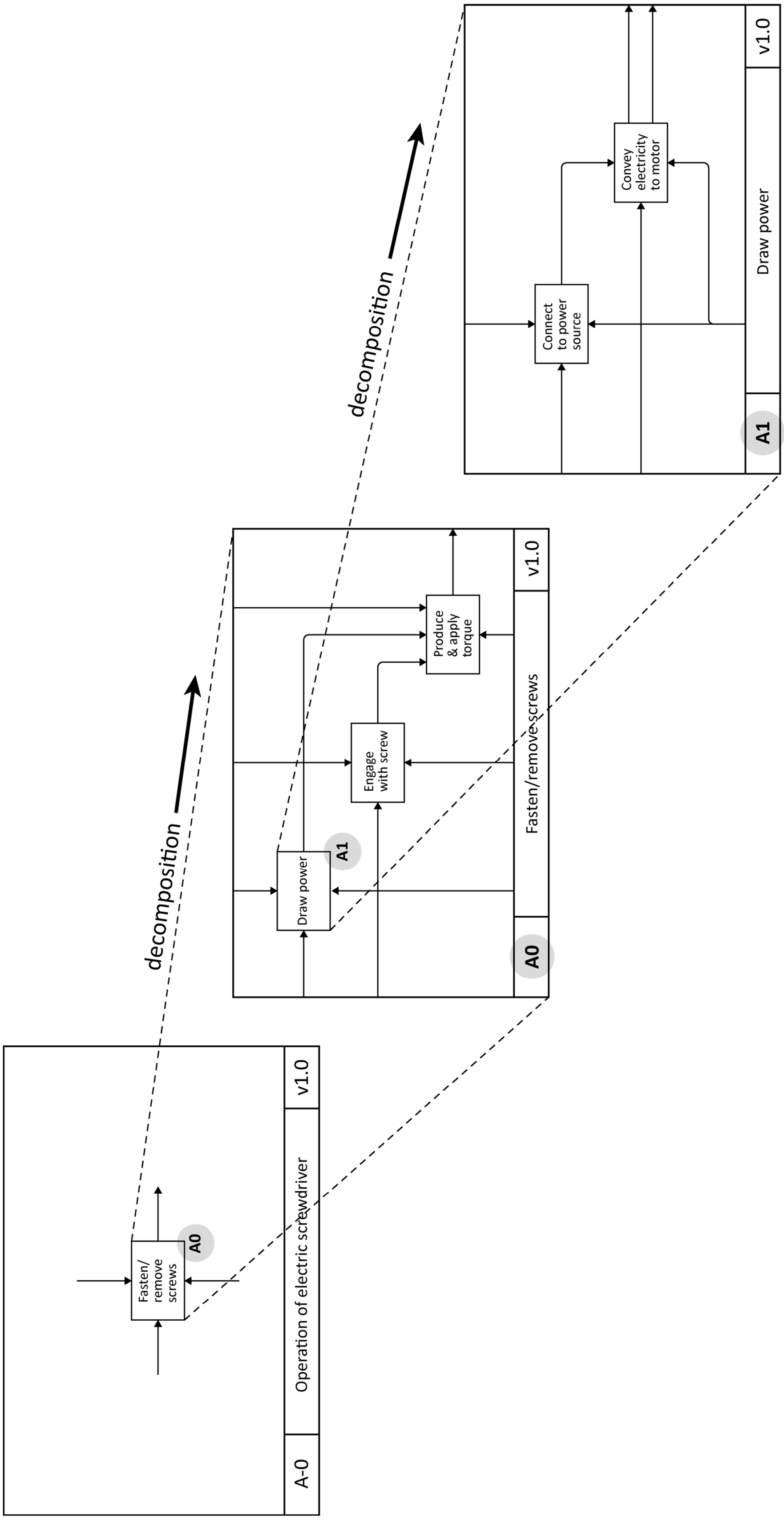


Figure 7-9: Decomposition of activities in an IDEF0 function model

Figure 7-10: Decomposition of activities in an IDEF0 function model

The major outcome of CS2 was an interpretation of current CW system behaviour from the perspective of the S-Cycle model. The interpretation was captured in a spreadsheet – an excerpt from this is included in Appendix 9. Additionally, the results were recorded visually on the IDEF0 diagrams comprising the CW system function model. The full set of interpreted diagrams is presented at the end of Paper D in Appendix 4. The interpretation process and major outcomes are discussed in Section 3 of Paper D. Nonetheless, a brief overview is provided here. Firstly, the wider SoI supporting the operation of the CW system activity was defined as a warship at sea undertaking a 90 day mission. This boundary was defined by the author in consultation with engineering designers at the company, and reflects the company's interest in the sustainability of the CW system whilst the ship has limited access to external resources. Inputs, mechanisms, and outputs in the function model were then interpreted and categorised as renewable resources, non-renewable resources, intended resources, intended yield, waste, or "unknown" if not covered by the S-Cycle model. To determine whether a particular resource involved in the activity was renewable or non-renewable, it was traced back to the stock that replenished it within the defined SoI. Additionally, the destination of intended yield and waste outputs within the SoI was also recorded. Note that informational inputs, outputs, and controls were not considered during the interpretation owing to the focus of the research on materials and energy as discussed in Chapter 1.

The S-Cycle interpretation of inputs, mechanisms, and outputs was checked by a group of 11 engineering designers at BAE Systems, collectively holding over 250 years of experience, who largely accepted it as correct. The exercise carried out by the engineering designers to check the interpretation formed part of WS1 and is discussed in detail in Section 7.2.1.

7.1.3.3 Case 3 (CS3)

CS3 was carried out by Student B in collaboration with the same company involved in CS2, i.e. BAE Systems. Unlike the thesis author in CS2, the student was based within the University of Strathclyde for the duration of the study, which ran between November 2013 and August 2014. During this time, they had several face-to-face meetings with representatives from the company. They also conducted an interview with a senior principal engineer holding over 35 years of experience, to obtain information on the system studied and feedback on their work. Additionally, they were in regular contact with two representatives from the company via email, delivering weekly updates on the project and requesting information.

CS3 consisted of Student B's postgraduate Masters dissertation project. The work conducted and the findings are reported in full in the student's dissertation. The aim of Student B's project investigation was to "define, evaluate, and analyse sustainability performance indicators for the cooling system on a ship" (Student B, 2014, p.3). To achieve this, the student built upon the work conducted in CS2 to model the CW system and interpret its behaviour using the S-Cycle model. As highlighted in Section 7.1.3.2, Steps 1 and 2 of the S-CPIP were carried out for the CW system during CS2. Although in the context of this thesis, the work carried out in CS3 may be viewed as a continuation of work conducted in CS2, Student B viewed CS3 as a self-contained project and took ownership of it as such. Thus, they carried out elements of Step 1 of the process, to secure the engagement of decision makers at BAE Systems and to explain the aim of their dissertation project. The student then carried out the final tasks of Step 2 not completed in CS2, i.e. the definition and ranking of goals, as well as Steps 3 and 4. However, rather than focusing on the assessment and analysis of sustainability performance for the whole CW system, they focused on the CW plant sub-system owing to time constraints on their dissertation project.

Student B was provided with a copy of Paper D and the CW system function model as the basis for their work (Appendix 4). Using the S-Cycle interpretation of the function model developed in CS3, they defined a set of ranked sustainability goals and associated performance metrics for the CWP sub-system of the CW system. The guideline documentation listing the sustainability goals and metrics is included alongside the documentation from CS1 in Appendix 8B. BAE Systems desired to obtain information on the sustainability performance of a specific CWP system currently being designed by the company. As the physical system had not yet been manufactured, limited data was available on its performance. Therefore, Student B used the CW system function model to develop a quantitative model that simulates the performance of the specific CWP system under study. Once values had been obtained for the metrics and indices using the quantitative model, Student B identified several areas where performance could potentially be improved. Additionally, they suggested actions that could be taken by the designers of the system to bring about the improvements. However, unlike Student A in CS1, Student B did not set formal performance improvement targets for the system. Rather, the potential improvements are described in a largely qualitative manner as part of the student's discussion in their dissertation.

7.1.4 Case study analysis

As discussed in Section 7.1.3, the work conducted in CS1 and CS3 by Students A and B is reported in the students' respective Masters dissertations. Similarly, the research carried out by the author in CS2 is documented in Paper D (Appendix 4). Additional documentation was also produced by the author over the course of CS2, including a log book of personal reflections and notes from unstructured interviews and group discussion sessions. In order to draw conclusions from the case studies regarding evaluation of the S-Cycle model, these documents were analysed. The analysis of documentation from each case study was carried out in the order the cases studies were conducted chronologically, and in two stages. Note that the analysis was carried out by the author alone.

The first stage in the analysis was in depth analysis of Student A's dissertation (CS1). That is, the dissertation was interpreted line-by-line. Statements written by the student were interpreted and assigned code identifiers, leading to a number of initial conclusions regarding different aspects of the S-Cycle model. Next, the documentation produced by the author (CS2) and the dissertation produced by Student B (CS3) were analysed in relation to the conclusions drawn from the analysis of Student A's dissertation. Additionally, a brief document provided by Student B containing written feedback on the model and guideline was also analysed. This documentation was analysed in less depth than the first dissertation. That is, the documents were not interpreted line-by-line. Rather, upon reading the documents, statements falling into one of the following three categories were recorded and assigned a code identifier:

- statements interpreted as *supporting* a conclusion drawn from the analysis of Student A's dissertation;
- statements interpreted as *contradicting* a conclusion drawn from the initial analysis; and
- statements considered to highlight *additional conclusions* with respect to one of the issue categories outlined above, which did not emerge from the initial analysis. In the case of these statements, a new conclusion was added to the relevant issue category.

7.2 Expert appraisal

As discussed in the introduction to Chapter 7, the S-Cycle model underwent appraisal by engineering designers and managers during two interactive workshops (WS1 and WS2). These workshops were carried out with participants from two different companies: WS1 involved participants from BAE Systems (where CS2 and CS3 were conducted as discussed in Section 7.1.3), and WS2 involved participants from a British energy company, hereafter referred to as Company A. The structure and content of the workshops differed slightly owing to differences in the settings:

- WS1 was held at BAE Systems at the end of CS2. In addition to evaluation of the model, this workshop also involved dissemination of the CW system function model and the findings of CS2 to participants. Additionally, participants were asked to check the author's S-Cycle interpretation of the function model, as highlighted in Section 7.1.3.2. The planned duration of this workshop was approximately 2 hours. It was felt that this would provide sufficient time to complete the practical exercise, questionnaire, and checking of the function model interpretation. From another perspective, it was considered short enough to maintain the attention of participants, who volunteered their time during a working day.
- WS2 was delivered as part of a continuing professional development course provided to employees of Company A at the University of Strathclyde. As such, the focus was primarily upon educating participants on sustainability and the S-Cycle model, as well as the process involved in applying it. The planned duration of this workshop was approximately 3 hours. It was felt that this would provide sufficient time to present a series of explanatory examples to educate participants, and also for them to complete the practical exercise and questionnaire.

During the practical exercise delivered at both workshops, participants were asked to apply the S-Cycle model to a system of their choice that they were familiar with. They were also instructed to annotate the model to indicate any aspects that they disagreed with or felt were incomplete. The questionnaire asked participants to rate the model's comprehensiveness, as well as various aspects of its utility, along a Likert scale running from *poor* to *excellent* around a neutral option of *no opinion*. A box for open responses was also included for each question to capture comments from participants. Comprehensiveness in this context refers to the degree to which the model covers the aspects of a technical system's behaviour that are relevant from a sustainability perspective. Utility refers to the model's usefulness and fitness for purpose. The aspects of utility that were considered were:

(i) ease of understanding by engineering designers;
(ii) the model's effectiveness as a tool for interpreting the behaviour of a technical system; and
(iii) the model's effectiveness as a tool for explaining the concept of sustainability.

In addition to the practical exercise and questionnaire, participants in WS1 were asked to consider selected activities from the CW system function model and indicate agreement or disagreement with how the author had interpreted them with the S-Cycle model.

Prior to the workshops, a pilot study was conducted so that: (i) the practical exercise, questionnaire, and exercise to check the interpretation of CW system activities would be understandable by participants; and (ii) sufficient and reliable data could be collected during the time allocated for each workshop. The pilot study is discussed in Section 7.2.1, before WS1 and WS2 are detailed in Section 7.2.2.

7.2.1 Pilot study

Three researchers in DMEM at the University of Strathclyde participated in the pilot study. They were selected as pilot participants on the basis that they had expertise in the area of systems engineering and engineering design (27 years of experience collectively), as well as experience working with engineering designers in industry. Their profiles are presented in Table 7-1 – each has been assigned a code identifier that is used throughout this thesis to maintain their anonymity. During the pilot, these participants were firstly provided with an introductory presentation on sustainability and the S-Cycle model. Following this, they completed the practical exercise and the questionnaire. The CW system activities to be checked were discussed, but the pilot participants felt that they did not have sufficient knowledge of the system to check the S-Cycle interpretation. Nonetheless, useful feedback on how to most effectively facilitate the task was obtained from the discussion. Following the pilot study, a number of changes were made to the practical exercise, the questionnaire, and the exercise to check the interpretation of CW system activities as discussed below.

Table 7-1: Profiles of researchers selected as pilot participants

Pilot participant ID	Field	Years of experience
PS-1	Systems/engineering design	6
PS-2	Product design/systems engineering	12
PS-3	Mechanical engineering	9

Changes to the practical exercise largely centred on an A3 template designed to facilitate application of the S-Cycle model to a system by workshop participants. Originally, the model was presented in the middle of the page, with boxes attached to each input/output for participants to provide examples from their selected system. All labels applied to inputs/outputs in the model (e.g. renewable resources, intended resources, waste, etc.) were abbreviated, and a key was provided separately. However, the pilot participants remarked that the layout, coupled with the abbreviations, made the exercise somewhat overwhelming. It was unclear where to start filling out the template, and it was difficult to simultaneously apply the model and refer to the abbreviations key. Following the pilot, the layout was changed so that the model was presented on the left hand side of the page. To provide more structure to the exercise, the response boxes were moved to the right hand side of the page and categorised as passive resources (i.e. renewable and non-renewable), active resources (i.e. renewable and non-renewable), and outputs (i.e. intended resources, intended yield, and waste). Each category was also numbered from 1 to 3. Additionally, labels were written in full on the template rather than abbreviated, negating the need for a separate key. An example of a completed template was also developed to provide a clearer idea of the expected outcome of the exercise. For both workshops, a system with no obvious relation to the participants' area of engineering expertise was chosen to ensure that responses would not be influenced by the example.

A second major change made to the exercise following the pilot was the decision to implement it as a group activity. Originally, it was intended to be completed by participants individually – however, during the pilot, the participants indicated that it would likely be easier and quicker to complete as a group. A number of minor changes were also made. For instance, the terms passive and active resource were not easily understood by the pilot participants. As such, the terminology of the IDEF0 language (i.e. inputs and mechanisms) was used in the evolved template, as it was felt that this would be more intuitive for engineering designers. Furthermore, the term intended yield was considered to have strong connotations to different concepts in other contexts, e.g. economics and agriculture. Thus, this was changed to intended output. This terminology is used throughout the remainder of this thesis. The final version of the template is included in Appendix 10A.

With respect to the questionnaire, the pilot participants felt that the information provided to them during the introductory presentation coupled with their experience during the practical exercise was not sufficient to enable them to answer several questions. These questions related to the model's effectiveness as a tool to support the improvement of a technical system's sustainability performance. It was decided to remove these from the questionnaire, as the practical exercise did not provide a deep enough understanding of the model's capabilities in this respect. Additionally, one of the questions was originally worded as: "Ease of use as a systems analysis tool." The pilot participants felt that the term "analyse" implied a much more detailed treatment of system behaviour than was actually achieved during the practical exercise. As such, it was decided to re-word the question to: "Ease of use as a tool for interpreting system behaviour." The questionnaire is also included in Appendix 10A.

Finally, although the exercise to check the sustainability interpretation of CW system activities was not actually carried out during the pilot study, the pilot participants provided useful feedback that resulted in a major change. Originally, it was intended that participants in WS1 would be given the interpreted IDEF0 diagrams from the function model (included alongside Paper D in Appendix 4) and asked to annotate these, indicating their agreement/disagreement with the interpretation and providing comments. On the basis of the pilot participants' experience working with engineering designers in industry, they suggested that the exercise would require more structure in order to be successful within the time allocated to the workshop. As such, it was decided to focus the exercise on key activities from the function model. The nature of the IDEF0 modelling language means that certain inputs, mechanisms, and outputs are repeated multiple times in the model. As such, activities where the majority of inputs, mechanisms, and outputs were duplicated elsewhere in the model were excluded from the exercise. The activities to be checked were presented on A3 paper to ensure they were clearly legible. Brief descriptions of each input/mechanism/output and its S-Cycle classification were provided alongside the activities, with a box for workshop participants to indicate agreement or disagreement with the author's interpretation and provide brief reasons for their response. The activities to be checked were split into two sets to be given to different groups of participants. An example of the format used for the activity sets is included in Appendix 10A.

7.2.2 Workshops

The two workshops carried out with practicing engineering designers in industry following the pilot are outlined in the following sub-sections. As shown, a combination of engineers and engineering managers with different levels of experience participated. Participants are collectively referred to as "engineering designers" throughout the thesis, reflecting their role in the engineering design process (discussed in Chapter 4).

7.2.2.1 Workshop 1 (WS1)

WS1 was held at BAE Systems on Wednesday 30th April 2014 with eleven participants. These participants were engineers and engineering managers working within the company, with years of experience ranging from 5.5 to over 40 as shown in Table 7-2. Collectively, the group held over 250 years of experience. Included in the group were an engineering manager and senior principal engineer for modelling and simulation, with 17 and 35+ years of experience respectively. Each participant has been assigned a code identifier that is used throughout this thesis to maintain their anonymity.

The workshop lasted for approximately two and a half hours. An introductory presentation on sustainability and the S-Cycle model was first provided. Following this, the practical exercise was completed by participants in groups of two to three. Participants were asked to select a sub-system they were familiar with within the boundary of a warship. A warship was selected as the context owing to the expertise and backgrounds of those involved. After a short break, a second presentation was provided, this time focusing on the work conducted to model the CW system and interpret its behaviour using the S-Cycle, which formed the focus of CS2. After this, participants were again split into groups of two or three and completed the exercise to check the author's sustainability interpretation of the CW system function model. Both sets of activities were checked independently by two groups. Finally, participants filled out the questionnaire before the close of the workshop. A selection of the completed templates from the practical exercise, A3 sheets from the exercise to check the CW system sustainability interpretation, and questionnaires are provided in Appendix 10B.

Table 7-2: Profiles of participants in workshop 1

WS1 participant ID	Profession	Years of experience
PW1-1	Engineer	2
PW1-2	Engineer	5.5
PW1-3	Engineer	5.5
PW1-4	Engineering manager	17+
PW1-5	Engineer	21
PW1-6	Engineer	26
PW1-7	Engineering manager	30+
PW1-8	Engineering manager	31
PW1-9	Engineering manager	35+
PW1-10	Engineer	35+
PW1-11	Engineering manager	44
	TOTAL:	250+

7.2.2.2 Workshop 2 (WS2)

WS2 was held at the University of Strathclyde on Monday 23rd June 2014 with sixteen participants from Company A. These participants included a mixture of engineers and managers (working in an engineering context), with years of experience ranging from 3 to 20 as shown in Table 7-3. Collectively, the group held over 175 years of experience. As with participants from WS1, each participant in WS2 has been assigned a code identifier that is used throughout this thesis to maintain their anonymity.

The workshop lasted for approximately three hours. One presentation was provided to participants. This covered: an introduction to sustainability and the S-

Cycle model (similar to the introductory presentation provided to participants in WS1); a series of examples to illustrate the application of the model to different systems at different levels within a combined heat and power (CHP) plant; an overview of the S-Loop model (Chapter 6) and the S-CPIP described in the guideline detailed in Section 7.1.1; and an example to illustrate the application of the process to improve a CHP plant's sustainability performance. Following a short break, the practical exercise was completed by participants in groups of five to six. In consultation with the workshop participants themselves, an offshore wind farm was used as the context. Once the teams had completed the exercise, a short discussion was held on the systems they had interpreted.

Table 7-3: Profiles of participants in workshop 2

WS2 participant ID	Profession	Years of experience
PW2-1	Engineer	6
PW2-2	Engineer	8
PW2-3	Engineer	10
PW2-4	Engineer	10
PW2-5	Engineer	12
PW2-6	Engineer	14
PW2-7	Engineer	20
PW2-8	Project manager (engineering)	3
PW2-9	Project manager (engineering)	6
PW2-10	Project manager (engineering)	7.5
PW2-11	Project manager (engineering)	10
PW2-12	Project manager (engineering)	13
PW2-13	Project manager (engineering)	14
PW2-14	Project manager (engineering)	20
PW2-15	Project manager (engineering)	20
PW2-16	Site manager (engineering)	5
	TOTAL:	175+

Before the close of the workshop, participants filled out the questionnaire. It should be noted that changes were made to the wording of two questions following analysis of the questionnaire responses received at WS1. During WS1, participants were asked to rate the model with respect to its "comprehensiveness in describing the physical aspects of a technical system's behaviour." This was intended to capture opinions on the comprehensiveness of the elements and relationships used to describe the behaviour of a technical system in the model. However, WS1 participants instead provided opinions on certain aspects of the model's utility (discussed in Chapter 8). In an effort to capture opinions on the model's comprehensiveness during WS2, the wording of the question was changed to "coverage of the sustainability aspects of a technical system's behaviour." Nonetheless, certain WS2 participants again provided comments on the utility of the model rather than the elements and relationships in response to this question (also discussed in Chapter 8). Furthermore, WS1 participants were asked to rate the model with respect to its "ease of use as a tool for interpreting the behaviour of a technical system." This was intended to elicit opinions on the model's fitness for purpose as an interpretation tool. However, participant PW1-7 commented that "you don't necessarily want or expect an analytical tool to be easy to use – [it] must match the complexity of the problem." On the basis of this insight, it was decided to alter the wording of this question to read "effectiveness as a tool for interpreting the behaviour of a technical system" for WS2.

A selection of the completed templates from the practical exercise and completed questionnaires are provided in Appendix 10B alongside the output from WS1.

7.3 Sustainability performance indicator study

As highlighted in the introduction to Chapter 7, the final element of the evaluation approach was an analytical study focusing on the rationalisation of SPIs applied to technical systems using the S-Cycle and the E^2 performance model. As discussed in Section 7.1.1, guidance on the identification and evaluation of SPIs provided in Step 4 of the S-Cycle guideline is largely drawn from the E^2 model. A brief overview of the study is provided here; however, readers are referred to Paper B (Appendix 2) for further details, where the study and findings are reported in full. The study was motivated by the observation that there is little formal guidance on what constitutes a comprehensive set of SPIs for a technical system. In response, the S-Cycle model was applied to develop a generic classification of SPIs to guide the selection of a comprehensive set for a technical system. The resulting classification is known as the S-Cycle Performance Matrix (Figure 7-11).

The first step in developing the matrix was the identification of criteria for comprehensive SPI sets from the literature. Literature on both performance measurement generally and sustainability performance evaluation of technical systems specifically was considered, leading to the following three criteria: (i) inclusion of both efficiency and effectiveness indicators, in line with the E^2 performance model defined by O'Donnell and Duffy (2005); (ii) coverage of all sustainability goals governing the technical system (Neely et al., 2002b); and (iii) inclusion of indicators measuring performance at different spatio-temporal scales (Ulgiati et al., 2011). Additionally, definitions of key terms involved in performance assessment were identified from the literature. In particular, the terms "SPI," "indicator" and "metric" have thus far been used synonymously to refer to some quantitative or qualitative measure of a system's sustainability performance in this thesis. However, they were more rigorously defined during the literature study to ensure consistency. The key definitions identified were as follows:

- *performance* refers to the efficiency and effectiveness of an activity (Neely et al., 2002a; O'Donnell and Duffy, 2005);
- *efficiency* is the ratio of what has been materially gained to what has been used, whilst *effectiveness* is the degree to which a goal has been met (O'Donnell and Duffy, 2005);
- *performance measurement* is the process of quantifying the efficiency and effectiveness of an activity (Neely et al., 2002a, b);
- a *performance indicator* is taken to be a parameter used to quantify the efficiency or effectiveness of an activity (Neely et al., 2002b);
- a *performance metric* is defined here as a specification for a broadly based performance indicator (Neely et al., 2002a); and
- a *measure* is considered to be an item of data required to compute a value for an indicator (Duffy, 2005).

The S-Cycle Performance Matrix is presented in Figure 7-11. A key to the abbreviations used is provided in Table 7-4. As shown, it is comprised of three basic elements: a set of generic sustainability goals for technical systems; a corresponding set of SPI archetypes for measuring efficiency and effectiveness against the goals; and associated metrics and measures for each SPI archetype. As shown in Figure 7-11, the scale(s) at which the measures comprising each metric may be evaluated is also indicated in the matrix. That is, local, regional, and/or global as discussed in Chapter 4 (Section 4.3.1). For example, the production of waste by a technical system may be assessed over the full life cycle, accounting for waste associated with the extraction, manufacturing, operation, and end of life phases. That is, waste production may be assessed at the global scale. In contrast, intended output is produced directly by the technical system during the operation phase only and thus, cannot be measured across the full life cycle. In other words, it can only be measured at the local scale.

To develop the matrix, generic sustainability goals for technical systems were firstly derived from the S-Cycle model. An initial set of SPI archetypes and associated metrics and measures relating to each goal was then defined on the basis of: (i) the behavioural aspects described in the S-Cycle model; and (ii) the efficiency and effectiveness definitions identified from the literature (outlined above). To evaluate this initial set, an analysis of 324 indicators identified from the literature sample presented in Table 6 of Paper B (Appendix 2) was conducted. The full list of indicators is presented in Appendix 7A (Table A7- 1). As shown in Table A7- 1, the indicators were associated with a combination of: (i) *ad hoc* evaluation approaches; and (ii) formal evaluation methods commonly applied to technical systems (discussed in Chapter 4), namely energy analysis, embodied energy analysis, emergy accounting, exergy analysis, life cycle assessment, and material flow analysis. Additionally, a limited number of indicators were found to be associated with less common formal methods (again shown in Table A7- 1). Furthermore, the indicators were applied to a broad range of technical systems, classified into seven categories: buildings and structural systems; energy conversion systems; fuel production systems; heating and cooling systems; machining and industrial processing systems; propulsive and transportation systems; and refining and distillation systems.

The analysis sought to determine:

i. whether the indicators currently applied to evaluate the sustainability performance of technical systems could be classified with respect to the proposed SPI archetypes and metrics; and
ii. whether there are any indicators currently applied to technical systems that are not described in the performance matrix, which may be suggestive of additional SPI archetypes, metrics, and potentially even sustainability goals.

The analysis was captured in a spreadsheet – an excerpt from this is presented in Appendix 7B. The findings of the analysis are discussed in Chapter 8.

Table 7-4: Abbreviations used in the S-Cycle Performance Matrix

Abbreviation	Meaning
S-Cycle abbreviations:	
IO	Intended output
PR	Passive resource
P-IR	Passive intended resource
P-NRR	Non-renewable passive resource
P-RR	Renewable passive resource
W	Waste
Performance abbreviations:	
ε	Effectiveness
η	Efficiency
Subscripts:	
L	Denotes a measure that may be evaluated at the local scale.
R	Denotes a measure that may be evaluated at the regional scale.
G	Denotes a measure that may be evaluated at the global scale.
Other:	
t	Time
t_{max}	Denotes the maximum time period a metric may be evaluated over.

Generic sustainability goals	ε/η	SPI archetypes	Metrics	S-Cycle metric definitions	Full metric definition
PRODUCE IO	ε	IO production	Absolute IO output	IO_L	Amount of IO produced over some time period (t_{max} = full operation phase).
			IO production rate	IO_L/t	Amount of IO produced per unit of time (t_{max} = full operation phase).
MINIMISE OVERALL RESOURCE USE	ε	Resource consumption	Absolute PR input	$PR_{L,R,G}$	Amount of PR consumed over some time period, including both renewable and non-renewable PR (t_{max} = full life cycle).
			PR consumption rate	$PR_{L,R,G}/t$	Amount of PR consumed per unit of time, including both renewable and non-renewable PR (t_{max} = full life cycle).
	η	Resource efficiency	Resource intensity	$PR_{L,R,G}/IO_L$	Amount of PR consumed per unit of IO produced over some time period (t_{max} = full life cycle).
			Resource productivity	$IO_L/PR_{L,R,G}$	Amount of IO produced per unit of PR consumed over some time period (t_{max} = full life cycle).
MINIMISE NRR USE	ε	NRR consumption	Absolute NRR input	$P\text{-}NRR_{L,R,G}$	Amount of non-renewable PR consumed over some time period (t_{max} = full life cycle).
			NRR consumption rate	$P\text{-}NRR_{L,R,G}/t$	Amount of non-renewable PR consumed per unit of time (t_{max} = full life cycle).
			NRR fraction	$P\text{-}NRR_{L,R,G}/PR_{L,R,G}$	Fraction of PR consumed over some time period that is non-renewable (t_{max} = full life cycle).
	η	NRR efficiency	NRR intensity	$P\text{-}NRR_{L,R,G}/IO_L$	Amount of non-renewable PR consumed per unit of IO produced over some time period (t_{max} = full life cycle).
			NRR productivity	$IO_L/P\text{-}NRR_{L,R,G}$	Amount of IO produced per unit of non-renewable PR consumed over some time period (t_{max} = full life cycle).
MINIMISE RR USE	ε	RR consumption	Absolute RR input	$P\text{-}RR_{L,R,G}$	Amount of renewable PR consumed over some time period (t_{max} = full life cycle).
			RR consumption rate	$P\text{-}RR_{L,R,G}/t$	Amount of renewable PR consumed per unit of time (t_{max} = full life cycle).
			RR fraction	$P\text{-}RR_{L,R,G}/PR_{L,R,G}$	Fraction of PR consumed over some time period that is renewable (t_{max} = full life cycle).
	η	RR efficiency	RR intensity	$P\text{-}RR_{L,R,G}/IO_L$	Amount of renewable PR consumed per unit of IO produced over some time period (t_{max} = full life cycle).
			RR productivity	$IO_L/P\text{-}RR_{L,R,G}$	Amount of IO produced per unit of non-renewable PR consumed over some time period (t_{max} = full life cycle).
MAXIMISE SELF-SUFFICIENCY	ε	IR production	Absolute passive IR output	$P\text{-}IR_L$	Amount of passive IR produced over some time period (t_{max} = full operation phase).
			Passive IR production rate	$P\text{-}IR_L/t$	Amount of passive IR produced per unit of time (t_{max} = full operation phase).
		IR consumption	Passive IR fraction	$P\text{-}IR_L/PR_L$	Fraction of PR consumed over some time period that was self-produced (t_{max} = full operation phase).
MINIMISE WASTE PRODUCED	ε	W production	Absolute W output	$W_{L,R,G}$	Amount of W produced over some time period (t_{max} = full life cycle).
			W intensity	$W_{L,R,G}/IO_L$	Amount of W produced per unit of IO produced over some time period (t_{max} = full operation phase).
			W production rate	$W_{L,R,G}/t$	Amount of W produced per unit of time (t_{max} = full life cycle).
	η	Resource inefficiency	Wastefulness	$W_L/PR_{L,R,G}$	Amount of W produced per unit of PR consumed over some time period (t_{max} = full operation phase).

Figure 7–10: The S-Cycle Performance Matrix

Figure 7-11: The S-Cycle Performance Matrix

7.4 Summary

This chapter has described the approach adopted to evaluate the S-Cycle model. This approach consisted of four elements, and involved three researchers in various capacities i.e. the author, and two Masters students (Student A and Student B). The approach is summarised below and in Table 7-5.

- Two worked examples, WE1 and WE2, which were produced by the author and Student B, respectively (Section 7.1.2). These provided a basic demonstration of the model, and its use alongside a guideline developed to support its application to a system. They involved application of the model to a bioethanol production system (WE1) and an engine (WE2).
- Three case studies (CS1, CS2, and CS3) involving application of the model to different technical systems in industry (Section 7.1.3). All of the systems studied represent sub-systems of a warship. The S-Cycle guideline was developed to support the application of the model and to foster a consistent approach among the three researchers conducting the studies (Section 7.1.1). CS1 was carried out by Student A in collaboration with Babcock Marine, and involved application of the model to two different types of HVAC system to determine the most sustainable option. CS2 was carried out by the author while based within BAE Systems, and involved application of the model to interpret the behaviour of a CW system from a sustainability perspective. Finally, CS3 was conducted by Student B in collaboration with BAE Systems, and involved the definition of SPIs for the CW plant sub-system of the CW system, and the development of a quantitative model to evaluate them. The outcomes of CS2 formed the basis for this work. An analysis of the documentation produced during CS1, CS2, and CS3 was conducted in order to draw conclusions regarding the evaluation of the model.
- A pilot study with three engineering design researchers, followed by appraisal of the model by engineering designers at two interactive workshops (WS1 and WS2) involving a practical exercise and self-report questionnaire (Section 7.2). WS1 was held at BAE Systems with 11 engineering designers from the company, collectively holding over 250 years of experience. WS2 was held at the University of Strathclyde as part of a continuing professional development course delivered to Company A, with 16 engineering designers participating. Collectively, this group held over 175 years of experience.
- An analytical study where the model was used to develop a generic classification of SPIs for technical systems, known as the S-Cycle Performance Matrix (Section 7.3). The matrix is comprised of three basic

elements: (i) a set of generic sustainability goals for technical systems, derived from the model; (ii) a corresponding set of SPI archetypes for measuring efficiency and effectiveness against the goals; and (iii) associated metrics and measures for each SPI archetype. The proposed set of SPI archetypes and associated metrics and measures was evaluated through an analysis of 324 indicators identified from the sustainability performance evaluation literature (the full list is presented in Table A7-1 of Appendix 7A).

The findings obtained from the evaluation are discussed in Chapter 8.

Table 7-5: Summary of evaluation approach

Element of approach	System studied	Complexity	Model user(s)	Outcomes
Worked examples	Bioethanol production system (WE1)	IV	Author	• visual interpretation of system behaviour from S-Cycle perspective • set of sustainability goals • set of SPIs
	Car engine (WE2)	III	Student B	• visual interpretation of system behaviour from S-Cycle perspective • set of sustainability goals • set of SPIs • suggested actions to improve sustainability performance
Case studies	HVAC system (CS1)	III	Student A	• textual interpretation of system behaviour from S-Cycle perspective • set of sustainability goals • set of SPIs and SPI values • set of performance improvement targets • suggested actions to improve performance
	CW system (CS2)	III	Author	• visual and textual interpretation of system behaviour from S-Cycle perspective
	CW plant system (CS3)	III	Student B	• set of sustainability goals • set of SPIs and SPI values • quantitative model of system behaviour • suggested actions to improve sustainability performance
Practical exercise	4½" gun on warship (WS1)	III	WS1 participants	• examples of S-Cycle model elements from systems studied (recorded on A3 templates) • observations on the use of the model by engineering designers
	Cold water distribution system (WS1)	III		
	Diesel generator	III		
	Gas turbine (WS1)	III		
	Transformer (WS2)	II	WS2 participants	
	Wind turbine (WS2)	IV		
Questionnaire	------------------------	-------------	-------------	• expert opinions on the model
SPI study	------------------------	-------------	Author	• a generic classification of SPIs for technical systems

8 Evaluation findings

In Chapter 7, the approach adopted to evaluate the S-Cycle model was described. This consisted of two worked examples (WE1 and WE2), three case studies (CS1, CS2, and CS3), a pilot study followed by two interactive workshops with engineering designers (WS1 and WS2), and an analysis of SPIs for technical systems. In this chapter, the findings of the evaluation with respect to three aspects of the model and its use outlined in Chapter 7 are reported. That is: (i) validity (Section 8.1); (ii) utility (Section 8.2); and (iii) applicability (Section 8.3). A summary of the chapter is provided in Section 8.4. Note that the objective of this chapter is to present the findings of the evaluation – their significance is discussed in Chapter 9.

8.1 Validity

To address issue I3 identified in Chapter 5, i.e. the lack of a fundamental formalism of sustainability, the S-Cycle must be validated as a formal representation of sustainability as discussed in Chapter 7. Validity in this thesis refers to the degree to which the elements and relationships comprising the S-Cycle can be considered to model the behaviour of a technical system from a sustainability perspective. To evaluate validity, evidence demonstrating whether or not the model elements and relationships are reflected in the behaviour of technical systems was sought. Two types of data were considered to constitute evidence in this respect: (i) examples of the behaviour of technical systems in industry, identified from e.g. technical specifications and the function model developed during CS2; and (ii) the opinions of technical systems experts in industry on the validity of the model elements and relationships. Evidence of this nature gathered through the research methods outlined in Chapter 7 is presented in the following sub-sections. The elements and relationships that were tested during evaluation are summarised in Table 8-1. As shown, the elements may be categorised as follows:

- *stock elements*, representing accumulations of non-renewable and renewable resources (E9 and E10);
- *input elements*, representing the inputs of passive and active resources to the technical system activity (E1 – E4); and
- *output elements*, representing the outputs of intended resources, intended output, and waste from the activity (E5 – E8).

The relationships consist of:

- a relationship between the technical system activity as a whole and the wider system of interest (RS1);

- relationships among the different input and output elements involved in the activity (RS2, RS3, and RS4); and
- relationships between the individual input and output elements and the stock elements (RS5 – RS11).

The findings of the evaluation with respect to the elements and relationships listed in Table 8-1 are presented in detail in the following sub-sections. Sections 8.1.1 and 8.1.2 focus on evidence to support the elements and relationships currently described in the model, whilst Section 8.1.3 focuses on additional elements and relationships identified during evaluation. With respect to Sections 8.1.1 and 8.1.2, Table 8-2 provides an overview of the degree to which each element and relationship was found to be supported. A tick indicates that support was identified, dashes indicate that no support was identified, and a slash indicates that the element/relationship was found to be partially supported. As shown, all were found to be supported to some extent, although support for E5 (i.e. A-IR) and RS9 (i.e. IO produced by a technical system activity contributes to NRR stocks within a wider SoI) was considerably less substantial than support for other elements and relationships.

As discussed in Chapter 7 (Section 7.2), workshop participants carrying out the practical exercises were instructed to indicate any aspects of the model that they disagreed with or felt were incomplete by annotating the model provided on their A3 response template. During analysis of the completed templates (Appendix 10B), it was observed that all groups were able to apply the model to a technical system, and none of the participants indicated disagreement with any part of the model. Therefore, the outcomes of the practical exercise from both WS1 and WS2 may be considered to provide support for all model elements and relationships as shown in Table 8-2. The completed response templates also yielded specific examples of certain elements and relationships, which are highlighted in the sub-sections below. Additionally, in the questionnaire delivered at the workshops, participants were provided with the opportunity to make comments on the model via open response boxes that accompanied the Likert scales (discussed in Section 8.2). None of the respondents from WS1 or WS2 indicated any disagreement with the model elements and relationships. As such, the questionnaire responses may also be considered to provide support for all elements and relationships as shown in Table 8-2.

Table 8-1: Model elements and relationships tested during evaluation

	Description	Identifier
Elements	Non-renewable active resources (NR-AR)	E1
	Non-renewable passive resources (NR-PR)	E2
	Renewable active resources (R-AR)	E3
	Renewable passive resources (R-PR)	E4
	Active intended resources (A-IR)	E5
	Passive intended resources (P-IR)	E6
	Intended output (IO)	E7
	Waste (W)	E8
	Non-renewable resource stocks (NRR stocks)	E9
	Renewable resource stocks (RR stocks)	E10
Relationships	A technical system (TS) activity operates within a wider system of interest (SoI).	RS1
	In a TS activity, R-AR and/or NR-AR use R-PR and/or NR-PR to produce IR, IO, and/or W.	RS2
	A-IR produced by a TS activity is used directly in the activity.	RS3
	P-IR produced by a TS activity is used directly in the activity.	RS4
	NR-AR involved in a TS activity originate from NRR stocks within a wider SoI.	RS5
	NR-PR involved in a TS activity originate from NRR stocks within a wider SoI.	RS6
	R-AR involved in a TS activity originate from RR stocks within a wider SoI.	RS7
	R-PR involved in a TS activity originate from RR stocks within a wider SoI.	RS8
	IO produced by a TS activity contributes to NRR stocks within a wider SoI.	RS9
	IO produced by a TS activity contributes to RR stocks within a wider SoI.	RS10
	W produced by a TS activity contributes to RR stocks within a wider SoI.	RS11

Table 8-2: Degree of support for the model elements and relationships

ID	Element of evaluation approach								
	Worked examples		Case studies			Practical exercise		Questionnaire	SPI analysis
	WE1	WE2	CS1	CS2	CS3	WS1	WS2		
Input elements:									
E1	---	---	---	✓	---	✓	✓	✓	/
E2	✓	✓	/	✓	---	✓	✓	✓	✓
E3	✓	✓	---	✓	---	✓	✓	✓	/
E4	✓	✓	/	✓	✓	✓	✓	✓	✓
Output elements:									
E5	---	---	---	---	---	✓	✓	✓	---
E6	---	---	---	✓	---	✓	✓	✓	✓
E7	✓	✓	✓	✓	---	✓	✓	✓	✓
E8	✓	✓	✓	✓	✓	✓	✓	✓	✓
Stock elements:									
E9	✓	---	---	✓	---	✓	✓	✓	---
E10	✓	---	---	✓	---	✓	✓	✓	---
Relationships:									
RS1	✓	---	---	✓	✓	✓	✓	✓	---
RS2	✓	✓	✓	✓	✓	✓	✓	✓	✓
RS3	---	---	---	---	---	✓	✓	✓	---
RS4	---	---	---	✓	---	✓	✓	✓	---
RS5	---	---	---	✓	---	✓	✓	✓	---
RS6	✓	---	---	✓	---	✓	✓	✓	---
RS7	✓	---	---	✓	---	✓	✓	✓	---
RS8	✓	---	---	✓	---	✓	✓	✓	---
RS9	---	---	---	---	---	✓	✓	✓	---
RS10	✓	---	---	✓	---	✓	✓	✓	---
RS11	✓	---	---	✓	---	✓	✓	✓	---

8.1.1 Model elements

As noted in the introduction to Section 8.1 and illustrated in Table 8-2, all model elements were found to be supported by the evaluation, albeit to varying extents. Supporting evidence identified for each type of element is presented in the following sections. That is, input elements (Section 8.1.1.1), output elements (Section 8.1.1.2), and stock elements (Section 8.1.1.3) as discussed above.

8.1.1.1 Input elements

All four input elements were found to be supported by the evaluation, albeit in varying degrees as shown in Table 8-2. That is, NR-AR (E1), NR-PR (E2), R-AR (E3), and R-PR (E4). Illustrative examples from the systems studied in different parts of the evaluation approach are presented in Table 8-3. Firstly, it may be seen in Table 8-2 that NR-AR (E1) was found to be supported less broadly than the other input elements. However, several examples were identified during CS2 and from the outcomes of the practical exercises delivered during WS1 and WS2. Additionally, the SPI analysis provided partial support for this element as discussed below. Support for NR-PR (E2) was identified from all parts of the approach with the exception of CS3. Both CS1 and CS3 also failed to provide supporting evidence for R-AR (E3), which was supported by findings from all other parts of the approach. Finally, as shown in Table 8-2, R-PR (E4) was found to be broadly supported.

It should be highlighted that in certain cases, only partial support for input elements was identified as illustrated in Table 8-2. For instance, in CS1, Student A interpreted electrical power and refrigerant as passive resources used by the HVAC system. However, they did not indicate whether these are renewable or non-renewable. Thus, the existence of passive resources is supported, but their nature as non-renewable or renewable is not. During the SPI analysis, an indicator that appears to focus on the consumption of active resources during the operation phase of the life cycle was identified. Rotella et al. (2012) evaluate the sustainability performance of a hard machining system. Among their indicators is one termed “wear rate,” measuring the amount of material worn off of the cutting tool per minute during operation. With respect to the activity carried out by the machining system, the cutting tool may be viewed as an active resource. That is, it transforms passive resources (e.g. a workpiece) into an output (e.g. a machined component). However, once again, the authors did not indicate the degree of renewability of the resource being consumed (i.e. the cutting component of the system). Therefore, the indicator may be seen to support the existence of active resources, but not their nature as non-renewable or renewable.

8.1.1.2 Output elements

As with the input elements discussed in Section 8.1.1.1, all four output elements were found to be supported by the evaluation in varying degrees, as shown in Table 8-2. That is, A-IR (E5), P-IR (E6), IO (E7), and W (E8). However, although A-IR (E5) was supported by the practical exercises and questionnaire delivered during WS1 and WS2 as discussed above, no specific examples of this element were identified from any of the systems studied. Illustrative examples of the other output elements are presented in Table 8-4.

Table 8-3: Examples of input elements from the systems studied during evaluation

Technical system	SoI	E1	E2	E3	E4
WE1:					
Bioethanol production system	Earth system	---------------	Coal	Enzymes	Water
WE2:					
Car engine	Earth system	---------------	Petrol	Machinery	Air
CS1:					
HVAC system	Unclear	---------------	Refrigerant (NRR/RR not specified)	---------------	Refrigerant (NRR/RR not specified)
CS2:					
CW system	Ship at sea	CW plant equipment	Control interface	Human operators	Sea water flow
CS3:					
CW plant system	Ship at sea	---------------	---------------	---------------	Refrigerant
WS1 practical exercise:					
Gas turbine	Ship's propulsion system	Major turbine components	---------------	Human operators	Air
Cold water distribution system	Ship at sea	Pump motor	Lubricants	Human operators	Sea water
4½" gun	Ship at sea	Servos	Ammunition	Human operators	Manual controls
Diesel generator	Ship's power generation system	Pipework	Lubricating oil	Human operators	Sea water
WS2 practical exercise:					
Wind turbine	Global ecosystem	Major turbine components	Diesel	Human operators	Wind
Transformer	Wind turbine	Transformer components	Oil	Human operators	Air

It may be seen in Table 8-2 that both IO (E7) and W (E8) were found to be broadly supported across all parts of the evaluation approach. In contrast, supporting evidence for P-IR (E6) was only identified from CS2, the practical exercises, and the indicator analysis. Furthermore, the number of examples identified in each case was rather limited. For instance, only a single example of P-IR emerged during CS2: oil extracted from the refrigerant flow leaving the compressors in the CW plants, which is then reused as a passive resource in the compressor's activity (discussed further in Section 8.1.2.2). Similarly, during the SPI analysis, just one indicator focusing on P-IR was found in the analysis sample, i.e. the recoverable exergy ratio applied by Aydin et al. (2013) to assess the sustainability performance of a turboprop aircraft. During the practical exercises at both workshops, certain groups of participants provided examples of P-IR. However, these were again rather limited in comparison to examples provided for other output elements.

8.1.1.3 Stock elements

Both stock elements were found to be supported by the evaluation. That is, NRR stocks (E9) and RR stocks (E10). As shown in Table 8-2, evidence to support these elements did not emerge from every part of the evaluation approach. Nonetheless, several examples of renewable and non-renewable stocks may be found in WE1, which focused on a bioethanol production system operating within the global ecosystem. For instance, RR stocks were found to include stocks of air, corn, enzymes, labour, machinery, and water. An NRR stock of coal was also identified. Likewise, a number of examples of both types of stock element were identified during CS2, which focused on a CW system operating within a warship at sea. For instance:

- the ship's staff was interpreted as a RR stock, since personnel may be brought on board whilst the ship is at sea;
- the stock of diesel in the ship's fuel tank was interpreted as an artificial RR stock, since the ship can be refuelled at sea;
- the sea the ship sails on, and the atmosphere surrounding it, were interpreted as natural RR stocks since they regenerate over time in response to consumption; and
- the stock of CW system equipment aboard the ship, including both active and redundant[9] equipment, was interpreted as an artificial NRR stock since the equipment cannot be replaced whilst the ship is at sea.

Thus, although NRR stocks and RR stocks were not found to be broadly supported across all parts of the evaluation approach, those parts that did yield evidence provided numerous examples.

8.1.2 Model relationships

As noted in the introduction to Section 8.1 and illustrated in Table 8-2, all model relationships were found to be supported by the evaluation, albeit to varying extents. These consist of: (i) a relationship between the technical system activity as a whole and the wider system of interest (RS1); (ii) relationships among the different input and output elements involved in the activity (RS2, RS3, and RS4); and (iii) relationships between the individual input and output elements and the stock elements (RS5 – RS11). Each of these categories is discussed in turn below.

[9] A number of the systems comprising a warship, including the CW system studied in CS2, are designed to contain redundant components so that their functioning can be maintained in the event of damage or failure whilst the ship is at sea and therefore not easily accessible for repair.

Table 8-4: Examples of output elements from the systems studied during evaluation

Technical system	SoI	E5	E6	E7	E8
WE1:					
Bioethanol production system	Earth system	--------------	--------------	Ethanol	Greenhouse gases
WE2:					
Car engine	Earth system	--------------	--------------	Mechanical power	Heat energy
CS1:					
HVAC system	Unclear	--------------	--------------	Cooling power	Carbon dioxide emissions
CS2:					
CW system	Ship at sea	--------------	Oil re-injected to compressor	Chilled water flow	Energy losses
CS3:					
CW plant system	Ship at sea	--------------	--------------	--------------	Refrigerant losses
WS1 practical exercise:					
Gas turbine	Ship's propulsion system	--------------	--------------	Rotational energy	Combustion by-products
Cold water distribution system	Ship at sea	--------------	Pump output pressure	Fresh water flow	Energy losses
4½" gun	Ship at sea	--------------	--------------	Motion of shell	Heat energy
Diesel generator	Ship's power generation system	--------------	Rotation to drive compressor	Shaft rotation	Exhaust gases
WS2 practical exercise:					
Wind turbine	Global ecosystem	--------------	Electricity used on-site	Electrical energy	Energy losses
Transformer	Wind turbine	--------------	Reused oil	Voltage level	Heat energy

8.1.2.1 Relationship between technical system activity and wider SoI

WE1, case studies CS2 and CS3, and the practical exercises delivered at both WS1 and WS2 were found to support RS1, i.e. *the operation of a technical system within the boundary of a wider SoI*. Firstly, in WE1, the model was applied to a bioethanol production system modelled by Ulgiati et al. (2011). The authors highlight that the system activity is dependent on a number of resource stocks external to the system *per se*, e.g. stocks of coal, water, corn, goods and machinery, and labour. To apply the S-Cycle model to the system, the boundary of the SoI was defined to include both the bioethanol production system and the supporting stocks (as shown in Figure 7-5 in Chapter 7).

Secondly, it was found during CS2 that the CW system activity was also dependent on a number of resource stocks and systems external to the system *per se*, e.g.:

- electricity to power the pumps and compressors (i.e. PR) was delivered by the ship's diesel generators, which in turn depend on a stock of diesel in the ship's fuel tank;
- demineralised water, used as the cooling medium (i.e. PR), was replenished from a stock of water in a storage tank serving several other systems on board; and
- sea water used to cool the condensers (i.e. PR) was drawn from the sea, which may be viewed as a natural resource stock external to both the CW system and the ship.

Furthermore, the CW system was observed to interact with the wider ship, as well as the sea and atmosphere surrounding it, via its outputs e.g.:

- the flow of chilled water produced by the CW system (i.e. IO) passes through other systems aboard the ship, such as the HVAC system and weaponry, where it is used as a cooling medium;
- the air removed from the system by vacuum degassers (i.e. W) is vented to the atmosphere; and
- waste heat carried back to the CW system from other equipment by the chilled water flow is carried by a flow of sea water (i.e. IO) overboard to the sea.

The boundary of the SoI in CS2 was defined to include the CW system plus the rest of the ship, the sea it sails on, and the atmosphere surrounding it.

Thirdly, during CS3, Student B defined a set of SPIs for the CW plant sub-system of the CW system studied in CS2. To facilitate evaluation of these SPIs, it was necessary for the student to develop a quantitative model. This model included variables relating to the performance of the CW plant sub-system (e.g. cooling capacity), but also variables relating to the performance of the wider CW system (e.g. chilled water flow rate) and its power source, a diesel generator (e.g. power output). In other words, the CW plant sub-system interacts with other systems on the ship during its operation, and its performance is affected by the performance of these systems.

Finally, all groups of participants who completed the practical exercise during both WS1 and WS2 were successfully able to identify a wider system within which their chosen technical system operated. This may be seen to provide further support for RS1 in addition to the evidence outlined above. The SoI boundaries defined during the exercises are summarised in Table 8-5

Table 8-5: SoI boundaries defined by workshop participants during practical exercise

Group	Participants	Technical system	SoI
WS1:			
1	PW1-1 PW1-5 PW1-8	Gas turbine	Ship's propulsion system
2	PW1-3 PW1-9	Cold water distribution system	Ship at sea
3	PW1-4 PW1-7 PW1-10	4½" gun	Ship at sea
4	PW1-2 PW1-6 PW1-11	Diesel generator	Ship's power generation system
WS2:			
1	PW2-7 PW2-9 PW2-10 PW2-12 PW2-14 PW2-15	Wind turbine	Global ecosystem
2	Not stated	Transformer	Wind turbine
3	Not stated	Wind turbine	Wind farm

8.1.2.2 Relationships among input and output elements

As shown in Table 8-2, RS2 was found to be supported by all parts of the evaluation approach. That is, *in a technical system activity, R-AR, NR-AR, and/or A-IR use R-PR, NR-PR, and/or P-IR to produce IR, IO, and/or W*. Table 8-6 presents several examples of activities involving different combinations of the aforementioned elements, identified from WE1, WE2, CS2, and the practical exercises carried out at WS1 and WS2. As highlighted in Section 8.1.1, no specific examples of the element A-IR (E5) were identified during the evaluation. Nonetheless, when viewed holistically, the example activities described in Table 8-6 may be seen to largely support RS2. Further support was found to emerge from the SPI analysis, where certain authors were observed to evaluate indicators focusing on multiple input and output elements for a single technical system. For instance, Aydin et al. (2013) evaluate the following indicators for a turboprop aircraft:

- Exergy efficiency, defined as the ratio of total useful exergy output to total exergy input. Useful exergy output may be viewed as IO in relation to the aircraft's activity, whilst the exergy input may be viewed as a passive resource.
- Waste exergy ratio, defined as the ratio of total waste exergy to total inlet exergy. Waste exergy may be viewed as W in relation to the aircraft's activity, whilst the inlet exergy may be viewed as a passive resource.

- Recoverable exergy ratio, defined as the ratio of recoverable exergy to total exergy input – in other words, the ratio of exergy output recovered for reuse in a technical system's activity to the total exergy consumed. The recovered exergy may be viewed as P-IR in relation to the aircraft's activity.

In Table 8-2, it may be seen that support for RS3 and RS4 was significantly less broad than support for RS1 and RS2. That is: *A-IR produced by a technical system activity is used directly in the activity* (RS3); and *P-IR produced by a technical system activity is used directly in the activity* (RS4). No support for these relationships was identified from the worked examples or the SPI analysis. However, both were found to be supported by the practical exercises and questionnaire in the sense that their validity was not questioned, as discussed in the introduction to Section 8.1. The case studies also failed to provide supporting evidence, with the exception of CS2 where one example was identified within the CW system studied. In Section 8.1.1.2, oil extracted from the refrigerant flow leaving the compressors was highlighted as an example of P-IR (E6) in this system. The oil is extracted by the compressor's oil separator, and is then reinjected directly into the compressor crankcase during operation where it serves to lubricate the compressor's internal components. An extract from the CW system function model (included alongside Paper D in Appendix 4) illustrating the compressor's activity and the P-IR relationship between the activity output and input is presented in Figure 8-1.

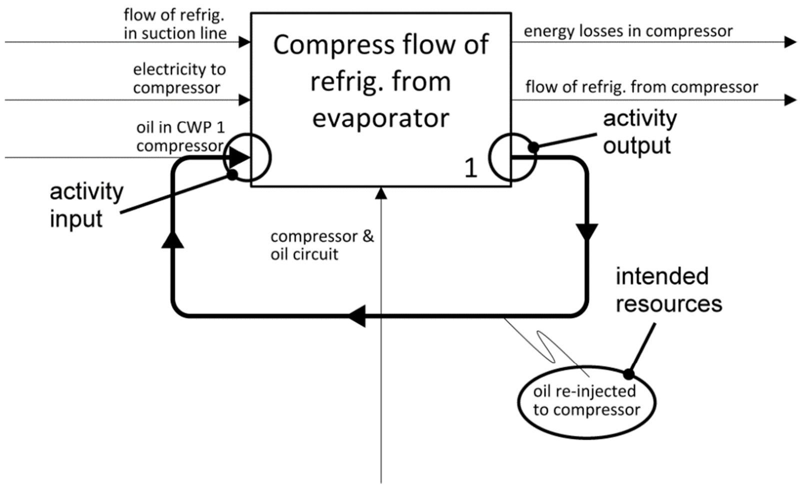


Figure 8-1: Examples of model relationship RS4 from the CW system function model

Table 8-6: Examples of activities identified during evaluation that provide support for model relationship RS2

INPUTS				OUTPUTS		
NR-AR	**NR-PR**	**R-AR**	**R-PR**	**IR**	**IO**	**W**
Bioethanol production (WE1):						
------------	Coal	Air; Corn; Electricity; Goods and services; Water.	Enzymes; Labour; Machinery; Yeasts.	------------	Dried grains; Ethanol.	Greenhouse gases; Solid emissions.
Mechanical power production (WE2):						
------------	Petrol	Machinery	Air	------------	Mechanical power	Greenhouse gases; Heat.
Remove waste heat from equipment aboard ship (CS2):						
Control system; CW system equipment; Heat exchangers.	Control interface	Human operators	Electricity; Fresh water; Oil; Refrigerant; Sea water; Waste heat.	------------	Warm sea water flow	Energy losses; Material losses; Unwanted air.
Compress flow of refrigerant from evaporator (CS2):						
Compressor and oil system	---------	------------	Electricity; Oil; Refrigerant flow.	Oil re-injected to compressor	Flow of refrigerant	Energy losses
Convert hydrocarbon energy to kinetic energy (WS1 practical exercise):						
Major turbine components	---------	Human operators	Air; Electrical power; Fuel.	------------	Rotational energy	Combus-tion by-products; Heat.
Distribute fresh water from reverse osmosis plant to consumers (WS1 practical exercise):						
Control system; Pump casing; Pump impeller; Pump motor.	Lubricants	Human operators	Electricity; Sea water.	Pump output pressure	Fresh water flow	Energy losses
Produce electricity from wind resource (WS2 practical exercise):						
Major turbine components	Diesel; Electricity Oil.	Human operators	Wind	Electricity for on-site usage	Electrical energy	Energy losses; Waste heat; Waste oil.

8.1.2.3 Relationships between input/output elements and stock elements

As discussed in Section 8.1.1.3, evidence supporting the two stock elements of the model, i.e. NRR stocks (E10) and RR stocks (E10), was seen to emerge from WE1, CS2, and the practical exercises delivered during WS1 and WS2. Evidence supporting the relationships between the input/output elements and the stock elements was also provided by these parts of the evaluation, as shown in Table 8-2. No supporting evidence was identified from other parts of the evaluation approach. To recap, the relationships are RS5 – RS11 in Table 8-1, representing the relationships between: (i) passive resource inputs and NRR stocks (RS5 and RS6) or RR stocks (RS7 and RS8); (ii) IO outputs and NRR stocks (RS9) or RR stocks (RS10); and (iii) W outputs and RR stocks (RS11).

As highlighted in the introduction to Section 8.1, support for RS9 was found to be considerably less substantial than support for other relationships. That is, *IO produced by a technical system activity contributes to NRR stocks within a wider SoI.* This relationship was observed to be supported by the practical exercises and questionnaire delivered at WS1 and WS2, in the sense that its validity was not questioned as discussed previously. However, no specific examples were identified during the evaluation. Illustrative examples of the other relationships listed above from the systems studied are presented in Table 8-7 and Table 8-8.

Table 8-7: Examples of relationships RS5 – RS8 from the systems studied during evaluation

Activity	SoI	Resource	Type	Origin within SoI	RS
Bioethanol production system (WE1):					
Bioethanol production	Earth system	Coal	NR-PR	Natural coal stocks	RS6
		Labour	R-AR	Human population	RS7
		Enzymes		Enzyme population	
		Air	R-PR	The atmosphere	RS8
		Water		Rivers and lakes	
		Corn		Corn fields	
CW system (CS2):					
Remove waste heat from equipment aboard ship	Ship at sea	Control system	NR-AR	Stock of CW system equipment aboard ship	RS5
		CW system equipment		Stock of CW system equipment aboard ship	
		Control interface	NR-PR	Stock of CW system equipment aboard ship	RS6
		Human operators	R-AR	Ship's staff (can be replenished at sea)	RS7
		Fresh water	R-PR	Stock of water in storage tank aboard ship	RS8
		Sea water		Sea	
		Refrigerant		Stock of refrigerant aboard ship (can be replenished at sea)	

		Oil		Stock of oil aboard ship (can be replenished at sea)	
		Electricity		Stock of diesel in ship's fuel tank (can be replenished at sea)	
		Waste heat		Stock of diesel in ship's fuel tank (can be replenished at sea)	

Table 8-8: Examples of relationships RS9 – RS11 from the systems studied during evaluation

Activity	SoI	Output	Type	Destination within SoI	RS
Bioethanol production system (WE1):					
Bioethanol production	Earth system	Dried grains	IO	Economic stocks for sale	RS10
		Ethanol			
		Greenhouse gases	W	Atmosphere	RS11
		Solid emissions			
CW system (CS2):					
Remove waste heat from equipment aboard the ship	Ship at sea	Flow of warm sea water overboard	IO	Sea	RS10
		Energy losses	W	CW system surroundings in ship	RS11
		Material losses			
		Unwanted air		Atmosphere	
Circulate cooling medium	Ship at sea	Unwanted air	W	Atmosphere	RS11
		Water losses		CW system surroundings in ship	
		Energy losses			
Chill cooling medium	Ship at sea	Refrigerant losses from CW plants	W	CW system surroundings in ship	RS11
		Energy losses in CW plants			
		Flow of warm sea water overboard		Sea	

8.1.3 Additional elements and relationships

As noted in the introduction to Section 8.1, the validity of the model refers to the degree to which its elements and relationships can be considered to model a technical system's behaviour from a sustainability perspective. In Sections 8.1.1.1 – 8.1.1.3, it was shown that all of the elements and relationships currently described in the model were found to be supported to some extent by the evaluation. Nonetheless, as discussed in Chapter 7, the model may be considered to be validated if it can be demonstrated that it *comprehensively* describes the behaviour of a technical system from a sustainability perspective. That is, if it can be shown that its elements and relationships cover all aspects of a technical system's behaviour that are relevant from a sustainability perspective. As discussed in the introduction to Section 8.1, none of the participants in the workshops indicated any disagreement with the model elements and relationships during the practical exercise and questionnaire. As such, these parts of the evaluation may be considered to suggest that the model can be viewed as comprehensive. However, an additional element (contaminant input) and corresponding relationship were identified during the case studies and SPI analysis – these are outlined in Section 8.1.3.1 below.

Additionally, in Chapter 6 (Section 6.3.3) it was shown that coupling relationships may exist between system activities. For example, the intended output or waste produced by one activity may be used as a passive resource by other activities in the system. Examples of coupling relationships were identified and modelled from a sustainability perspective during CS2 – these are presented in Section 8.1.3.2.

8.1.3.1 Contaminants

As discussed in Chapter 7, CS2 involved the development of a function model of the CW system. This model describes in detail the major activities carried out by the system (see Appendix 4). Each activity in the function model was interpreted using the S-Cycle model, providing support for the majority of the elements and relationships in the latter as shown in Table 8-2 in the introduction to Section 8.1. However, an aspect of behaviour not currently represented in the S-Cycle model was also identified: the consumption of a contaminant input from the wider SoI by the technical system activity. That is, an input that cannot be classified as a passive resource, since it does not contribute to the production of IR or IO. Rather, it appears to be detrimental to the production of these outputs. The example identified from the CW system constituted an unwanted input of air to the system activity from the system's immediate working environment. The air was modelled as a contaminant input to the activity *circulate cooling medium* in the CW system function model (Appendix 4). Figure 8-2 presents an excerpt from the IDEF0 diagram within the function model that describes the sub-activities involved in this parent activity. As shown, the activity carried out by the CW circulation pumps consumes air bubbles alongside its passive resources. These air bubbles cause cavitation within the pumps that reduces the CW flow rate within the system. Reduced flow rate in turn reduces the system's effectiveness at removing heat from equipment aboard the ship (Paper D, Appendix 4). To maintain the correct flow rate, the unwanted air is removed via exposure of the CW flow to a vacuum by a machine known as a vacuum degasser. The vacuum degasser is activated when the air content of the CW flow rises above a predefined threshold level. The air is then vented to the atmosphere as waste.

Figure 8-3 illustrates the proposed contaminant input in the S-Cycle model. The single example of this type of input identified from the CW system (air as discussed above) was found to originate from a RR stock within the wider SoI, i.e. the atmosphere. Although no examples were identified from the evaluation, it is reasonable to suggest that contaminants may also originate from NRR stocks. Thus, relationships between the contaminant input and both NRR and RR stocks are illustrated in Figure 8-3.

CS3 was found to provide further insight into the nature of contaminants. During CS3, Student B defined a set of sustainability goals for the CW plant sub-system of the CW system. Forming part of this set are two waste-focused goals, namely:

- minimise oil losses per hkW; and
- minimise refrigerant losses per hkW

The student noted that the two goals defined "could be improve[d] by adding another performance criteria [i.e. goal] that integrates the notion of environmental impact: Minimise the Global Warming Impact per hkW" (Student B, 2014, p.46). Global warming is widely believed to be caused by the release of excessive greenhouse gases (e.g. carbon dioxide) into the atmosphere, where they interfere with the Earth system's natural temperature regulation processes (Rockström et al., 2009; Ehrlich and Ehrlich, 2013; UNEP, 2012). It may be seen that this involves the same mechanism described above in relation to the CW system. That is, the consumption of a contaminant input (i.e. excessive greenhouse gases) by a system activity (i.e. Earth system temperature regulation) leading to a reduction in the activity's effectiveness (i.e. an inability to maintain a stable global temperature). Thus, the additional goal suggested by Student B may be seen to suggest that the potential for a system activity's W outputs to act as contaminant inputs in other activities may be important from a sustainability perspective. A number of impact indicators identified during the SPI analysis may be seen to support this notion, appearing to focus on the potential for system activity outputs to interfere in natural activities. For instance, the indicators acidification potential and eutrophication potential appear to assess the potential for a system activity's outputs to disrupt the natural processes of pH regulation and nutrient cycling, respectively (Urban et al., 2010; Stupak et al., 2011; UNEP, 2012).

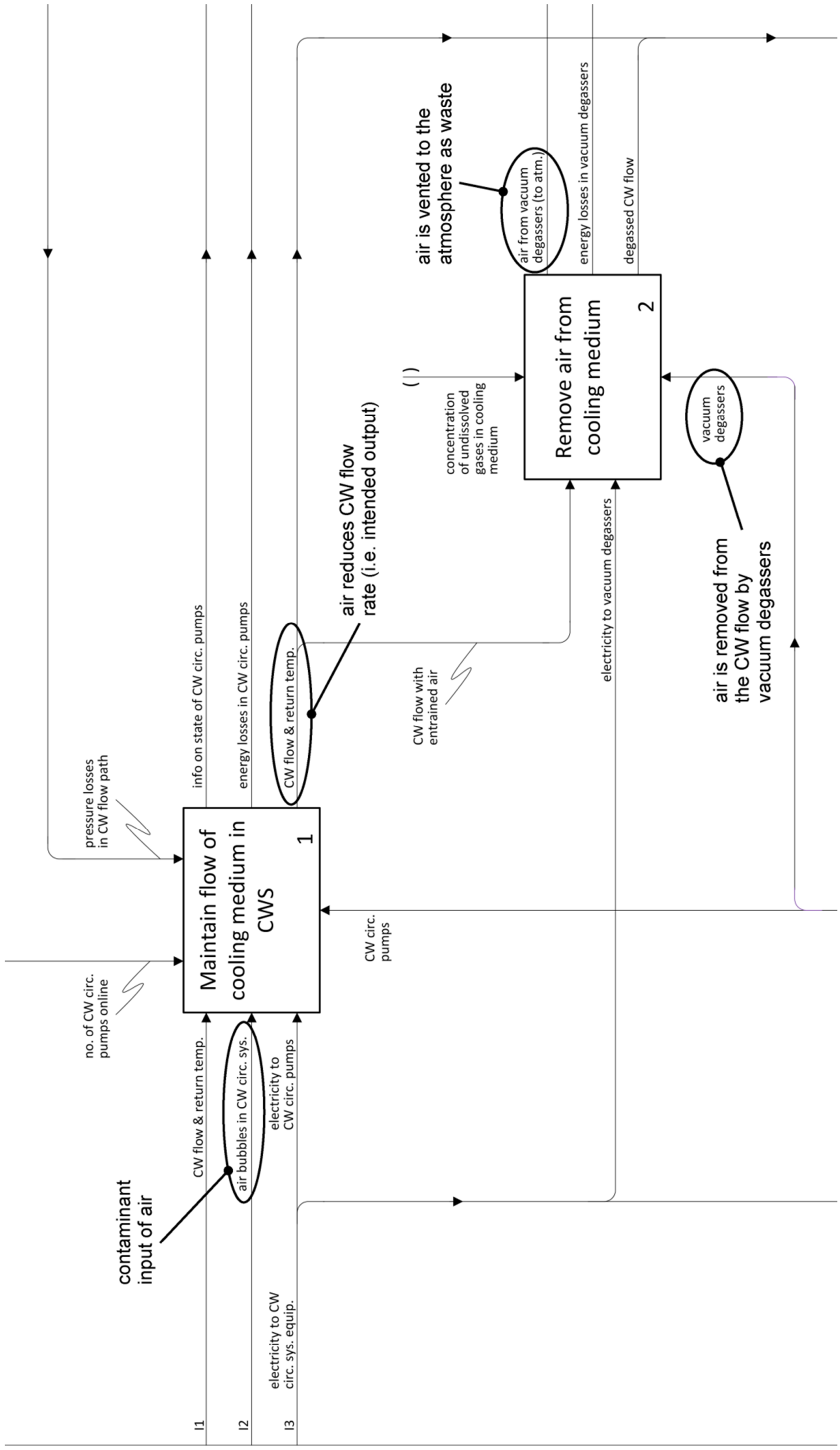


Figure 8-2: Consumption of a contaminant input of air by a CW system activity

Figure 8-2: Consumption of contaminant input of air by a CW system activity

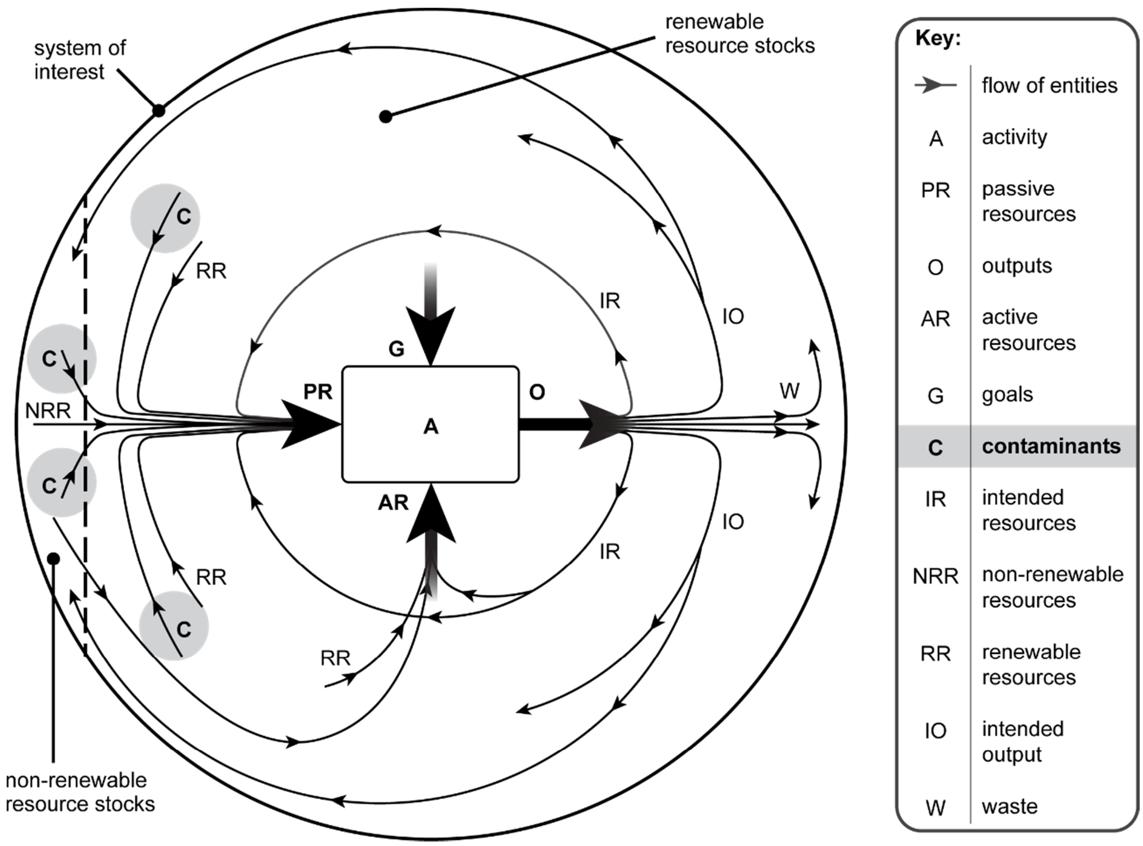


Figure 8-3: The S-Cycle model with proposed contaminant inputs

8.1.3.2 Activity coupling relationships

In Chapter 6, it was shown that coupling relationships may exist between different activities operating within a particular SoI. Four different types of coupling relationship were proposed based on the literature:

(i) the use of one activity's IO as PR in another activity;
(ii) the use of one activity's IO as AR in another activity;
(iii) the use of one activity's W as PR in another activity; and
(iv) the use of one activity's W as AR in another activity.

The S-Cycle model describes the behaviour of a technical system operating within a wider SoI using an activity formalism. CS2 demonstrated that this activity may be decomposed using other tools, such as the IDEF0 modelling language, to identify sub-activities and the coupling relationships among them. The S-Cycle model may then be applied to each sub-activity individually, to interpret its behaviour from a sustainability perspective. Applying this process to the CW system during CS2 led to the identification of a number of instances of coupling relationship (i), as discussed below.

Figure 8-4 and Figure 8-5 overleaf present excerpts from the S-Cycle interpretation of the CW system function model (Appendix 4), illustrating the above relationships. Figure 8-4 presents an excerpt from the A0 diagram, which illustrates the major activities carried out by the CW system. As shown, the IO produced by activity 3 contributes to the passive resources used by activity 4, and the IO produced by activity 4 is used as a passive resource by activity 5. Figure 8-5 presents an excerpt from the A511 diagram, which illustrates the activities carried out by the high pressure equipment within one of the CW plants. It may be seen that: (i) the IO produced by activity 1 is used as a passive resource by activity 2; (ii) the IO produced by activity 2 is used as a passive resource by activity 3; and (iii) the IO produced by activity 3 is used as a passive resource by activity 4.

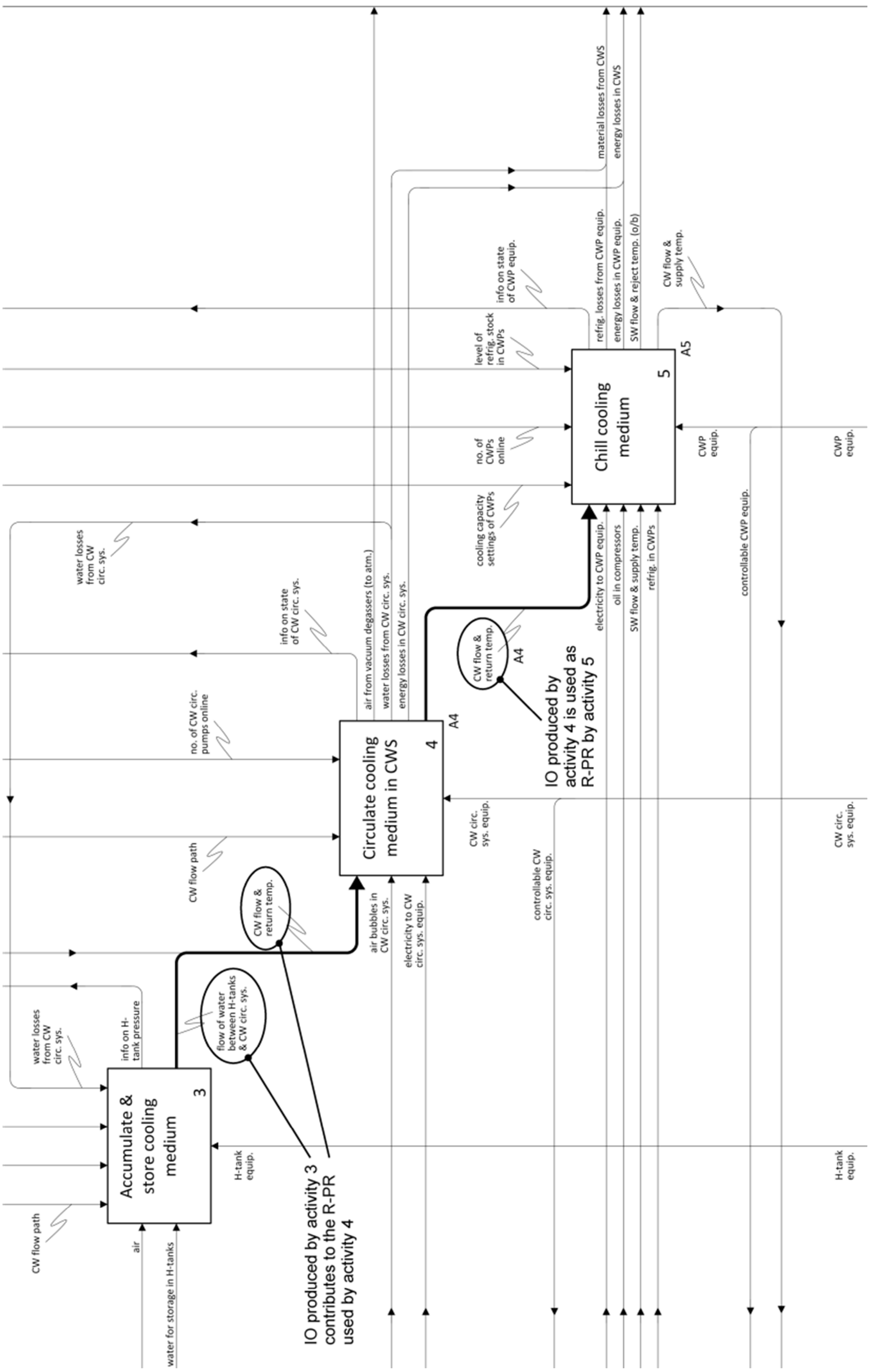


Figure 8-4: Examples of activity interrelationships from the CW system function model – A0 diagram

Figure 8-4: Examples of activity interrelationships from the CW system function model – A0 diagram

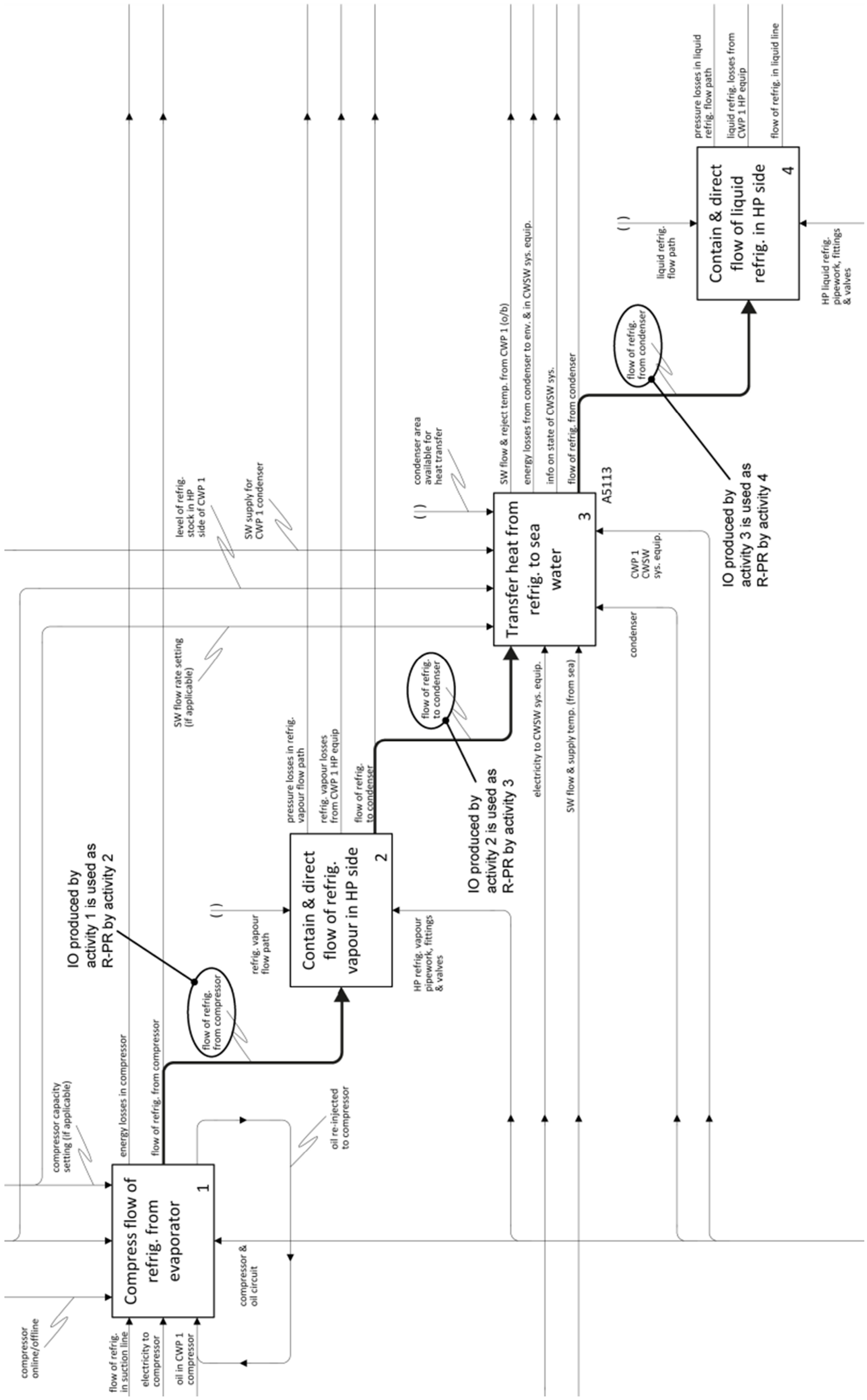


Figure 8-5: Examples of activity interrelationships from the CW system function model – A511 diagram

Figure 8-5: Examples of activity interrelationships from the CW system function model – A511 diagram

8.2 Utility

To address issue I2 identified in Chapter 5, i.e. the lack of a common approach for identifying appropriate SPIs for technical systems, it must be demonstrated that the S-Cycle can be used to identify appropriate SPIs in this context as discussed in Chapter 7. Furthermore, it must be demonstrated that the model can be understood and applied by its intended users, e.g. engineering designers. In Chapter 7, the term utility was outlined as encompassing both of these aspects. The findings of the evaluation with respect to the utility of the S-Cycle model are discussed in the following sub-sections.

As discussed in Chapters 3 and 6, identifying SPIs involves the interpretation of a system's behaviour by decision makers. A key issue to emerge from the evaluation in this respect is the nature of the model's scope of application, and the influence of this scope on the way system behaviour is interpreted. This is discussed in Section 8.2.1 below. Additionally, questionnaire respondents at WS1 and WS2 were asked to rate the model's effectiveness as a tool for interpreting the behaviour of a technical system. The responses received are reported in Section 8.2.2. As stated above, utility also refers to the degree to which the model can be understood by the decision makers who would be carrying out the interpretation. Consequently, questionnaire respondents were asked to rate two further aspects of the model: (i) ease of understanding; and (ii) effectiveness as a tool for explaining the concept of sustainability in a technical systems context. The responses received are also discussed in Section 8.2.2. General comments regarding the model's ability to support the identification of SPIs were also provided by questionnaire respondents at both WS1 and WS2. These are outlined in Section 8.2.3, with further insights gained from the SPI analysis also presented in this section.

8.2.1 Scope of application

The findings from CS2 and workshops WS1 and WS2 provide insight into the nature of the model's scope of application. Specifically, the spatial and temporal boundaries within which the S-Cycle model was applied were found to influence the way that technical system behaviour was interpreted. For example, as discussed in Section 8.1.2.1, the SoI for interpreting CW system behaviour in CS2 was defined as the CW system plus the rest of the ship, the sea it sails on, and the atmosphere surrounding it. It was then assumed that the ship would be at sea for approximately 90 days. In turn, this is the time period across which the CW system's behaviour was interpreted (using the CW system function model as a basis, as discussed previously). The renewability of the passive and active resources involved in the CW system activity was determined by tracing them back to the stocks they were replenished by within the boundary of the SoI. When carrying out the interpretation, it became apparent that different spatial and temporal boundaries may lead to different interpretations of what is renewable and non-renewable. For example, consider the oil used to lubricate the compressors in the CW plants within the CW system. As shown in Table 8-9, this may be interpreted as both RR and NRR depending on the boundaries defined.

Table 8-9: Different interpretations of the renewability of oil as an input to the compressor in a CW plant

SoI	Timescale	Renewability	Rationale
Warship at sea	5 days (no replenishment at sea)	Non-renewable	Stock = reserve oil on board ship; cannot be renewed within 5 days.
Warship at sea	90 days (with replenishment at sea)	Renewable	Stock = reserve oil on board ship; can be renewed if needed via supply ship within 90 days.
Warship within operational and support environment	2 years (various periods at sea and in the dock)	Renewable	Stock = Royal Navy's reserve oil on the shore; can currently be renewed within 2 years.
The whole Earth system	2 years (various periods at sea and in the dock)	Non-renewable	Stock = stock of crude oil in Earth system; cannot be renewed significantly within 2 years.

The influence of the SoI boundary on the interpretation of behaviour was also found to be highlighted in the questionnaire responses received from certain participants in WS2. For example, participant PW2-7 noted that the model's effectiveness as a tool for interpreting technical system behaviour is "very dependent on the definitions and boundary chosen." Similarly, participant PW2-13 noted that their understanding of sustainability and the model *per se* was "very dependent on [the] system boundary." Additionally, they stated that the model's effectiveness as a tool for interpreting behaviour appears to be "[very] dependent on [the] system and integrated nature with [the] 'whole' system." Finally, PW2-1 remarked that they "like[d] how changing the definition of the system [of interest] changes the sustainability of the system as this highlights how perceptive sustainability can be."

The impact of temporal boundaries on the interpretation of behaviour was found to be further highlighted in the outcomes of WS1. For instance, in the response sheet received from a group involved in checking the author's S-Cycle interpretation of the CW system function model (discussed in Chapter 7), one group noted that the interpretation of resources as renewable or non-renewable "depends on time." They also posed the question, "sustainable for how long?"

During the practical exercise, participants were only asked to define a SoI boundary for their chosen technical system and not a timescale for interpreting behaviour. However, one of the groups completing the practical exercise during WS1 noted on their response template that spare components (i.e. active resources) may be needed by their chosen system, but that this “depends on time.”

As highlighted above, the SoI boundary defined in CS2 in turn influenced the length of the timescale that behaviour was interpreted over. This suggests that the two aspects may be related. Similar observations were made during the practical exercise delivered at WS1. For instance, one group of participants applied the model to a gun on a warship, and defined the wider SoI as the ship. However, they noted on their response template that over a timescale of 1 year, a supply ship would be included within the SoI boundary alongside the warship. In contrast, over a timescale of 10 days, the supply ship would be excluded from the SoI. This may be seen to suggest that changing the timescale over which behaviour is interpreted may alter the SoI boundary. When asked to provide examples of non-renewable and renewable resources from their chosen technical system, another group posed two questions on their template: “from system of interest point of view?” and “over what timescale?” Again, this may be seen to suggest the existence of a relationship between the two aspects. Furthermore, certain participants raised the question of whether the SoI boundary defined when applying the model may be influenced by other predefined boundaries, such as economic and political boundaries.

Finally, participants in both WS1 and WS2 also emphasised the need for any assumptions made when defining the SoI boundary and timescale to be clearly stated. For example, participant PW1-5 indicated in their questionnaire response that the model is an effective tool for explaining the concept of sustainability “as long as all assumptions are listed.” Similarly, PW2-10 remarked that “defining the system and any assumptions is key” with respect to understanding sustainability and the model. As discussed in Chapter 9, further research is needed to determine whether a rigorous process for defining the scope of application for the S-Cycle model may be developed.

8.2.2 Questionnaire findings

As discussed in the introduction to Section 8.2, three aspects of the model’s utility were evaluated through the questionnaire delivered at WS1 and WS2. These are discussed in the following sub-sections: (i) effectiveness as a tool for interpreting the behaviour of a technical system (Section 8.2.2.1); (ii) ease of understanding by engineering designers (Section 8.2.2.2); and (iii) effectiveness as a tool for explaining the concept of sustainability in a technical systems context (Section 8.2.2.3). As discussed in Chapter 7, workshop participants were asked to rate the model with respect to each of the aforementioned aspects along a Likert scale, running from *poor* to *excellent* around a neutral option of *no opinion*. A box for open responses was also included for each question.

In total, 21 questionnaire responses were received. 54% of participants in WS1 (i.e. 6 out of 11 participants) were unable to provide responses owing to constraints on their time. The 5 participants who provided responses were PW1-2, PW1-5, PW1-6, PW1-7, and PW1-11. Furthermore, as discussed in Chapter 7, WS2 was delivered as part of a continuing professional development (CPD) course for Company A. Participant PW2-9 provided negative comments at the end of their questionnaire response questioning the relevance of the workshop material in relation to the CPD course, suggesting that their response may have been influenced by their opinion of the CPD course. As such, it was decided to discount their response from the analysis. Therefore, a total of 20 questionnaire responses were considered as part of the evaluation. This represents 74% of the total participants in WS1 and WS2 (i.e. 27 participants).

8.2.2.1 Effectiveness as a tool for interpreting system behaviour

Figure 8-6 presents the ratings obtained for aspect (i) described above, i.e. effectiveness as a tool for interpreting the behaviour of a technical system. It may be seen that again, the majority of respondents (50%) rated the model *good*. However, a relatively large percentage of respondents rated the model as *fair* in this respect, i.e. 25%. A further 25% indicated that they had *no opinion*. None of the respondents rated the model as *poor* or *excellent* in this aspect. As discussed in Chapter 7, the wording of this question in the questionnaire was altered between WS1 and WS2. As such, it should be noted that the ratings provided by WS1 and WS2 participants may potentially be based on different interpretations of the question (discussed further in Chapter 9).

Generally, those indicating that they had *no opinion* on this aspect stated that they needed to see more examples of the model's application to be able to provide an opinion. For instance, participant PW2-8 commented that it "[would] be good to see [the] results of implementing it in real life." In a similar vein, PW2-15 noted: "This is a whole new area so it's hard to contextualise it." In contrast, participant PW2-2 rated the model *good* in this aspect and provided comments on how it could be used within their own field of work, i.e. energy: "Could be used to help improve efficiency procedures and thus costs in power utility." PW1-5 also rated the model *good* in this aspect; however, they suggested that applying the model involves "very focused interpretation of a system not always understood by all engineers."

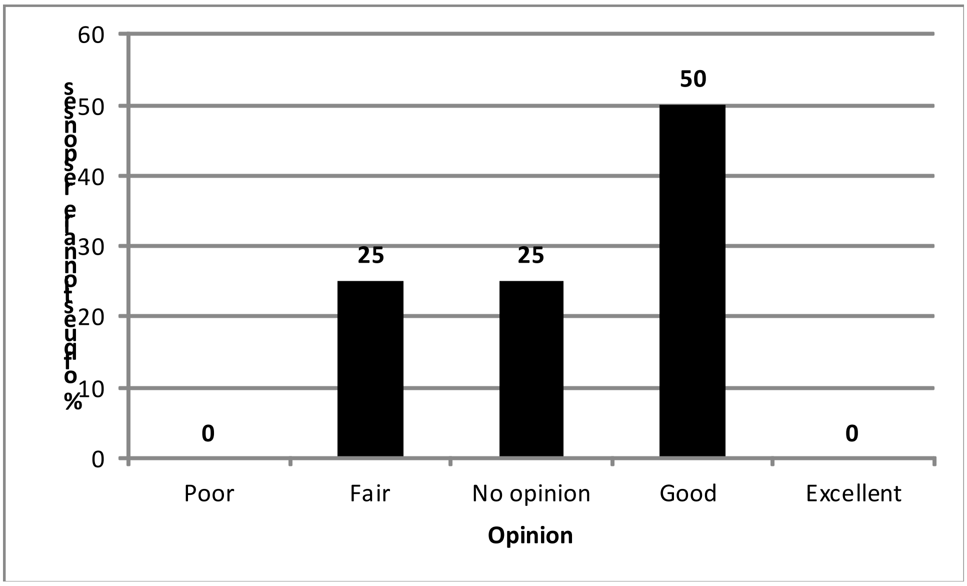


Figure 8-6: Questionnaire ratings for "effectiveness as a tool for interpreting a technical system's behaviour"

As touched upon in Section 8.2.1, certain respondents provided comments suggesting that the model's effectiveness as an interpretation tool was affected by its scope of application. For example, participant PW2-3 stated that the model "can be applied to any system, but boundary analysis means results very open to interpretation." Participant PW2-11 noted that it "[appears] that it is always required to assess the top level [i.e. Earth system level] to understand properly what is renewable and truly sustainable." Both of these participants rated the model as *fair* with respect to this aspect.

Participant PW1-5 provided a comment relating the model's effectiveness as an interpretation tool to the expertise of the model user, stating that the model supports "[very] focused interpretation of a system not always understood by all engineers." Two other participants provided similar comments regarding the expertise of model users, although these were made in relation to the question focusing on comprehensiveness that was discussed in Chapter 7 (Section 7.2.2.2). Participant PW2-13 stated that it is necessary "to have the correct experts and facilitators around the table to make it [the model] work." More generally, participant PW2-16 remarked that "the user is the challenge" with respect to the application of the model.

Finally, participant PW1-6 rated the model as *fair* with respect to its effectiveness as an interpretation tool. They commented that “a measure of sustainability to compare system design options” is needed. Participant PW2-10 indicated that they had *no opinion* on this aspect of the model, but provided similar comments to PW1-6: “Feel this could be very useful with modelling/numbers to back up the diagram, but I don’t know at present.” Comments relating to the identification of SPIs are discussed further in Section 8.2.3.1 below.

8.2.2.2 Ease of understanding

As shown in Figure 8-7, the majority of respondents (75%) rated the model *good* with respect to aspect (ii) above, i.e. ease of understanding. 5% rated it *excellent*, whilst 10% rated it *fair* and 10% indicated that they had *no opinion* on this aspect. None of the respondents rated the model *poor* in this aspect. A number of respondents reported that the model was easier to understand when accompanied by an explanation and examples. For instance, PW2-13 felt that it was “actually slightly counter-intuitive until you have looked at a variety of systems at different sub-levels.” Similarly, PW2-16 wrote: “With [the] explanation [it] is good. First glance it can be confusing.” As discussed in Chapter 7, it was decided to adopt the terminology of the IDEF0 language to describe the system activity during the workshops. That is, inputs and mechanisms rather than passive and active resources. PW2-5 suggested that: “Some of the definitions could be improved. For instance, mechanism when refer[ring] to plant and equipment and humans cause[s] confusion.”

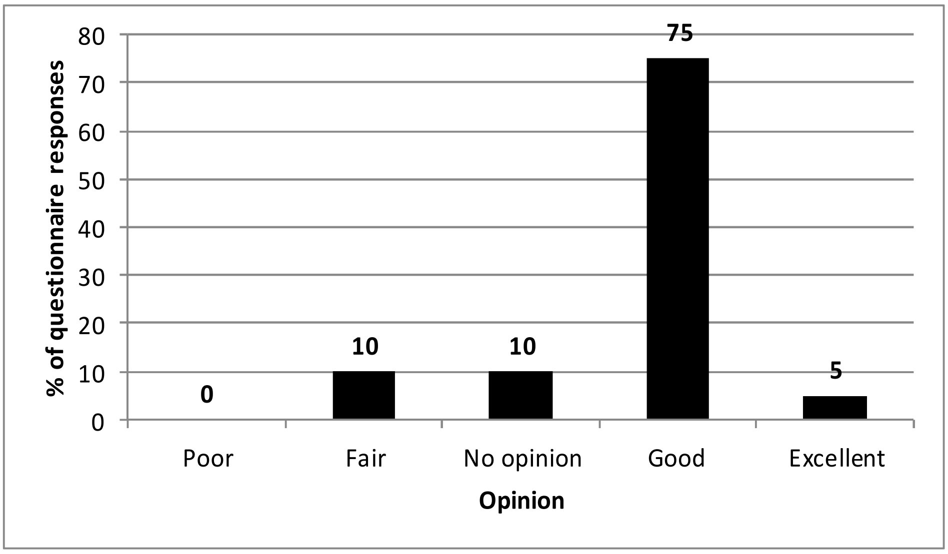


Figure 8-7: Questionnaire ratings for “ease of understanding”

8.2.2.3 Effectiveness as a tool for explaining sustainability

As shown in Figure 8-8, the majority of respondents (62.5%) rated the model *good* with respect to aspect (iii) outlined above, i.e. effectiveness as a tool for explaining the concept of sustainability. 15% rated it as *excellent* in this respect, whilst 17.5% indicated that they had *no opinion*. None of the respondents rated the model as *poor* in this aspect.

As discussed in Section 8.2.2.1, certain participants provided comments relating the model's effectiveness as an interpretation tool to its scope of application. Similar comments were provided with respect to the model's effectiveness as a tool for explaining sustainability. For example, participant PW1-5 rated this aspect of the model as *good*, but with the caveat that "all assumptions are listed and the [SoI] boundary is set." PW2-10 provided similar comments: "Potentially good if system definition/assumptions explained." Participant PW2-6 also rated the model as *good* in this dimension, and remarked that it provides a means to convey the concept of sustainability: "Sustainability is hard to define, as discussed in class. Therefore, using such a diagram [the S-Cycle model] helps to visual[ise] this concept through examples." Participant PW2-1 rated the model as *excellent* in this dimension, and noted that it conveys the notion that a human's perception of sustainability is affected by the SoI boundary: "I like how changing the definition of the system changes the sustainability of the system as this highlights how perceptive sustainability can be."

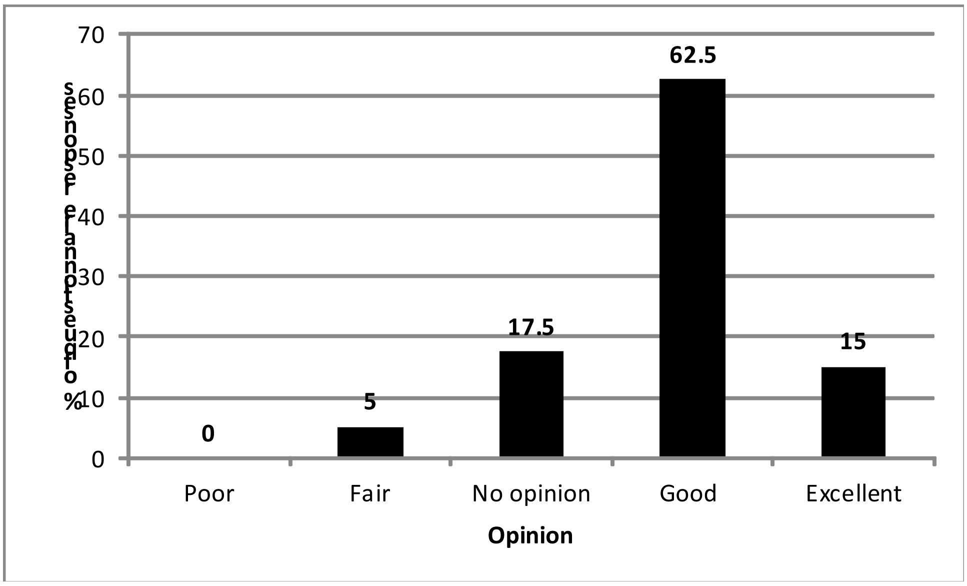


Figure 8-8: Questionnaire ratings for "effectiveness as a tool for explaining the concept of sustainability"

8.2.3 Identification of SPIs

As discussed in the introduction to Section 8.2, comments regarding the model's ability to support the determination of SPIs were also identified from the questionnaire responses discussed in Section 8.2.2. These are outlined in Section 8.2.3.1 below. Further insights into this aspect gained from the SPI analysis are presented in Section 8.2.3.2.

8.2.3.1 Questionnaire comments

As discussed in Chapter 7 (Section 7.2.2), participants at both WS1 and WS2 were provided with an introductory presentation on sustainability and the S-Cycle model. At WS1, this was followed by a presentation disseminating the CW system function model and the results of interpreting this model using the S-Cycle model. Following the introductory presentation at WS2, a series of examples where the model was applied to interpret the behaviour of a combined heat and power plant and its sub-systems were presented. All of the applications of the model presented at the two workshops were qualitative in nature. That is, none of the work presented involved the quantification of system behaviour through the identification of SPIs. In turn, as noted previously, questionnaire respondents at both workshops provided feedback regarding the model's ability to support the determination of SPIs for technical systems. This is briefly discussed below.

Firstly, several respondents indicated that they felt the model was lacking the ability to support identification of SPIs. For instance, as highlighted in Section 8.2.2.3, participant PW2-4 rated the model as "good" with respect to its effectiveness as a tool for explaining sustainability. However, they provided the following comment alongside their rating: "Model explains sustainability but does not appear to help identify a measure of how sustainable a system is." Participant PW2-10 provided comments regarding the model's effectiveness as an interpretation tool, suggesting that the model's utility may be affected by its ability to support the quantification of system behaviour: "Feel this could be very useful with modelling/numbers to back up the diagram [S-Cycle model], but I don't know at present."

Secondly, respondents also suggested that the model should be able to support the comparison of different systems on the basis of their sustainability performance, e.g. through the definition of SPIs and the benchmarking of system performance. For instance, participant PW2-11 provided the following comment:

- "Quantification is required for how sustainable a system is, then benchmarking and assessment."

Other participants provided similar comments:

- Participant PW1-6 commented that "a measure of sustainability to compare system design options" is needed.
- Participant PW1-11 noted that they would "like to see some metrics to allow comparison of sustainability across different systems."
- Participant PW2-3 remarked: "Setting goals [is] important, how is sustainability measured? Comparisons between systems as part of cost/benefit would be useful."

Additionally, during WS1, certain participants indicated verbally that a quantitative model of the CW system's behaviour from a sustainability perspective was desirable. It was suggested that this would facilitate investigations into the potential impact of system changes on sustainability performance, e.g. during the design process where it may be desired to select the most sustainable system layout from a range of potential solutions.

The feedback outlined above was addressed by CS1, CS3, and the SPI analysis as illustrated in Figure 7-1 in Chapter 7. This is discussed in depth in Chapter 9, and the key findings of the SPI analysis are presented in the following sub-section.

8.2.3.2 SPI analysis findings

The S-Cycle Performance Matrix (Figure 7-11) introduced in Chapter 7 (Section 7.3) consists of a set of generic sustainability goals and corresponding SPI archetypes, as well as associated metrics and measures for each archetype. These were all derived from the S-Cycle model, with the development of the SPI archetypes, metrics, and measures further informed by the E^2 performance model (O'Donnell and Duffy, 2005). As discussed in Chapter 7, the proposed matrix was evaluated through an analysis of 324 indicators identified from the sustainability performance evaluation literature (the full list of indictors is presented in Table 7A-1 in Appendix 7A). The findings of the analysis are reported in full in Section 5.3 of Paper B (Appendix 2) – an overview of the key findings is provided below. Note that a selection of the SPIs analysed during evaluation of the matrix were highlighted as providing support for certain model elements in Section 8.1.1.

In total, 88.6% (287) of the indicators considered during the analysis were found to be immediately classifiable with respect to both the SPI archetypes and metrics proposed in the initial performance matrix. Of the remaining 11.4% (37), 48.6% (18) were found to be classifiable with respect to the SPI archetypes, but not the metrics. Thus, in total, 94.1% (305) of the indicators analysed were found to be classifiable with respect to the proposed SPI archetypes. An overview of the archetypes found to be supported and unsupported is provided in Table 8-10 alongside examples where applicable.

Upon closer examination, the 18 indicators whose metrics did not align with any of those proposed in the performance matrix were seen to suggest additional metrics that had been overlooked. These are presented in Table 8-11, alongside the indicators from the sample that they were based on. Furthermore, additional formulae were identified for two metrics proposed in the matrix. Firstly, it was observed that in one source (Ofori-Boateng and Lee, 2014), the wastefulness metric was computed as the ratio of passive resources to waste produced rather than the ratio of waste produced to passive resources consumed as proposed in the matrix (although the latter formula was found to be supported as shown in Table 8-10). Secondly, it was also observed that in the above source (Ofori-Boateng and Lee, 2014), the resource productivity metric was computed via the following equation rather than as the ratio of intended output produced to passive resources consumed: $1 - \left(\frac{W_L}{PR_{L,R,G}}\right)$, where W_L is the amount of a particular type of waste produced by the system at the local scale, and $PR_{L,R,G}$ is the amount of a particular passive resource consumed at the local, regional, or global scale.

On top of additional metrics for proposed SPI archetypes, one indicator identified in the sample was seen to suggest an additional SPI in relation to the goal *minimise overall resource use*. As discussed in Section 8.1.1.1, Rotella et al. (2012) evaluate an indicator termed "wear rate," measuring the amount of material worn off of the cutting component of a hard machining system during operation. The cutting component may be viewed as an active resource in the machining system's activity, transforming a workpiece (i.e. passive resource) into a machined component (i.e. intended output). Thus, the wear rate indicator appears to measure the consumption of active resources during the operation phase of the life cycle (i.e. at the local scale). This is suggestive of an additional SPI archetype, i.e. *active resource consumption* in relation to the goal *minimise overall resource use*.

The notion of contaminants was introduced in Section 8.1.3.1. That is, an input to a system activity that cannot be classified as a resource, and appears to be detrimental to the production of intended resources and intended output by the activity. An example of a contaminant input was identified during CS2. It was also highlighted that a sustainability goal defined by Student B during CS3, as well as impact indicators considered in the SPI analysis, seem to suggest that the potential for a system activity's waste outputs to act as contaminant inputs in other activities may be important from a sustainability perspective. This in turn suggests that there may be an additional generic sustainability goal for technical systems that is not presently included in the performance matrix: *minimise the contaminating potential of outputs*.

Table 8-10: List of supported and unsupported SPI archetypes and metrics

SPI archetypes	Metrics	Examples	Sources
IO production	Absolute IO output	Total exergy output	Ofori-Boateng and Lee (2014)
	IO production rate	Exergy output rate	Caliskan et al. (2012)
	Relative IO production	Electricity generation by treated waste	Coelho et al. (2012)
Passive resource consumption	Absolute PR input	Cumulative energy demand	Thiers and Peuportier (2012); Antony et al. (2014)
	Energy payback time	Energy payback period	Adams and McManus (2014); Kim et al. (2014)
	Relative PR consumption	Environmental loading ratio	Ulgiati et al. (2011); Buonocore et al. (2012); Moss et al. (2014)
	PR consumption rate	Energy consumption per day	Caliskan et al. (2012)
Active resource consumption	N/A (future research)	Wear rate	Rotella et al. (2012)
Passive resource efficiency	Resource intensity	Material intensity, abiotic factor	Raugei et al. (2005)
	Resource productivity	Primary energy efficiency	Denholm et al. (2005)
		Exergy efficiency	Ofori-Boateng and Lee (2014)
NRR consumption	Absolute NRR input	Fossil fuel consumption	Kim et al. (2014)
	NRR consumption rate	Emergy from local non-renewable resources (per year)	Buonocore et al. (2012)
	NRR fraction	Currently unsupported	----------------------
NRR efficiency	NRR intensity	Embodied energy per MJ of electricity	Buonocore et al. (2012)
	NRR productivity	EROI of electricity	Buonocore et al. (2012)
RR consumption	Absolute RR input	Water consumption	Thiers and Peuportier (2012)
	RR consumption rate	Total water demand (per year)	Buonocore et al. (2012)
	RR fraction	Energetic renewability ratio	Balta et al. (2010)
RR efficiency	RR intensity	Water demand per MJ of electricity generated	Buonocore et al. (2012)
	RR productivity	Currently unsupported	----------------------
IR production	Absolute passive IR	Currently	----------------------

SPI archetypes	Metrics	Examples	Sources
	output	unsupported	
	Passive IR production rate	Currently unsupported	-----------------------
IR consumption	Passive IR fraction	Recoverable exergy ratio	Aydin et al. (2013)
Waste production	Absolute W output	Carbon dioxide equivalent emissions	Rosato et al. (2014)
	W concentration (new)	NOx concentration	Bianchi et al. (2014)
	W intensity	CO2 emission intensity	Uddin and Kumar (2014)
	W production rate	CO2 emissions rate	Waheed et al. (2014)
Resource inefficiency	Wastefulness	Waste exergy ratio	Aydin et al. (2013)
		Thermodynamic sustainability index	Ofori-Boateng and Lee (2014)

Whilst all of the SPI archetypes proposed in the initial performance matrix were found to be supported in the analysis sample along with the majority of the proposed metrics, there are certain metrics that do not appear to be supported. Namely, these are: (i) *non-renewable resource fraction*; (ii) *renewable resource productivity*; (iii) *absolute passive IR output*; and (iv) *intended resource production rate*. Additionally, the nature of certain indicators identified in the sample in relation to the performance matrix was found to be unclear. As such, they were deemed not to be classifiable with respect to the performance matrix in its present form. Broadly speaking, these indicators may be split into two categories, which are discussed in greater depth on pp. 65 – 69 of Paper B (Appendix 2): (i) indices that seem to relate output to resources in some way, but do not appear to be classifiable as efficiency indicators; and (ii) indices that appear to benchmark the performance of one system against the performance of another system, some theoretical level of performance, or performance at another scale.

A refined version of the S-Cycle Performance Matrix, taking into account the observations discussed above, is presented in Figure 8-9 overleaf. Areas requiring clarification through further research, along with additional goals, SPI archetypes, and metrics that were revealed during the indicator analysis are highlighted in grey.

Table 8-11: Additional metrics suggested by indicators in the analysis sample

Table 8-11: Additional metrics suggested by indicators in the analysis sample

New metric	SPI archetype	S-Cycle metric definition	Full metric definition	Indicators used as basis	Sources
Energy payback time	Passive resource consumption	$PR_{e\_R,G}/IO_{e\_annual}$	Number of years required for the energetic IO produced by a technical system to equal the energetic PR it consumes over its full life cycle.	• Energy payback period	Adams and McManus (2010); Kim et al. (2014); Pacca et al. (2007); Uddin and Kumar (2010)
Relative IO production	IO production	IO_{a_L}/IO_{b_L}	Amount of IO type *a* produced per unit of IO t*ype b* produced over some time period (t_{max} = full operation phase).	• Electricity generation by treated waste • Thermal energy generation by treated waste	Coelho et al. (2012)
Relative PR consumption	Passive resource consumption	$P\text{-}NRR_{L,R,G}/P\text{-}RR_{L,R,G}$	Amount of non-renewable PR consumed per unit of renewable PR consumed over some time period (tmax = full life cycle).	• Environmental loading ratio	Buonocore et al. 2012
W concentration	W production	$W_{a\_L,R,G}/W_{L,R,G}$	Amount of W type *a* produced as a fraction of the total W produced over some time period (t_{max} = full life cycle).	• Emission index of carbon dioxide • Emission index of carbon monoxide • Emission index of hydrocarbons • Emission index of NOx	Chandrasekaran and Guha (2013)
				• Smoke opacity	Singh et al. (2014)

Generic sustainability goals	ε/η	SPI archetypes	Metrics	S-Cycle metric definitions	Full metric definition
PRODUCE IO	ε	IO production	Absolute IO output	IO_L	Amount of IO produced over some time period (t_{max} = full operation phase).
			IO production rate	IO_L/t	Amount of IO produced per unit of time (t_{max} = full operation phase).
			Relative IO production [new]	IO_{a_L}/IO_{b_L}	Amount of IO 'type A' produced per unit of IO 'type B' produced over some time period (t_{max} = full operation phase).
MINIMISE OVERALL RESOURCE USE	ε	Passive resource consumption	Absolute PR input	$PR_{L,R,G}$	Amount of PR consumed over some time period, including both renewable and non-renewable PR (t_{max} = full life cycle).
			Energy payback time [new]	$PR_{e\_R,G}/IO_{e\_L\_annual}$	Number of years required for the energetic IO produced by a technical system to equal the energetic PR it consumes over its full life cycle.
			Relative PR consumption [new]	$P\text{-}NRR_{L,R,G}/P\text{-}RR_{L,R,G}$	Amount of non-renewable PR consumed per unit of renewable PR consumed over some time period (t_{max} = full life cycle).
			PR consumption rate	$PR_{L,R,G}/t$	Amount of PR consumed per unit of time, including both renewable and non-renewable PR (t_{max} = full life cycle).
		Active resource consumption (new)	Future research	Future research	Future research
	η	Passive resource efficiency	Resource intensity	$PR_{L,R,G}/IO_L$	Amount of PR consumed per unit of IO produced over some time period (t_{max} = full life cycle).
			Resource productivity	$IO_L/PR_{L,R,G}$	Amount of IO produced per unit of PR consumed over some time period (t_{max} = full life cycle).
				$1 - (W_L/PR_{L,R,G})$ [new]	Amount of PR transformed to IO rather than W over some time period (t_{max} = full life cycle)
MINIMISE NRR USE	ε	NRR consumption	Absolute NRR input	$P\text{-}NRR_{L,R,G}$	Amount of non-renewable PR consumed over some time period (t_{max} = full life cycle).
			NRR consumption rate	$P\text{-}NRR_{L,R,G}/t$	Amount of non-renewable PR consumed per unit of time (t_{max} = full life cycle).
			NRR fraction	$P\text{-}NRR_{L,R,G}/PR_{L,R,G}$	Fraction of PR consumed over some time period that is non-renewable (t_{max} = full life cycle).
	η	NRR efficiency	NRR intensity	$P\text{-}NRR_{L,R,G}/IO_L$	Amount of non-renewable PR consumed per unit of IO produced over some time period (t_{max} = full life cycle).
			NRR productivity	$IO_L/P\text{-}NRR_{L,R,G}$	Amount of IO produced per unit of non-renewable PR consumed over some time period (t_{max} = full life cycle).
MINIMISE RR USE	ε	RR consumption	Absolute RR input	$P\text{-}RR_{L,R,G}$	Amount of renewable PR consumed over some time period (t_{max} = full life cycle).
			RR consumption rate	$P\text{-}RR_{L,R,G}/t$	Amount of renewable PR consumed per unit of time (t_{max} = full life cycle).
			RR fraction	$P\text{-}RR_{L,R,G}/PR_{L,R,G}$	Fraction of PR consumed over some time period that is renewable (t_{max} = full life cycle).
	η	RR efficiency	RR intensity	$P\text{-}RR_{L,R,G}/IO_L$	Amount of renewable PR consumed per unit of IO produced over some time period (t_{max} = full life cycle).
			NRR productivity	$IO_L/P\text{-}RR_{L,R,G}$	Amount of IO produced per unit of non-renewable PR consumed over some time period (t_{max} = full life cycle).
MAXIMISE SELF-SUFFICIENCY [future work required to clarify SPI archetypes and metrics]	ε	IR production	Absolute passive IR output	$P\text{-}IR_L$	Amount of passive IR produced over some time period (t_{max} = full operation phase).
			Passive IR production rate	$P\text{-}IR_L/t$	Amount of passive IR produced per unit of time (t_{max} = full operation phase).
		IR consumption	Passive IR fraction	$P\text{-}IR_L/PR_L$	Fraction of PR consumed over some time period that was self-produced (t_{max} = full operation phase).
MINIMISE WASTE PRODUCED	ε	W production	Absolute W output	$W_{L,R,G}$	Amount of W produced over some time period (t_{max} = full life cycle).
			W concentration [new]	$W_{a\_L,R,G}/W_{L,R,G}$	Amount of W 'type A' produced as a fraction of the total W produced over some time period (t_{max} = full life cycle).
			W intensity	$W_{L,R,G}/IO_L$	Amount of W produced per unit of IO produced over some time period (t_{max} = full operation phase).
			W production rate	$W_{L,R,G}/t$	Amount of W produced per unit of time (t_{max} = full life cycle).
	η	Resource inefficiency	Wastefulness	$W_L/PR_{L,R,G}$	Amount of W produced per unit of PR consumed over some time period (t_{max} = full operation phase).
				$PR_{L,R,G}/W_L$ [new]	Amount of PR consumed per unit of W produced over some time period (t_{max} = full operation phase).
MINIMISE CONTAMINATING POTENTIAL OF OUTPUTS	ε	Future work	Future work	Future work	Future work

Figure 8-9: Refined version of the S-Cycle Performance Matrix

Figure 8-9: Refined version of the S-Cycle Performance Matrix

8.3 Applicability

The findings of the evaluation with respect to the validity and utility of the model were presented in Sections 8.1 and 8.2, respectively. As noted in the introduction to Chapter 7, the final aspect of the model considered during evaluation was its applicability. Applicability in this context refers to the extent to which the S-Cycle model has been applied to interpret the behaviour of different technical systems in different sectors (Sim, 2000). As discussed in Chapter 7, the model must be demonstrated to be applicable to at least two distinct technical systems in order to address all three of the research issues identified in Chapter 5. That is, the lack of a *consistent* view on sustainability improvement (I1), a *common* approach for SPI identification (I2), and a *fundamental* formalism of sustainability (I3).

Technical systems may be differentiated in a number of ways. For instance, Hubka and Eder (1988) propose several classification criteria, including function, branch of the economy, complexity, type of operand, etc. In this thesis, the technical systems studied during evaluation have been classified with respect to their function, degree of complexity, and industrial sector of origin. As discussed in Chapter 4, function refers to 'what the technical system is for' (Gero and Kannengiesser, 2004). With respect to degree of complexity, Hubka and Eder (1988, p.97) propose four categories that have been adopted to classify technical systems in this thesis:

- I = "Elementary system produced without assembly operations" – a part or component. Examples include bolts, springs, and washers.
- II = "Simple system that can fulfil some higher functions" – a group, mechanism, or sub-assembly. Examples include a gear box, brake unit, and shaft coupling.
- III = "System that consists of sub-assemblies and parts that perform a closed function" – a machine, piece of apparatus, or device. Examples include a lathe, motor vehicle, and electric motor.
- IV = "Complicated system that fulfils a number of functions and that consists of machines, groups and parts that constitute a functional and spatial unity" – a plant, piece of equipment, or complex machine unit. Examples include various items of factory equipment.

Finally, industrial sector of origin in this thesis refers to the sector that the system is typically designed to serve. In addition to the above three aspects, each system's broader context was also considered. For instance, the CW system studied in CS2 formed part of a warship, and the systems considered by participants in WS2 formed part of a wind farm.

An overview of the systems the model was applied to during evaluation is provided in Table 8-12, highlighting the three aspects outlined above along with each system's broader context. It may be seen that the worked examples, case studies, and practical exercises demonstrated that the model can be applied to different technical systems by different users, including researchers and engineering designers. Overall, the model was applied to ten distinct systems during the evaluation, with the majority originating in the energy and marine (defence) sectors (with the exception of the car engine studied in WE2, which originated in the automotive sector). Most of the systems were of a relatively high degree of complexity according to the classification scheme proposed by Hubka and Eder (1988), i.e. levels III and IV. Questionnaire responses received from two participants in WS2 were found to provide further evidence to support the model's applicability to different technical systems. PW2-6 remarked: "From the short time we have had to interpret the model, I can see that it could be used for numerous technical systems." Likewise, participant PW2-3 stated that the model "can be applied to any system."

During CS2, the S-Cycle was applied to interpret a function model of the CW system built using the IDEF0 modelling language, as discussed in Chapter 7 (Section 7.1.3.2). The following IDEF0 diagrams were interpreted: A-0; A0; A4; A5; A51; A511; A5113; and A514 (included in Appendix 4). As shown in Figure 7-9, these diagrams describe the activities carried out by the CW system as a whole (A-0 diagram) and various sub-systems (A0 – A514 diagrams). A number of the sub-systems interpreted using the S-Cycle may be considered to exist at the same level within the overall hierarchy of the CW system, e.g. the control system, header tank equipment, circulation system, chilling system, and heat exchange mechanisms as shown in Figure 7-9. Others may be considered to exist at different hierarchical levels (system hierarchies are discussed in Chapter 6). For example, the compressor may be viewed as a sub-system of the CW plant and in turn, the CW plant may be viewed as a sub-system of the chilling system (again illustrated in Figure 7-9). Additionally, during the practical exercise delivered to engineering designers from Company A during WS2, participants applied the model to a wind turbine and a transformer. The group focusing on the transformer indicated that it may be considered to be a sub-system of a wind turbine. As shown in Figure 8-10, the application of the model to systems at different hierarchical levels during CS2 and WS2 may be contrasted with WE1 (bioethanol production system), WE2 (petrol car engine), and CS1 (HVAC system), where the model was applied at one system level only. Note that during CS3, Student B used the S-Cycle interpretation of the CW system function model developed in CS2 as the basis for identifying SPIs for the CW plant, i.e. a sub-system of the CW system. As such, CS3 is not included in Figure 8-10.

Table 8-12: Overview of systems the model was applied to during evaluation

Function	Sector	Complexity	Context	Model users
Bioethanol production system (WE1):				
To produce bioethanol from corn.	Energy	IV	Ecological and economic systems	Author
Petrol car engine (WE2):				
To produce mechanical power from fuel and air.	Automotive	III	Car	Student B
HVAC system (CS1):				
To produce and distribute fresh air at a desired temperature within a ship.	Marine (defence)	III	Warship	Student A
CW system (CS2):				
To produce and distribute a flow of chilled water to equipment aboard a ship.	Marine (defence)	III	Warship	Author
CW plant system (CS3):				
To remove waste heat from a flow of cooling medium and reject it to the environment.	Marine (defence)	III	Warship	Student B
Cold water distribution system (WS1 practical exercise):				
To distribute fresh water from a reverse osmosis plant to consumers on a ship.	Marine (defence)	III	Warship	WS1 participants
Gas turbine (WS1 practical exercise):				
To convert the energy embodied within a hydrocarbon into mechanical (rotational) energy.	Marine (defence)	III	Warship	WS1 participants
4½ " gun (WS1 practical exercise):				
To deliver a shell with a desired trajectory.	Marine (defence)	III	Warship	WS1 participants
Diesel generator (WS1 practical exercise):				
To convert diesel and air into mechanical power.	Marine (defence)	III	Warship	WS1 participants
Wind turbine (WS2 practical exercise):				
To convert wind energy into electrical energy.	Energy	IV	Wind farm	WS2 participants
Transformer (WS2 practical exercise):				
To transform voltages from their original level to some desired level.	Energy	II	Wind farm	WS2 participants

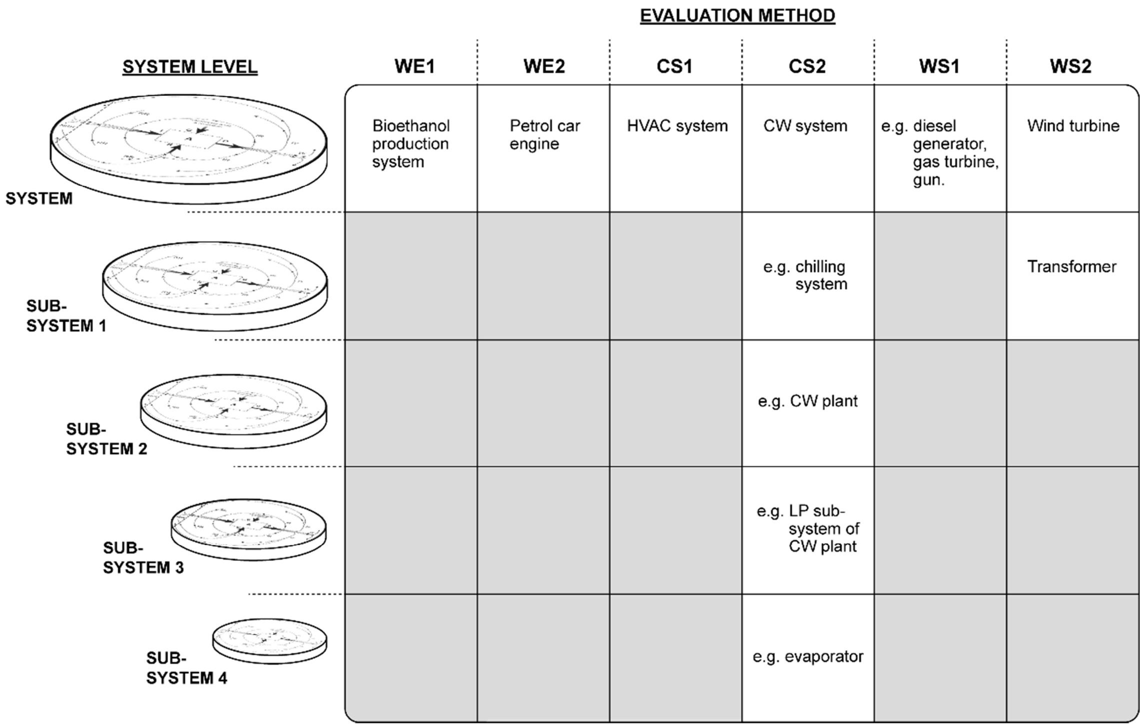


Figure 8-10: Summary of model application levels during evaluation

8.4 Summary

Chapter 7 outlined the approach adopted to evaluate the S-Cycle model. Chapter 8 has presented the findings of the evaluation. The findings relate to three aspects of the model and its use:

(i) *validity*, referring to the degree to which the elements and relationships can be considered to model a technical system's behaviour from a sustainability perspective;

(ii) *utility*, referring to how effectively the model supports the identification of SPIs for technical systems; and

(iii) *applicability*, referring to the extent to which the model has been applied to interpret the behaviour of different technical systems in different sectors.

With respect to validity, support was identified for all model elements and relationships across the different parts of the evaluation approach, in varying degrees. Support for activity coupling relationships (identified in Chapter 6) was also identified. Support for one model element (i.e. active intended resources) and one relationship (i.e. intended output produced by a technical system activity contributes to NRR stocks within a wider SoI) was found to be considerably less substantial than support for the other elements and relationships in the model. An additional element and corresponding relationship were also identified – namely, a contaminant input to a system activity, that appears to originate from stocks within the wider SoI and is detrimental to the production of intended resources and intended output by the activity.

The findings regarding the model's utility relate to its: (i) scope of application; (ii) effectiveness as a tool for interpreting a technical system's behaviour from a sustainability perspective; (iii) ease of understanding by engineering designers; and (iv) effectiveness as a tool for explaining sustainability. General comments regarding the model's ability to support the determination of SPIs for technical systems were also identified. With respect to (i), it was found that the spatial and temporal boundaries within which the S-Cycle model is applied influence the way that technical system behaviour is interpreted by the model user. In turn, it may be concluded that the SoI boundary and the timescale over which behaviour is interpreted form two basic components of the model's scope of application. Both must be properly defined to ensure that technical system behaviour is interpreted appropriately. Aspects (ii), (iii), and (iv) were evaluated through the questionnaire. The model was rated as "good" with respect to all three aspects by the majority of questionnaire respondents, i.e. 75%, 50%, and 62.5% of respondents, respectively. Respondents also highlighted a need for quantitative measures of system sustainability and questioned the model's ability to support the identification of SPIs. Nonetheless, the SPI analysis demonstrated that the model may be applied to define SPIs for technical systems. It was found that 94.1% of the 324 indicators analysed could be classified with respect to the SPI archetypes derived from the model and organised within the S-Cycle Performance Matrix.

Lastly, the model was applied to ten distinct technical systems during the evaluation, by a mixture of researchers and engineering designers. The systems studied originated in the energy and marine (defence) sectors (with the exception of a car engine studied in WE2, which originated in the automotive sector). They fulfilled different functions and were of a relatively high degree of complexity. Furthermore, during CS2 and the practical exercise delivered at WS2, the model was applied to systems existing at different levels within the overall hierarchy of a CW system and a wind turbine, respectively.

Part 3: Reflections

9 Discussion

As stated in Chapter 5, the aim of the research reported in this thesis is to develop a generic model of technical system sustainability. The work is intended to address three issues for research on the sustainability of technical systems, identified from the literature reviewed in Chapters 3 and 4. That is, the lack of a:

I1. consistent view on how the sustainability of human activities and systems can be improved;

I2. common approach for identifying appropriate sustainability performance indicators (SPIs) for technical systems; and

I3. fundamental formalism to describe the basic constitution of sustainability generally and in turn, sustainability of technical systems.

To achieve the research aim, the S-Cycle and S-Loop models were developed through inductive research reported in Chapter 6. Chapters 7 and 8 presented the approach adopted to evaluate the S-Cycle model and the evaluation findings, respectively. Part 3 of this thesis presents reflections on the research, beginning in this chapter with a discussion of the work as a whole. The following aspects are considered: (i) the research findings (Section 9.1); (ii) the research methods and techniques (Section 9.2); and (iii) the research approach overall (Section 9.3). Future research is outlined in Section 9.4, and a summary of the chapter is provided in Section 9.5.

9.1 Research findings

The S-Cycle and S-Loop models are considered to have a number of advantages and disadvantages, identified through reflection. The S-Cycle is firstly considered in Section 9.1.1, followed by the S-Loop in Section 9.1.2.

9.1.1 The S-Cycle model and guideline

With respect to issue I3 above, it was shown in Chapter 6 (Section 6.1) that sustainability may be viewed as constituting an ability, which is a property of a system and manifested as behaviour that produces the effect of maintenance/continuation of the system *per se*, or some other entity. The S-Cycle model (Figure 6-5, Section 6.5.1) formalises the behaviour of a technical system from a sustainability perspective. That is, it describes the aspects of behaviour through which the property of sustainability is manifested in a technical system. The model consists of: an activity formalism representing the operation of a technical system; a boundary delimiting the wider system of interest (SoI) within which the technical system operates; and two stock elements and a number of flow elements representing the interactions between the technical system and the SoI from a sustainability perspective.

To support the application of the S-Cycle model to technical systems during evaluation, the S-Cycle guideline was developed (Chapter 7, Section 7.1.1). The guideline details a six-step process for evaluating and improving the sustainability performance of a technical system, known as the S-Cycle Performance Improvement Process (S-CPIP). Guidance on defining and evaluating SPIs is largely drawn from the E^2 performance model (O'Donnell and Duffy, 2005), which describes performance in terms of efficiency and effectiveness. Both the S-Cycle model and the guideline are discussed in Sections 9.1.1.1 – 9.1.1.5 below. A summary of advantages and disadvantages is provided in Section 9.1.1.6.

9.1.1.1 Model elements and relationships

In Chapter 8 (Section 8.1), it was shown that the evaluation findings provided support for all model elements and relationships identified through the inductive research. Having said this, support for some was observed to be considerably less substantial than for others, as highlighted in Chapter 8. Although their validity was not questioned by workshop participants, no examples of the following elements and relationships were identified:

- *active intended resources* (E5) and the corresponding relationship, *A-IR produced by a technical system activity is used directly in the activity* (RS3); and
- *intended output contributes to non-renewable resource stocks* (RS9).

Additionally, only limited examples of *passive intended resources* (E6) and the corresponding relationship, *P-IR produced by a TS activity is used directly in the activity* (RS4), were identified. Given the absence of examples, it is possible that these elements and relationships are not valid. However, it may also be the case that the systems studied simply did not exhibit these kinds of behaviour. For example, instances of technical systems exhibiting the behaviour described by E5/RS3 may be identified in other contexts. An example is a production system comprised of robotic systems (active resources) that produces further robotic systems to drive the production system (active intended resources) (Fanuc, 2009). Further investigation of the nature of both intended active and passive resources in technical system activities is recommended as an area for future research in Section 9.4.

Regarding RS9 above, non-renewable stocks were described in Chapter 3 as those that do not regenerate significantly along anthropological timescales. Essentially, humans perceive the regeneration rate of these stocks to be zero because regeneration occurs over significantly longer timescales than consumption by human activities. For instance, crude oil stocks regenerate gradually along geological timescales of millions of years through the process of anaerobic decomposition (Viva Labs Inc., 2015). However, they are consumed at a considerably faster rate by human activities, with billions of barrels of crude oil produced per day by drilling and extraction activities to satisfy economic demand. Thus, a non-renewable resource stock may be more fully described as one where the regeneration rate is either zero, or far exceeded by the consumption rate. This is illustrated in the context of the Earth system using the S-Cycle in Figure 9-1. On this basis, it seems that RS9 is likely to be valid. The behaviour of the technical systems studied during evaluation was considered over relatively short timescales, i.e. not exceeding the operation phase of the life cycle (discussed further in Section 9.1.1.3). As such, given that RS9 appears to be manifested over considerably longer timescales as discussed above, it may be expected to some degree that instances would not be identified. The above discussion also raises the question of whether waste outputs from system activities may also, in the long term, contribute to non-renewable stocks. This is not clear from the research findings, and requires investigation over timescales that would likely exceed the life cycle of any technical system.

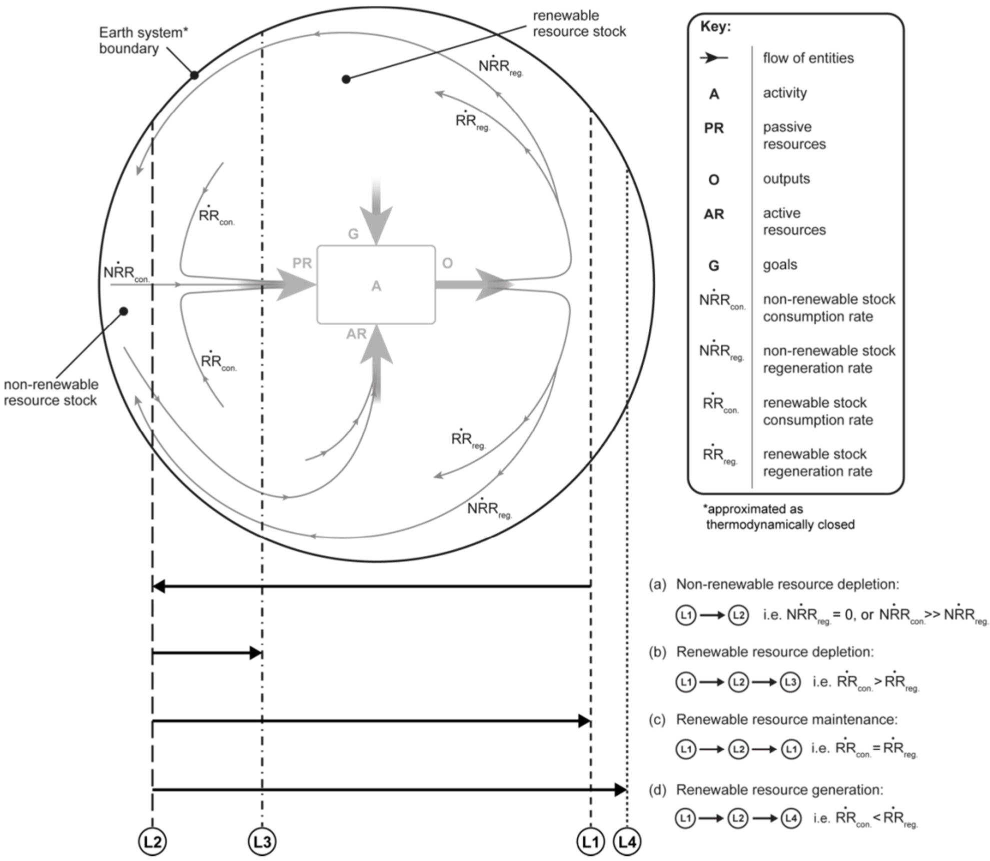


Figure 9-1: Consumption and production of resources in the Earth system

An additional element and corresponding relationship that were not determined through the inductive research conducted initially were identified during CS2. Namely, a contaminant input to the system activity from resource stocks within the wider SoI. A refined version of the S-Cycle model including contaminant inputs is presented in Figure 8-3 in Chapter 8 (Section 8.1.3.1). On the basis of the evaluation findings discussed above, it may be concluded that the refined model comprehensively describes the material and energetic aspects of behaviour that manifest the property of sustainability in a technical system. Further investigation of the nature of contaminant inputs through application of the refined model is recommended in Section 9.4.

9.1.1.2 Artefact and sector independence

During evaluation, the S-Cycle was applied to ten distinct technical systems. It may therefore be concluded that the model is artefact independent. However, all of the systems studied originated in the energy and marine (defence) sectors (with the exception of the car engine studied in WE2, which originated in the automotive sector). Furthermore, although the systems studied may be considered to be distinct as shown in Table 8-12 (Chapter 8, Section 8.3), the majority exist within the context of either a windfarm or a warship. Consequently, future research focusing on evaluation of the model's applicability to different systems in additional sectors is recommended in Section 9.4.

Evaluation of the S-Cycle model was conducted entirely within a technical systems context. That is, the model was not applied to other types of system, and the opinions of experts in other contexts were not elicited. Nonetheless, the model was developed on the basis of literature spanning nine sectors identified as making major contributions to sustainability research (Chapter 6). Furthermore, as discussed in Chapter 6 (Section 6.3), the concepts of activity and system that underpin the model are generic, and may be translated to other contexts. As such, it is suggested that in addition to technical systems, the model may potentially be applicable to different types of system in other contexts. Accordingly, future research focusing on evaluation of the model beyond a technical systems context is suggested in Section 9.4.

9.1.1.3 Scope of application

In Chapter 4 (Section 4.3), it was highlighted that the sustainability performance of a technical system may be interpreted differently depending on the spatio-temporal scale of the assessment. In this respect, a key finding to emerge from evaluation of the S-Cycle model is that the renewability of resources may be interpreted differently depending on how the SoI boundary and timescale for interpreting behaviour are defined. This was observed when applying the model to the CW system in CS2 (as discussed in Chapter 8, Section 8.2.1), and is illustrated in Table 8-9, which presents interpretations of the renewability of oil (used to lubricate the compressors) within different SoI boundaries and timescales. It was also highlighted in questionnaire responses provided by participants at WS1 and WS2, and in annotations certain groups added to their A3 templates during the practical exercise (reported in Section 8.2.1).

To interpret the renewability of resources involved in the CW system activity studied in CS2, they were traced back to the stock they were replenished by within the SoI, i.e. a warship at sea (Chapter 7, Section 7.1.3.2). In this respect, the SoI boundary appears to delimit the resource stocks that should be considered. For instance, as shown in Table 8-9, different SoI boundaries imply that the oil used in the CW system compressors should be traced back to different stocks:

- within the boundary of a warship at sea, the oil is replenished by the stock of oil on board the ship; and
- within the boundary of the whole Earth system, the oil is replenished by the natural stock of crude oil.

It seems that the timescale then defines the period over which the consumption and regeneration behaviour of these stocks should be considered in order to determine renewability. For example, in Table 8-9, the stock of oil on board the ship at sea is considered over timescales of (i) five and (ii) ninety days, leading to different interpretations of the stock's regeneration behaviour:

- over a timescale of five days, the stock cannot be renewed; and
- over a timescale of ninety days, the stock can be renewed via a supply ship.

It may be concluded from the findings discussed above that the SoI boundary and the timescale for interpreting behaviour both form basic aspects of the scope of application for the S-Cycle model. Both should be properly defined so that technical system behaviour is interpreted appropriately from a sustainability perspective. Guidance on defining the scope of application currently outlined in the S-Cycle guideline focuses solely upon defining the technical system to be studied[10]. Analysis of Student A's Masters dissertation revealed that in the absence of guidance, they did not define a wider SoI boundary or a timescale during CS1. This may explain why the student did not provide any indication of whether resources used in the HVAC system activity were renewable or non-renewable (discussed in Chapter 8, Section 8.1.1.1).

[10] In the current version of the guideline, the term SoI is applied to the technical system under study rather than the wider system.

As discussed in Chapter 8 (Section 8.2.1), the evaluation findings suggest that a relationship may exist between the SoI boundary and the timescale for interpretation. Furthermore, evaluation highlighted that the SoI boundary for sustainability may be impacted by other pre-existing boundaries. For instance, in a large-scale, complex technical system such as a warship, disciplinary, organisational, and even cultural boundaries may exist between design teams developing different parts of the system (M'Pherson, 1980; Hubka and Eder, 1988) It may in turn be challenging to define an SoI boundary that intersects these pre-existing boundaries, particularly if doing so requires the co-operation of disparate groups of decision makers. The evaluation findings may be seen to provide insight into the role of the SoI boundary and timescale in determining the renewability of resources, as discussed above. However, the findings do not explain the nature of any relationship that may exist between the two aspects, or between the SoI boundary and other kinds of boundary. Future research in these areas is proposed in Section 9.4, towards the development of rigorous guidance on how to define the scope of application for the S-Cycle model.

A final point regarding the scope of application for the S-Cycle is that during all three case studies, technical system behaviour was interpreted over timescales not exceeding the operation phase of the life cycle. That is, the renewable and non-renewable resources, intended resources, intended outputs, and waste associated with the systems during the materials extraction, manufacturing, and disposal/recycling phases of the life cycle were not considered. This was largely due to the time constraints of PhD research, as well as limitations regarding the availability of life cycle data on the systems. Given the potential impact of different timescales on the interpretation of resource renewability as discussed above, this should be addressed in any future industrial studies on the nature of the scope of application for the S-Cycle model (Section 9.4).

9.1.1.4 Identification of SPIs

As discussed in Chapter 7 (Section 7.1.1), the S-Cycle guideline is oriented towards assessing and improving a technical system's sustainability performance. Step 1 of the S-CPIP centres on motivating sustainability improvement efforts among decision makers. Steps 2 – 4 focus on sustainability performance evaluation, whilst Steps 5 and 6 entail taking action to improve performance (Figure 7-3). During CS1 and CS3 (Sections 7.1.3.1 and 7.1.3.2), Students A and B carried out Steps 1 – 4. That is:

- Step 1 – Motivating and understanding sustainability;
- Step 2 – Understanding the system of interest;
- Step 3 – Assessing sustainability performance; and

- Step 4 – Analysing sustainability performance.

Both students were able to define a set of sustainability goals and SPIs for a technical system (included in Appendix 8B), i.e. the HVAC system (CS1) and CW plant system (CS3) on a warship. The indicators identified in CS3 were developed by Student B in close conjunction with decision makers from BAE Systems, which may be seen to provide a degree of confidence in their appropriateness for the system studied.

The use of the S-Cycle model as a basis for identifying SPIs was further evaluated through an analytical study of 324 performance indicators. These were associated with a combination of *ad hoc* approaches and formal evaluation methods, and applied to a broad range of technical systems falling into seven categories (Chapter 7, Section 7.3). During the study, the S-Cycle was applied alongside the E^2 model to develop the S-Cycle Performance Matrix, a set of generic sustainability goals and SPI archetypes for technical systems. As reported in Chapter 8 (Section 8.2.3.2), in total, 94.1% (305) of the indicators analysed were found to be classifiable with respect to the proposed SPI archetypes.

On the basis of the above findings, it may be concluded that the S-Cycle model supports the identification of appropriate SPIs for technical systems. Furthermore, the guideline can be considered to provide a common approach to this activity across different technical systems. Both of the systems studied in CS1 and CS3 originated in the marine (defence) sector and formed part of a warship, as discussed in Section 9.1.1.2. As such, future studies involving application of the model and guideline to identify SPIs for a more extensive range of technical systems is recommended in Section 9.4. A disadvantage of the research is that the use of the guideline by engineering designers in industry was not evaluated. It was applied by the author, Student A, and Student B in the capacity of researcher. This was largely due to constraints on the time available for conducting case studies in the context of PhD research, and access to practicing engineering designers in industry. Future research to address this through further industrial case studies is also recommended in Section 9.4.

As discussed in Chapter 7, the S-Cycle's utility encompasses not only its effectiveness in supporting the identification of SPIs, but also the degree to which it can be understood and applied by its intended users i.e. engineering designers. The model underwent expert appraisal by engineering designers from BAE Systems and Company A at two workshops, where participants were asked to apply the model to a technical system in a practical exercise (Chapter 7 (Section 7.2). 74% of the total participants in the two workshops also provided opinions on various aspects of the model's utility through a self-report questionnaire. As discussed in Chapter 8 (Section 8.1), all groups of participants were able to apply the model to a technical system during the practical exercise (the systems considered are presented in Table 8-12). Furthermore, the majority of questionnaire respondents provided positive ratings for the model (Section 8.2.2):

- effectiveness as a tool for interpreting system behaviour – 50% rated *good* (Figure 8-6);
- ease of understanding – 75% rated *good*, and 5% rated *excellent* (Figure 8-7); and
- effectiveness as a tool for explaining the concept of sustainability – 62.5% rated *good*, and 15% rated *excellent* (Figure 8-8).

From the above findings, it may be concluded that the S-Cycle can be applied and understood by engineering designers. Nonetheless, certain comments provided by questionnaire respondents suggest that the model's abstract nature can make it difficult to comprehend in the absence of concrete examples (Chapter 8). For example, as reported in Section 8.2.2.1, certain respondents conveyed that they needed to see the outcomes of more real world applications of the model in order to formulate an opinion on its effectiveness as an interpretation tool. In Section 8.2.2.2, comments indicating that respondents found the model confusing prior to explanation and demonstration through example applications were reported. Following the pilot study prior to the workshops (Chapter 7, Section 7.2.1), certain terminology in the model was changed in order to make it more readily understandable by engineering designers. However, the evaluation findings suggest that further research on the comprehension of the model by these users may be needed (discussed in Section 9.4).

9.1.1.5 Consistency and system relationships

As demonstrated by the findings presented in Chapter 8 (Sections 8.1 and 8.3), the S-Cycle can be applied to interpret the behaviour of both coupled activities at the same system level, and activities/sub-activities operating at different system levels within a technical system. Therefore, it may be concluded that the model provides a consistent view on behaviour from a sustainability perspective throughout a technical system. That is, a consistent view of system activities operating at: (i) the *same* hierarchical level; and (ii) *different* hierarchical levels, as illustrated in Figure 9-2.

A key observation to emerge from the inductive research reported in Chapter 6 is that sustainability may be viewed as an emergent system property. That is, a property that depends upon both the components and relationships in a system. To define sustainability goals that are likely to result in improved system sustainability performance, knowledge of the relationships between the system activities is therefore needed. That is, coupling relationships as identified in Chapter 6, but also activity/sub-activity relationships such as those identified in the CW system function model developed during CS2 (illustrated in Figure 7-9 in Chapter 7, Section 7.1.3.2). Knowledge of relationships may be viewed as significant from other standpoints. For instance, in the context of sustainable complex systems design, Alfaris et al. (2010, p.1) state that "[the] work of parameter identification and modeling of coupling relationships precedes what is typically understood as mathematical modeling and optimization." This was demonstrated to some extent during Chapter 7 (Section 7.1.3.3), where Student B used the CW system function model as the basis for a quantitative model of the CW plant system. Furthermore, knowledge of activity/sub-activity relationships can support the identification of suitable aggregation functions (e.g. additive, multiplicative, etc.) for SPIs defined to measure performance at the whole system level (Hubka and Eder, 1988; O'Donnell and Duffy, 2005; Bodini, 2012).

Given the S-Cycle's applicability to system activities at various hierarchical levels as discussed above, it may be concluded that the model provides a consistent basis for modelling both coupling and activity/sub-activity relationships from a sustainability perspective, as illustrated in Figure 9-2. The significance of activity relationships is not currently explained in the guideline, and no guidance on how to model them is provided. To address this, future research focusing on more extensive modelling of system relationships using the S-Cycle model and guideline is outlined in Section 9.4.

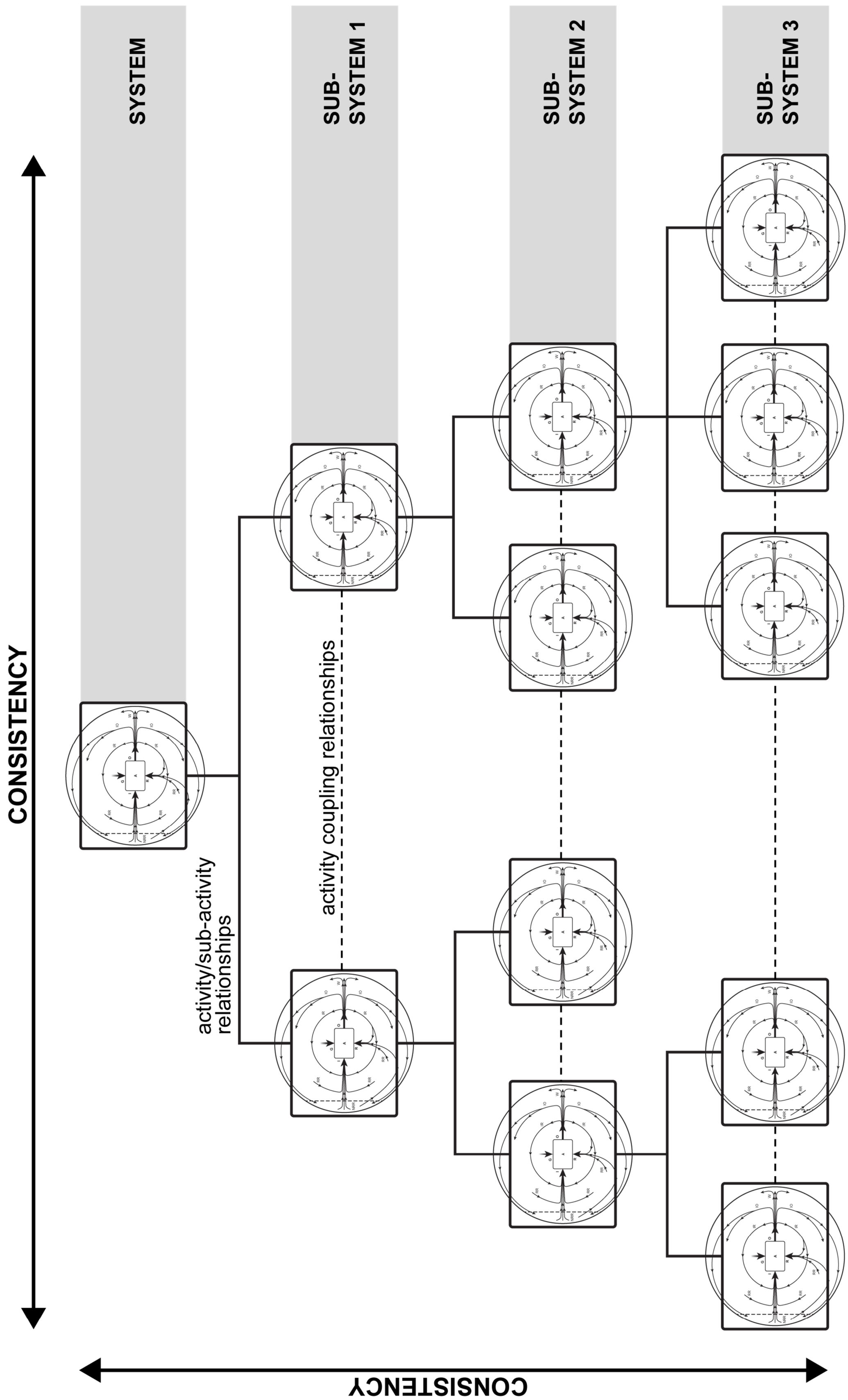


Figure 9-2: S-Cycle consistency in a technical system

Figure 9-2: S-Cycle consistency in a technical system

9.1.1.6 Summary of advantages and disadvantages

On the basis of the discussion presented in Sections 9.1.1.1 – 9.1.1.5 above, the advantages and disadvantages associated with the S-Cycle model and guideline may be summarised.

The key advantages are considered to be:

- ☑ The refined model comprehensively describes the material and energetic aspects of behaviour that manifest the property of sustainability in a technical system.
- ☑ The model was applied to ten distinct technical systems during evaluation, and is therefore considered to be artefact independent.
- ☑ The model was developed on the basis of literature spanning nine sectors and as such, may potentially be applicable to different types of system in other contexts.
- ☑ The model supports the identification of appropriate SPIs for technical systems, with the guideline providing a common approach to this activity across different technical systems.
- ☑ The model can be applied and understood by its intended users, i.e. engineering designers in industry.
- ☑ The model can be applied to interpret activity behaviour at different system levels, and is therefore considered to provide a consistent basis for modelling activity relationships throughout a technical system from a sustainability perspective.

The key disadvantages are viewed as:

- ☒ Support was not identified for two model elements and corresponding relationships during evaluation, i.e.: the production and consumption of active intended resources; and intended output contributing to non-renewable resource stocks.
- ☒ The majority of the technical systems studied during evaluation originated in the energy and marine (defence) sectors, and formed part of either a wind farm or a warship. Thus, both the applicability of the model, and its utility in terms of SPI identification, are limited to these areas until further evaluation is conducted in additional sectors.
- ☒ The guideline does not clearly explain how to define the scope of application for the S-Cycle model, i.e. the need to define both the SoI boundary and a timescale for interpreting behaviour is not conveyed.
- ☒ The use of the guideline by engineering designers in industry was not evaluated during the research. During the case studies, the author, Student A, and Student B applied the guideline solely in the capacity of researcher.

- ☒ The abstract nature of the model can make it difficult for engineering designers to comprehend in the absence of concrete examples.
- ☒ The guideline does not provide guidance on how to model activity relationships in a technical system from a sustainability perspective.

9.1.2 The S-Loop model

The S-Cycle model discussed in Section 9.1.1 is the foundation of the S-Loop model (Figure 6-7, Chapter 6), which formalises an iterative process of interpretation and action undertaken by humans striving for sustainability. The process is represented as operating between the external and interpreted worlds, i.e. the world extrinsic to the human mind (where systems and activities exist), and the inner mental world of a human being (where knowledge exists), respectively. Humans interpret activity behaviour within a particular SoI to produce knowledge, then take action on the basis of this knowledge to alter behaviour, before interpreting behaviour post-action to produce further knowledge that determines further action, and so on and so forth.

The S-Loop addresses issue I1 stated previously. That is, the lack of a consistent view on how the sustainability of human activities and systems can be improved (Chapter 5, Section 5.1). Thus, it is considered to position the S-Cycle model within the context of human interpretations of the meaning and value of sustainability (Chapter 3, Sections 3.1 – 3.3). The S-Loop was developed on the basis of the same broad body of literature considered in order to build the S-Cycle model. From this perspective, the model is considered to provide a comprehensive view on the fundamental elements involved in human efforts towards sustainability. It is also potentially applicable in multiple sectors. The model was evaluated through WE1, where it was applied to a bioethanol production system described in the literature (Section 6.3 of Paper C, Appendix 3). Further evaluation in industry is needed to gain deeper insights into these aspects (elaborated in Section 9.4). However, both the S-Loop *per se* and WE1 underwent peer review by three independent reviewers as part of Paper C (Appendix 3), which was subsequently published in the Journal of Environmental Management. This endorsement of the work may be seen to provide a degree of support for the model's validity.

In summary, the advantages of the S-Loop model are considered to be:

- ☑ The model positions the S-Cycle within the context of human interpretations of sustainability.
- ☑ It comprehensively describes the fundamental elements involved in human efforts towards sustainability.

- ☑ It was developed on the basis of literature spanning nine sectors and as such, is potentially broadly applicable.
- ☑ Endorsement of the model through peer review and publication in the Journal of Environmental Management provides a degree of support for its validity.

The disadvantages are viewed as:

- ☒ The model was not applied to technical systems in industry during the research, and opinions on the model were not elicited from engineering designers.

9.2 Research methods

As discussed in Chapter 2, five research methods were applied during the research, namely: inductive literature investigation (Chapter 6), worked examples, case study, expert appraisal through a practical exercise and questionnaire, and an analytical study of performance indicators (Chapters 7 and 8). The advantages and disadvantages each of these are briefly discussed below.

9.2.1 Inductive literature investigation

The S-Cycle and S-Loop models were developed through an inductive literature investigation (reported in Chapter 6). Detailed observations regarding the nature of sustainability and its achievement were firstly made on the basis of the literature from nine sectors. The models were then developed by inferring the general elements and relationships involved in sustainability from the observations.

The investigation cannot be described as comprehensive given the size and variety of the sustainability literature as noted in Chapter 3. However, its broad scope may be viewed as a key advantage. This facilitated investigation of the basic constitution of sustainability – that is, the fundamental elements of the concept, rather than contextual interpretations. Furthermore, all elements and relationships comprising the S-Cycle model were identified through this investigation, with the exception of the contaminant input (discussed further below).

A disadvantage of this method is that the literature was gathered and analysed by a single researcher (the author) following a largely non-systematic process. As such, it is possible that the findings may be subject to bias. These concerns are mitigated to an extent by the evaluation findings, which provide considerable support for the validity of the S-Cycle model and a degree of support for the S-Loop model. Nonetheless, the possibility of bias could have been more rigorously addressed through the involvement of an additional researcher to interpret the literature (discussed further in Section 9.3), and/or through the use of the systematic review method. Systematic literature review is a research method whereby every high quality publication on a particular topic is gathered and analysed through a rigorous, transparent, and replicable process. The intention is that all valid and reliable evidence relating to a particular issue or phenomenon is considered by the researcher, minimising the potential for bias in the investigation findings. A systematic review is typically undertaken by more than one researcher, which may have been difficult to achieve given the resources typically available to a PhD researcher.

9.2.2 Worked examples

Two worked examples (WE1 and WE2) were developed independently by two researchers to provide initial evaluation of the S-Cycle model, as well as the S-Cycle guideline and the S-Loop to a limited extent (Chapter 7, Section 7.1.2 and Section 6.3 of Paper C, Appendix 3). In WE1, the S-Cycle and S-Loop models were applied to a bioethanol production system described in the literature by the author. In WE2, the S-Cycle model and guideline were applied to a petrol car engine by Student B.

The initial evaluation provided by WE1 was critical in securing publication of the S-Cycle and S-Loop models in an international journal (Paper C, Appendix 3), whilst WE2 supported Student B in securing the interests of decision makers from BAE Systems at the start of CS3. A key advantage of using worked examples in this way is that they provided evaluation rapidly, without the need to negotiate access to companies in industry. However, a drawback is that they did not provide thorough evaluation of the models. For instance, WE1 provided a degree of support for the validity of the S-Loop model, but limited findings relating to its applicability and utility. Furthermore, neither WE1 nor WE2 revealed the additional contaminant input included the refined S-Cycle model (identified through CS2). Finally, both worked examples were developed using data extracted from the literature rather than gathered in industry. This is considered to be a disadvantage, given that the S-Cycle and S-Loop models were initially developed from the literature. The use of student design projects focusing on technical systems as a data source could have provided a means to address this, whilst still avoiding the need for industrial access.

9.2.3 Case studies

Three case studies were carried out to evaluate the S-Cycle model and guideline through application to different sub-systems of a warship (Chapter 7, Section 7.1.3). These were: CS1, where two HVAC systems were compared on the basis of their sustainability performance (conducted by Student A); CS2, focusing on interpretation of a CW system's behaviour from a sustainability perspective (conducted by the author); and CS3, focusing on the identification of SPIs for a CW plant system (conducted by Student B). CS1 was carried out in conjunction with the company Babcock, whilst CS2 and CS3 were conducted at BAE Systems.

In contrast with the worked examples discussed above, the case studies provided in depth evaluation. That is, they were conducted in industry, focusing on industrial systems as opposed to those described in the literature, and over time – the duration of CS1 and CS3 was approximately 10 months, and CS2 approximately 7 months. A key advantage of the studies is that they were conducted independently by different researchers, facilitating triangulation of the findings. Cross-case analysis was conducted to compare the findings from each study with one another (Chapter 7, Section 7.1.4). The findings were also compared with the findings from other parts of the evaluation approach. This facilitated assessment of the degree of convergence between the case studies and the other evaluation methods (as shown in Table 8-7 and discussed further in Section 9.3). A disadvantage of the case studies is that CS2 and CS3 were conducted at the same company, and both companies involved in the three studies operate within the same sector. Further case studies carried out at companies in additional sectors could serve to increase confidence in the findings of CS1, CS2, and CS3, and could provide additional insights that were not revealed by these studies. Furthermore, during all three case studies, the model and guideline were applied by researchers rather than engineering designers (i.e. the intended users). Observing their application by the latter may have yielded additional insights into their utility that were not revealed to the researchers. The possibility of future research in this area, employing observational and participatory methods, is discussed in Section 9.4.

The use of multiple data collection techniques may be viewed as another advantage of the case studies. That is, the analysis of technical documentation describing the three technical systems studied, and unstructured interviews with engineering designers familiar with the systems. In CS2 and CS3, this supported the collection of comprehensive data as a basis for applying the S-Cycle model. A disadvantage of CS1 in this respect is that only limited data on the HVAC systems under study was available to Student A. Instead, they largely used data gathered from technical documentation describing HVAC systems installed on trains. However, it is suggested that this is unlikely to have had a significant impact on the evaluation findings. Firstly, the HVAC system on a train is a technical system and as such, is a suitable basis for evaluation of the S-Cycle. Secondly, there are no considerable differences between the basic functioning and structure of the HVAC system on a train and a warship (Student A, 2013).

During CS2, the IDEF0 modelling language was applied to develop a function model of the CW system studied (Chapter 7, Section 7.1.3.2). This model was validated by engineering designers at BAE Systems and used to support application of the S-Cycle to the CW system. That is, the function model was interpreted from a sustainability perspective using the S-Cycle. The function model describes in detail the overall activity carried out by the CW system, and 43 interconnected sub-activities. Interpreting this model facilitated identification of the contaminant input that did not emerge from the inductive literature investigation. Furthermore, owing to the hierarchical structure inherent in IDEF0 function models, considerable insights into the S-Cycle's applicability at different system levels were generated.

The interpretation of the function model was carried out by the author, and then checked by engineering designers from BAE Systems to address any misinterpretations or bias. The designers largely agreed with the original interpretation; however, their ability to carry out this check effectively was largely dependent upon their understanding of the S-Cycle model and the IDEF0 language. The check was conducted during WS1 following presentations on sustainability and the S-Cycle, and the practical exercise (discussed further in Section 9.2.4), in order to familiarise participants. Furthermore, as discussed in Chapter 7 (Section 7.1.3.1), the IDEF0 language was chosen because: (i) it was familiar to BAE Systems designers; and (ii) it employs a representation similar to the activity formalism adopted in the S-Cycle. Nonetheless, participants are likely to have had less knowledge of the S-Cycle than the author, and it is possible that this may have affected their conclusions regarding the accuracy of the interpretation. This could potentially have been addressed by involving Students A and B in checking the interpretation, given that the former gained experience with the S-Cycle over the course of 10 months during CS1 and CS3. This was not possible owing to constraints regarding the completion dates of the students' respective Masters courses.

In summary, the advantages of the case studies are considered to be:

- ☑ The studies provided in depth evaluation of the S-Cycle model, i.e. were conducted in industry focusing on industrial systems rather than systems in the literature, and over time (between 7 – 10 months).
- ☑ The studies were conducted independently by three different researchers, facilitating triangulation of the findings through cross-case analysis. The findings of each study were also triangulated with findings from the other evaluation methods.
- ☑ Multiple data collection techniques were applied during each study, i.e. analysis of technical documentation and unstructured interviews with engineering designers.
- ☑ The use of the IDEF0 modelling technique during CS2 (i.e. the CW system function model) facilitated identification of the contaminant input missed during the inductive literature investigation, and generated considerable insights into the model's applicability at different system levels.

The disadvantages are viewed as:

- ☒ Both CS2 and CS3 were conducted at the same company, and both companies involved in the studies operate within the same sector.
- ☒ The model and guideline were applied solely by researchers in each study. Observing their application by the intended users, i.e. engineering designers, may have yielded additional insights into their utility that were not revealed to the researchers.
- ☒ The author's interpretation of the CW system function model was checked by engineering designers, who are likely to have had less knowledge of the S-Cycle than the author. This may potentially have affected their conclusions regarding the accuracy of the interpretation.

9.2.4 Expert appraisal workshops

As discussed in Chapter 7 (Section 7.2), the opinions of 27 engineering designers, collectively holding over 425 years of experience, were elicited through a practical exercise and questionnaire delivered at two workshops. Participants in WS1 worked in the marine (defence) sector (BAE Systems), whilst those in WS2 worked in the energy sector (Company A). Prior to the workshops, a pilot study was conducted with three engineering design researchers to test the practical exercise and questionnaire.

The workshops facilitated elicitation of a breadth of expert opinion within a short period of time, which is considered to be a key advantage of this evaluation method. Each workshop lasted for no more than three hours. Alternative methods for eliciting opinions could have been, for instance, one-to-one interviews or a questionnaire self-administered by respondents in their own time. However, all of the participants were industrialists with significant demands on their time. Thus, it is suggested that gathering opinions from the same number of participants (27) within the time permitted by PhD research may not have been possible had these methods been applied. As noted above, workshop participants were from two different sectors. Whilst the workshops provided breadth of opinion in terms of individual engineering designers, a more comprehensive range of opinions could have been obtained by running workshops with participants from additional sectors. This was not done during the research owing to PhD time constraints.

Whilst the workshops yielded a broad set of opinions on the S-Cycle model, a drawback is that they were not conducive to gathering in depth opinions that could have provided deeper insights into the model. Although open response boxes were included in the questionnaire alongside Likert scales for ratings, the comments provided were necessarily brief given the time constraints of each workshop. Furthermore, as discussed in Chapter 8 (Section 8.2.2), several participants noted in their questionnaire responses that they did not feel they had sufficient understanding of or experience with the model to formulate opinions on its certain aspects of its validity and utility. This could potentially have been addressed by allotting more time for the workshops, and developing further exercises to provide participants with more extensive experience of applying the model. Given the constraints on participants' time as discussed above, this may have been difficult to achieve during the research. However, it presents an avenue for future research (Section 9.4).

Regarding the length of the workshops, it was found that insufficient time was allotted for participants to complete both the practical exercise and the questionnaire during WS1. As discussed in Chapter 7 (Section 7.2), the planned duration was 2 hours. However, as noted in Section 7.2.2.1, the workshop ran for approximately 2.5 hours. Owing to constraints on their time, this meant that 54% (6 out of 11) of the participants were unable to provide responses to the questionnaire. Additionally, weaknesses may be identified in the questionnaire *per se*. As stated in Chapter 7 (Section 7.2.2.2), the wording of two questions was altered following insights gained during WS1. As such, responses provided by participants in WS1 and WS2 may be based on different interpretations of these questions. Since the questionnaire responses received at WS1 and WS2 were analysed as a single set of data (Chapter 8, Section 8.2.2), this may reduce the reliability of the findings. Additionally, one of the altered questions gathered opinions on a different aspect of the model than intended (Chapter 7, Section 7.2.2.2). These issues could potentially have been addressed by conducting more than one pilot study prior to the workshops, in order to more thoroughly test and refine the questionnaire and the timing of the workshop. This was not done during the research owing not only to PhD time constraints, but also constraints on the time of potential pilot participants, i.e. engineering design researchers at the University of Strathclyde.

A disadvantage of the questionnaire is the possibility that the responses obtained are subject to bias. For example, 54% (6 out of 11) participants in WS1 had worked closely with the author previously during CS2. Therefore, it is possible that their responses may have been biased by personal opinions. As discussed in Chapter 7 (Section 7.2), WS2 was delivered to participants from Company A as part of a continuing professional development (CPD) course. As shown in Chapter 8 (Section 8.2.2), one participant provided comments suggesting that their response may have been influenced by their opinion of the CPD course. The response was subsequently discounted and as such, did not influence the questionnaire findings.

A final point to be highlighted regarding the methods used for expert appraisal is that the model was applied by participants under the controlled conditions of a structured workshop. These experiences then served, at least partially, as the basis for their opinions of the model. It is possible that participants may have provided additional insights and opinions on the model had they been applying it in an uncontrolled industrial context over a period of time, i.e. in a real world situation. This could be explored through future research focusing on the use of the model by engineering designers in industry, which, as noted in Section 9.1.1.4, is proposed in Section 9.4.

In summary, the advantages of the expert appraisal workshops are considered to be:

- ☑ They facilitated elicitation of a breadth of expert opinion within a short period of time. Each workshop lasted no more than three hours, and a total of 27 engineering designers collectively holding over 425 years of experience participated.
- ☑ Opinions were elicited from engineering designers in two industrial sectors, i.e. energy and marine (defence).

The disadvantages are viewed as:

- ☒ A more comprehensive range of opinions could have been gathered through the involvement of participants from additional sectors.
- ☒ Owing to the format of the workshops and the time constraints on running them, they were not conducive to the elicitation of in depth opinions on the model. Furthermore, they may not have provided participants with

sufficient experience with the model to formulate opinions on certain aspects of its validity and utility.

- ☒ The wording of one of the questionnaire questions was altered between the two workshops. The responses provided by participants at WS1 and WS2 may therefore have been based on different interpretations of the question, which may reduce the reliability of the questionnaire findings.
- ☒ The questionnaire responses may be subject to bias, e.g. personal biases owing to working relationships with the author.

9.2.5 Analytical study of performance indicators

As discussed in Chapter 7 (Section 7.3), the S-Cycle model and guideline were further evaluated through an analytical study of 324 performance indicators applied to evaluate the sustainability performance of technical systems. A major output from the study was the S-Cycle Performance Matrix (Chapter 8, Section 8.2.3.2).

The major advantage of the study is considered to be its comprehensive coverage of different indicators. In Chapter 4 (Section 4.3.2), a range of different performance evaluation methods commonly applied to technical systems was identified. This included both *ad hoc* approaches, and formal evaluation methods. Namely, the latter includes embodied energy analysis, emergy accounting, energy analysis, exergy analysis, life cycle assessment, and material flow accounting. As shown in Appendix 7A, indicators from all of these methods, as well as *ad hoc* approaches, were included in the analysis sample. Furthermore, the sample consisted of a significant number of indicators, i.e. 324 as stated above.

The analysis was conducted in a methodical fashion, whereby the same analysis procedure was applied to each indicator in the sample, and the results recorded in a consistent manner (Appendix 7B). However, a disadvantage is that the analysis was carried out by the author alone. The findings are dependent on the author's interpretation of the indicators, which could potentially be faulty or subject to bias. This could have been addressed by involving additional researchers in the analysis process (discussed further in Section 9.3). However, the impact of any bias or misinterpretation present in the study on the overall evaluation findings is considered to be minimised through triangulation with other research methods.

9.3 Overall approach

As discussed in Chapter 2, the process of research should be controlled, systematic, reliable and verifiable, empirical, and critical. To achieve this, the adoption of a suitable research approach is crucial. A researcher's understanding of a particular research problem is affected by their philosophical worldview. In turn, this understanding informs decisions regarding their research approach. In the research reported in this thesis, the philosophy of critical realism was adopted owing to the involvement of both natural systems and processes, and subjective aspects of human beings such as meanings and values (Section 2.3.1). In accordance with the critical realist worldview, the research methodology was multi method and triangulated to address potential misinterpretations and bias. Multiple triangulation was achieved, i.e. the research was triangulated with respect to data sources, investigators, theories, and methods (Section 2.3.2).

The data sources used in the research included samples of sustainability literature, technical documentation describing systems in industry, engineering designers from industry, and a sample of performance indicators applied to assess the sustainability performance of technical systems. This combination of data sources facilitated thorough investigation of the constitution of sustainability using both empirical and industrial data.

Between-method triangulation was achieved through the application of five research methods as discussed in Section 9.2. Furthermore, within-method triangulation was achieved through two independent worked examples, and three independent case studies. Method triangulation provides a means to assess the degree of convergence among different sets of findings, i.e. the extent to which findings yielded by different methods are in agreement (Shih, 1998). In Chapter 8, the degree of convergence among the research methods was considered in terms of findings relating to the validity of the S-Cycle model, as illustrated in Table 8-2 (Section 8.1). Method triangulation has also been said to increase the researcher's knowledge and understanding of the research area (Shih, 1998; Wang and Duffy, 2009). In this vein, the appraisal workshops provided expert opinions on the model that were not yielded by any other method. Thus, triangulating the literature investigation, worked examples, case studies, and analytical study with the workshops provided greater insights into the model than could have been obtained with the former alone.

On the basis of work conducted by other authors, literature review, worked examples, and case studies may be considered to be valid research methods providing a degree of reliability in a technical systems context (e.g. Duffy and O'Donnell 1998; O'Donnell and Duffy, 2002, 2005; Gorod et al., 2015). The interactive workshops employed two data collection techniques: a practical group exercise involving application of the S-Cycle to a system, and a self-report questionnaire. The practical exercise was developed by the author and tested through a pilot study, which provides a degree of confidence in its validity and reliability as a data collection technique. As with the methods discussed previously, questionnaire has been shown to be a valid and reliable technique in a technical systems context (e.g. Wang, 2008), although weaknesses regarding the construction and testing of the questionnaire delivered at the workshops were identified in Section 9.2.4.

Theory triangulation was achieved through the adoption of an inductive process to build the S-Cycle model, and a deductive process to evaluate it. The model was firstly built by making inferences from observations on the constitution of sustainability gathered from the literature (induction). The proposed model was then applied to technical systems, and conclusions about its validity, utility, and applicability were drawn from observations gathered using the evaluation methods discussed above (deduction). As discussed in Chapter 8 (Section 8.1), all model elements and relationships were found to be supported by the evaluation findings, with one additional element and corresponding relationship identified. Thus, the findings from the inductive and deductive processes may be considered to largely converge. Additionally, however, the deductive process generated further insights into the constitution of sustainability that were not highlighted by the inductive process.

Finally, investigator triangulation was achieved through the involvement of three researchers in the evaluation of the S-Cycle, namely the author, Student A, and Student B as discussed in Chapter 7 (Section 7.1). This provided multiple perspectives on the model and the S-Cycle guideline, and mitigated against the potential for bias and faulty interpretations to some degree. The worked examples were developed independently by the author and Student B, whilst the case studies were carried out independently by the three researchers. Students A and B had limited knowledge of and experience with the S-Cycle model. This may be viewed as an advantage, in that it highlighted shortcomings in the guideline that may otherwise have been missed. For instance, as discussed in Chapter 9 (Section 9.1.1.3), Student A did not define a SoI boundary or a timescale for interpreting the behaviour of the HVAC system studied in CS1. This is considered to highlight the need for further development and evaluation of guidance on defining the model's scope of application for inclusion in the guideline. However, it is also possible that misinterpretations of certain aspects of the model and guideline by the students could have negatively impacted upon the quality and reliability of the findings from the worked examples and case studies. For example, as discussed in Chapter 7 (Section 7.1.3.1), an output produced by Student A during CS1 was a textual interpretation of the studied HVAC system's behaviour from a sustainability perspective. In Section 8.1 of Chapter 8, evidence supporting the validity of the S-

Cycle model was identified from this interpretation by the author. However, the quality of the evidence provided by the interpretation is at least partially dependent upon how well Student A understood the S-Cycle. For example, the student did not identify any examples of intended resources in the HVAC system. As such, their interpretation of the system's behaviour does not support the validity of this model element and its corresponding relationships. However, it is possible that intended resources were reflected in the behaviour of the HVAC system, but not recognised by the student owing to a lack of experience and/or understanding of the S-Cycle model and guideline. Nonetheless, concerns regarding misinterpretations of this nature are considered to be mitigated to some extent by the following:

- Triangulation of the students' case studies (CS1 and CS2), from both a within-method and between-method perspective.
- The supervision each student received from decision makers at their case study companies and academic advisers at the University of Strathclyde. Additionally, the outcomes of both students' studies were subject to considerable scrutiny by engineering design academics through evaluation and grading of their Master's dissertations.

Investigator triangulation could have been beneficial in other parts of the research. For instance, as discussed in Sections 9.2.1 and 9.2.5, both the inductive literature investigation and the analytical study of indicators were carried out by the author alone. Given that the findings yielded by each of these methods were necessarily affected by the author's interpretations, the involvement of more than one researcher could have addressed any potential misinterpretations and bias. However, access to additional researchers was not available during these parts of the research and as such, investigator triangulation was not possible.

A final reflection on the research approach relates to the manner in which it was developed and the potential alternatives in this respect. Design research shares a broad range of epistemological relationships with research in the natural, formal, human, social, and applied sciences (Reich, 1994; Horváth and Duhovnik, 2005). In turn, design research has traditionally been considered to borrow research methods and approaches from these related areas (Bender et al., 2002; Horváth and Duhovnik, 2005). For instance, both the case study method applied to evaluate the S-Cycle model, and the overall triangulation approach adopted to carry out the research, are traditionally associated with research in the social sciences (Denzin, 1970; Yin, 2003). However, in recent years, there have been efforts by certain researchers to develop formal, structured approaches that are specifically oriented towards the general goals of design research, i.e.: (i) the development of models/theories about the phenomenon of design; and (ii) the development of knowledge, methods, and tools to better support the design process (Bender et al., 2002). A notable example is the Design Research Methodology (DRM) developed by Blessing and Chakrabarti (2009). The DRM suggests a structured approach to design research, consisting of an initial research clarification phase followed by any number of alternating descriptive and prescriptive studies as required given the research aim. Blessing and Chakrabarti (2009) present the methodology as sufficiently flexible for adaption to different research problems, but sufficiently structured to ensure that research is conducted efficiently and effectively. The DRM was not considered as a research approach owing to the researcher's lack of experience and knowledge of research methodology at the beginning of the PhD. It is difficult to know, in retrospect, whether different outcomes may have been achieved through adoption of the DRM. However, this kind of pre-structured approach may have improved the performance (i.e. efficiency and effectiveness) of the research process and the time taken to complete each phase. In turn, this could have permitted industrial evaluation of the S-Loop model , which was not carried out due to time constraints.

In summary, the advantages of the research approach are considered to be:

- ☑ The adopted critical realist worldview was suitable for studying sustainability, owing to the involvement of natural systems/processes and human beings.
- ☑ The constitution of sustainability was investigated using both empirical and industrial data, through the triangulation of literature and industrial data sources.
- ☑ Between-method triangulation was achieved through the use of five research methods. Within-method triangulation was achieved through two independent worked examples, and three independent case studies. This allowed the degree of convergence among the evaluation findings to be assessed, and provided greater insights into the S-Cycle model than could be obtained by using the methods in isolation.
- ☑ Theory triangulation was achieved through the adoption of an inductive process to build the S-Cycle and S-Loop models, and a deductive process to evaluate them. The latter generated additional insights into the constitution of sustainability that were not highlighted by the former.
- ☑ Investigator triangulation was achieved through the involvement of three researchers in the evaluation, i.e. the author (WE1 and CS2), Student A (CS1), and Student B (WE2 and CS3). This provided multiple perspectives on the S-Cycle model and guideline, and highlighted shortcomings in the guideline that may otherwise have been missed.

The disadvantages are viewed as:

- ☒ It is possible that Students A and B could have misinterpreted certain aspects of the S-Cycle model and guideline during CS1 and CS3. This in turn could have affected the reliability of the case study findings.
- ☒ Investigator triangulation was not achieved during the inductive literature investigation or the analytical study of performance indicators, which could have addressed the potential for misinterpretations and bias on the part of the author.
- ☒ The adoption of a formal, structured approach, such as the DRM outlined by Blessing and Chakrabarti (2009), could have improved the performance of the research process and permitted industrial evaluation of the S-Loop model.

9.4 Future work

The advantages and disadvantages associated with the research findings, methods, and approach were discussed in Sections 9.1 – 9.3. A number of avenues for future research were highlighted. These are elaborated in the following sub-sections. Possible future applications of the S-Cycle model and guideline are discussed in Section 9.4.1, and future research to evaluate the S-Loop model is outlined in Section 9.4.2.

9.4.1 The S-Cycle model and guideline

In Sections 9.1.1 and 9.1.2, several areas for further research on the S-Cycle model and guideline were identified, which are elaborated below. Namely:

- further investigation of the nature of intended resources and contaminant inputs in technical system activities (Section 9.4.1.1);
- further evaluation in different sectors and focusing on different types of system (Section 9.4.1.2);
- evaluation of use by engineering designers in industry (Section 9.4.1.3);
- further investigation of the scope of application for the model (Section 9.4.1.4); and
- further investigation of system relationships (Section 9.4.1.5).

9.4.1.1 Intended resources and contaminants

As stated in Section 9.1.1.1, further investigation of two aspects of behaviour described in the S-Cycle model is recommended: active and passive intended resources, for which limited support was identified during evaluation; and contaminant inputs, identified through evaluation and incorporated into the refined model. Future work to apply the S-Cycle to a more extensive range of systems (discussed in Section 9.4.1.2 below) could provide deeper insights into the nature of the above aspects. In particular, a specific topic of research on contaminant inputs may be the notion of 'contaminant thresholds.' For example, the specific contaminant identified in CS2 was an input of air to the CW system (discussed in Chapter 8, Section 8.1.3.1). This air was removed from the system by a vacuum degasser, which begins to operate once the air content of the chilled water flow in the system reaches a certain threshold level. This suggests that a technical system may have associated contaminant thresholds. That is, for a particular contaminant, an input level beyond which the system's functioning may be disrupted. An input level below this threshold may be tolerated with minimal disruption to system operation. However, this was not investigated in the current work owing to time and resource constraints.

9.4.1.2 Sector evaluation

As discussed in Section 9.1.1.2, it may be concluded from the evaluation findings that the S-Cycle is artefact-independent. However, the majority of the technical systems studied during evaluation originated in the energy and marine (defence) sectors and thus, its applicability to different sectors is currently limited. Furthermore, during CS1 and CS3, the S-Cycle guideline was applied alongside the model to identify SPIs for two systems originating in the marine (defence) sector. The use of the guideline to determine SPIs for systems in other sectors was not evaluated (discussed in Section 9.1.1.4). To gain further insights into both the extent of the model's applicability, and the guideline's degree of generality, future case studies focusing on the identification of SPIs for technical systems in additional sectors are strongly recommended.

It was posited in Section 9.1.1.2 that the S-Cycle model may be applicable to other types of system, given its foundation in literature from a broad range of sectors. This presents an additional avenue for future studies. For instance, during CS2, decision makers from BAE Systems expressed an interest in applying the model to their organisational system, the wider business, and ultimately the supply chain driving the business. Exploratory studies in these areas could demonstrate the feasibility of using the model and guideline to assess and improve the sustainability performance of other types of system.

9.4.1.3 Industrial user evaluation

The expert appraisal workshops conducted during evaluation (discussed in Section 9.2.4) involved participants from the energy and marine (defence) sectors.

Further workshops involving participants from additional sectors could be beneficial in terms of gathering a broader range of opinions on the S-Cycle model. Additionally, building upon WS1 and WS2, more detailed opinions could potentially be gathered via future workshops by allotting more time for their delivery, and developing additional exercises to provide participants with more extensive experience of applying the model.

As discussed in Sections 9.1.1.4 and 9.2.3, the use of the model and guideline by engineering designers in an uncontrolled industrial context was not evaluated during the research. Furthermore, the evaluation findings suggest that the model may be difficult for engineering designers to comprehend in the absence of concrete examples. On this basis, future case studies focusing on the application of the model and guideline by designers in industry are recommended. These could involve participatory research methods to facilitate direct observation of decision makers in an uncontrolled organisational setting, which may provide insights into how the model can be made more readily understandable to its intended users. It may also highlight shortcomings in the guideline that have not been identified through the research reported in this thesis. In depth, one-to-one interviews with engineering designers in this context could also yield more insightful expert opinions on the model than could be gathered during the appraisal workshops (discussed in Section 9.2.4).

9.4.1.4 Scope of application

In Section 9.1.1.3, it was concluded on the basis of the evaluation findings that the SoI boundary and the timescale for interpreting system behaviour both form basic aspects of the scope of application for the S-Cycle model. However, this is not conveyed in guidance on how to define the scope provided in the guideline. Updating and evaluating this part of the guideline is a fundamental area to be addressed by future research, given that the scope must be properly defined for behaviour to be interpreted appropriately using the S-Cycle.

The evaluation findings open up several avenues for future investigation in this area. Firstly, the findings suggest that a relationship may exist between the SoI boundary and the timescale for interpreting behaviour. Explanatory research is needed to establish and describe the nature of any such relationship. Knowledge in this respect could provide the foundation for developing a rigorous process for defining the scope of application that may be incorporated into the guideline. Secondly, participants in WS1 highlighted that the SoI boundary may be impacted by other pre-existing boundaries. In the design of a large-scale, complex technical system such as a warship, several boundaries may exist between design teams working on different parts of the system e.g. disciplinary, organisational, and cultural as discussed in Section 9.1.1.3. This could provide the context for future studies on the nature of the SoI boundary in relation to other types of boundary, and the impact of the latter on the definition of the former.

Finally, as discussed in Section 9.1.1.3, the S-Cycle was applied to interpret the behaviour of technical systems over timescales not exceeding the operation phase of the life cycle during evaluation. As such, future industrial case studies applying the model across greater portions of the life cycle are strongly recommended. A study focusing on the full life cycle of a system would entail modelling and evaluation of direct material and energetic inputs/outputs associated with the system during its operational life, but also the indirect inputs/outputs associated with materials extraction, manufacturing, transportation, and disposal/recycling activities. It is not immediately clear from the current research what the SoI boundaries may be for such a study. Clarification of these boundaries through case studies may reveal general precedents for technical systems, which could in turn contribute to the development of a formal process for defining the S-Cycle's scope of application as discussed above. An opportunity to explore the relationship between the SoI boundary and timescale, as recommended above, would also be presented. Furthermore, case studies focusing on broader portions of the life cycle may reveal the need for additional guidance and supporting documentation in the guideline, e.g. there may be differences in the manner that sustainability performance data is recorded, analysed, and interpreted in different phases of the life cycle. For instance, it may not be appropriate to evaluate all aspects of behaviour in all phases of the life cycle, as suggested in Section 7.3 of Chapter 7.

9.4.1.5 System modelling

As discussed in Section 9.1.1.5, the evaluation findings suggest that the S-Cycle provides a consistent basis for modelling both coupling and activity/sub-activity relationships throughout a technical system. Knowledge of these relationships is needed for a number of applications (see Section 9.1.1.5). However, whilst the nature of activity coupling relationships from a sustainability perspective was investigated during the research (Chapter 8, Section 8.1.3.2), the nature of activity/sub-activity relationships was not considered. Furthermore, as highlighted in Section 9.1.1.5, no guidance on modelling system activity relationships is currently provided in the guideline.

To address the above shortcomings, future studies aiming to model the activity relationships in a large-scale, complex technical system are recommended. That is, according to Hubka and Eder's (1988) classification scheme adopted in Chapter 8

(Section 8.3), systems of complexity level IV and beyond. Complex systems typically exhibit a high degree of interconnectivity, and would therefore provide the basis for more extensive investigation of activity relationships using the S-Cycle model. For example, the warship that provided the context for the three case studies conducted during evaluation of the S-Cycle may be viewed as an instance of a large-scale complex technical system. During WS1, engineering designers from BAE Systems expressed an interest in extending the application of the S-Cycle from the CW system studied in CS2 to the full range of interconnected sub-systems comprising a warship. This would involve extensive modelling of activity relationships, i.e. both coupling relationships between activities at the same system level, and activity/sub-activity relationships between activities at different system levels. Studies of this kind could generate insights into the nature of these relationships and how they should be modelled, that could subsequently inform the development of guidance for inclusion in the guideline.

9.4.2 The S-Loop model

A final and significant avenue for future research is further evaluation of the S-Loop model, which as discussed in Section 9.1.2, was evaluated through a worked example (WE1) that underwent peer review and was eventually published in the Journal of Environmental Management. Whilst the S-Cycle model describes the behaviour through which technical system sustainability is manifested, the S-Loop model describes the process through which behaviour is assessed and managed for improved sustainability. As such, the elicitation of opinions on the model from engineering managers in industry could provide a means for further evaluation.

Case studies focusing on the implementation and use of the model in industry are also strongly recommended. The S-Cycle guideline may be viewed as an implementation of the S-Loop model from a performance perspective, in the sense that the S-CPIP outlined in the guideline mirrors the general process of interpretation and action described in the S-Loop (illustrated in Figure 9-3). Steps 1 – 4 of the former, focusing on motivating improvement efforts and interpreting behaviour through performance evaluation, were carried out during the case studies as discussed in Section 9.1.1.4. However, Steps 5 and 6, which focus on taking action to improve performance, were not applied. An area for future research may therefore be application of the full S-CPIP to an organisation's technical systems/products, using the S-Loop model to support the management of sustainability performance improvement across different systems.

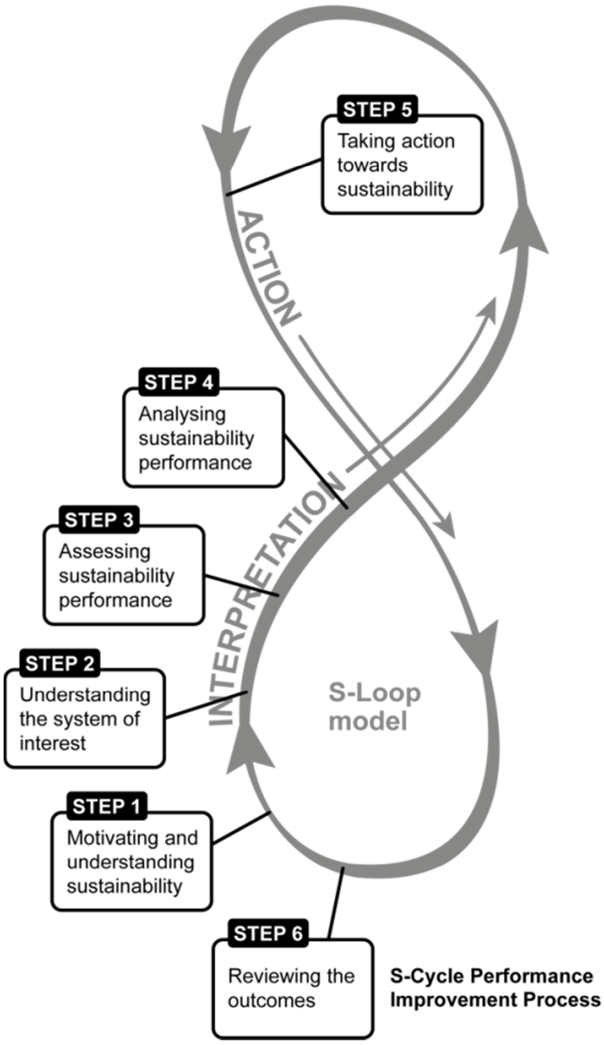


Figure 9-3: Mapping the S-Cycle Performance Improvement Process to the S-Loop model

9.5 Summary

This chapter has presented a discussion on the research reported in this thesis. The research findings, methods, and approach were discussed and critiqued in Sections 9.1, 9.2, and 9.3, respectively. A number of advantages and disadvantages, identified through reflection, were discussed in each case. On the basis of this discussion, a number of areas for future research were outlined in Section 9.4. A summary of the advantages, disadvantages, and recommendations/future work is provided in Table 9-1.

Table 9-1: Summary of the discussion

Advantages	Disadvantages	Recommendations
THE S-CYCLE MODEL AND GUIDELINE		
☑ Refined model comprehensively describes the material and energetic aspects of behaviour that manifest sustainability in a technical system. ☑ Model is artefact independent. ☑ Model was developed on the basis of literature spanning nine sectors. ☑ Model supports the identification of appropriate SPIs for technical systems, and guideline provides a common approach across different systems. ☑ Model can be applied and understood by engineering designers. ☑ Model provides a consistent basis for interpreting behaviour and modelling system relationships throughout a technical system.	☒ Support was not identified for two elements and corresponding relationships during evaluation. ☒ Applicability and utility of the model is currently limited to the energy and marine (defence) sectors. ☒ Guidance on how to define the scope of application for the model in the guideline does not convey the need to define both the SoI boundary and a timescale for interpretation. ☒ Use of the guideline by engineering designers in industry was not evaluated. ☒ The model's abstract nature can make it difficult to comprehend in the absence of concrete examples. ☒ Guideline does not provide guidance on how to model activity relationships from a sustainability perspective.	○ Further investigation of intended resources and contaminant inputs. ○ Evaluation of the model's applicability to technical systems in additional sectors, as well as other types of system. ○ Further investigation of the nature of the scope of application for the model, and development of rigorous guidance on how to define it. ○ Application of the model and guideline to identify SPIs for a more extensive range of technical systems. ○ Further evaluation of the use of the model and guideline by engineering designers in industry.
THE S-LOOP MODEL		
☑ Positions the S-Cycle within the context of human interpretations of sustainability. ☑ Comprehensively describes the fundamental elements involved in human efforts towards sustainability. ☑ Developed on the basis of literature spanning nine sectors. ☑ Endorsed through peer review and publication in the Journal of Environmental Management.	☒ Not applied to technical systems in industry during the research, and opinions on the model were not elicited from engineering designers.	○ Further evaluation through industrial case studies.
RESEARCH METHODS		
Inductive literature investigation		
☑ Covered literature spanning nine different sectors, facilitating investigation of the	☒ Literature was gathered and analysed by a single researcher following a largely non-systematic	○ Concerns regarding bias are mitigated to some extent by evaluation findings that strongly

fundamental elements involved in sustainability. ☑ Lead to identification of all S-Cycle model elements and relationships with the exception of one.	process, meaning that findings may be biased.	support the validity of the S-Cycle, and provide a degree of support for the S-Loop. ○ Involve more than one researcher to interpret the literature. ○ Conduct a systematic review of the sustainability literature, or part thereof.
Worked examples		
☑ Provide evaluation of the S-Cycle and S-Loop models rapidly, without the need for industrial access.	☒ Did not provide thorough evaluation of the S-Cycle and S-Loop models. ☒ Based on data extracted from the literature rather than gathered in industry.	○ Use student design projects focusing on technical systems as a data source.
Case studies		
☑ Provided in depth evaluation of the S-Cycle model. ☑ Conducted independently by three researchers, facilitating triangulation of the findings through cross-case analysis. ☑ Involved multiple data collection techniques. ☑ Use of the IDEF0 modelling technique led to identification of the contaminant input, and generated insights into the S-Cycle's applicability at different system levels.	☒ CS2 and CS3 were conducted at the same company, and both companies involved in the studies operate in the same sector. ☒ The model and guideline were applied by researchers during the studied. Observing their application by engineering designers may have yielded additional insights into their utility that were not revealed to the researchers. ☒ The conclusions of engineering designers who checked the S-Cycle interpretation of the CW system function model may have been affected by a lack of knowledge of the S-Cycle model.	○ Further case studies using participatory methods to observe the use of the S-Cycle model and guideline by engineering designers in industry. ○ Involve participants with greater knowledge of the S-Cycle in checking the author's interpretation of the CW system function model (e.g. Students A and B).
Expert appraisal workshops		
☑ Facilitated elicitation of a breadth of expert opinion on the S-Cycle model within a short period of time, involving 27 engineering designers collectively holding over 425 years of experience. ☑ Opinions were elicited from engineering designers in two industrial sectors, i.e. energy and marine (defence).	☒ A more comprehensive range of opinions could have been elicited through the involvement of participants from further sectors in addition to energy and marine (defence). ☒ Not conducive to the elicitation of in depth opinions that could provide deeper insights. ☒ May not have provided participants with sufficient understanding of and experience with the S-Cycle to formulate opinions. ☒ Owing to a change of wording in the questionnaire between WS1 and WS2, responses	○ Run further workshops involving participants from additional sectors. ○ Allot more time for the workshops to provide participants with more extensive experience of applying the model. ○ Conduct more than one pilot study prior to the workshops to more thoroughly address issues such as timing and interpretation of questionnaire questions.

	to one question could be based on different interpretations. ☒ Questionnaire responses may be subject to bias, e.g. personal biases arising from working relationships with the author.	
Analytical study of performance indicators		
☑ Comprehensive coverage of indicators associated with different sustainability performance evaluation methods.	☒ Analysis findings are dependent on the author's interpretation of the indicators, which could be faulty/biased.	○ Involve additional researchers in the analysis to address potential misinterpretations and bias.
RESEARCH APPROACH		
☑ Critical realist worldview was suitable for investigating sustainability. ☑ Constitution of sustainability was investigated using both empirical and industrial data. ☑ Five research methods were triangulated (between-method), with two of these also triangulated within-method, facilitating assessment of convergence and generating additional insights. ☑ Theory triangulation was achieved through the use of induction to build the models, and deduction to evaluate them. ☑ Investigator triangulation was achieved through involvement of three researchers in evaluation.	☒ Students A and B who conducted CS1 and CS3 could have misinterpreted the S-Cycle model and guideline. ☒ Investigator triangulation was not achieved during the inductive literature investigation or analytical study. ☒ The adoption of a formal, structured approach (e.g. Blessing and Chakrabarti's (2009) DRM) could have improved the performance of the research process and permitted industrial evaluation of the S-Loop model.	○ Triangulation of the case studies amongst one another and with other evaluation methods minimises the impact of any misinterpretations on the overall evaluation findings. ○ Involve additional researchers in the inductive literature investigation and analytical study.
FUTURE WORK		
• Further investigation of intended resources and contaminant inputs. • Further evaluation of the S-Cycle model and guideline in additional sectors. • Further evaluation of the use of the S-Cycle model and guideline by engineering designers in industry. • Further investigation of the scope of application for the S-Cycle, towards the development of rigorous guidance on how to define it. • Further investigation of system relationships and the use of the S-Cycle to model them in a large-scale, complex technical system. • Further evaluation of the S-Loop model through industrial case studies.		

10 Conclusion

The aim of the research reported in this thesis was to develop a generic model of technical system sustainability. The work was undertaken to address three salient issues for sustainability research (Chapter 5), determined through reviews of the literature on sustainability of society (Chapter 3) and sustainability of technical systems (Chapter 4). That is, the lack of a: consistent view on sustainability improvement (I1); common approach for identifying technical system SPIs (I2); and a fundamental formalism to describe the constitution of sustainability both generally, and in a technical systems context (I3). As shown in Figure 10-1, the issues are addressed by six knowledge contributions. An overview of these is provided below.

The primary knowledge contribution is:

K1. The S-Cycle model (Figure 6-5, Chapter 6), a generic model describing the aspects of behaviour through which the property of sustainability is manifested in a technical system. The model was built through inductive literature research and evaluated through worked examples, case studies, expert appraisal workshops, and an analytical study of performance indicators. The S-Cycle addresses issue I3 above.

The following are viewed as secondary knowledge contributions resulting from the research:

K2. The S-Loop model (Figure 6-7, Chapter 6), a generic model describing an iterative process of interpretation and action undertaken by humans striving for sustainability in a particular system of interest (SoI). The S-Cycle model is the foundation of the S-Loop. The S-Loop was developed through inductive literature research, and evaluated through a worked example (WE1) eventually published in the Journal of Environmental Management.

K3. A conceptual exposition of sustainability, consisting of three viewpoints on the concept that may be used to characterise sustainability in different contexts: V1 – lexical definitions of sustainability; V2 – sustainability objectives; and V3 – interpretations of the constitution of sustainability. The exposition is formalised in Figure 3-2 (Chapter 3, Section 3.1.1). Insights into the meaning, value, and constitution of sustainability provided by the exposition and its construction supported identification of issues I1 and I3 in Chapter 5 by highlighting shortcomings in the literature.

K4. The Design Sustainability Matrix (DSM), a classification of design philosophies, methods, and tools applied in sustainability-oriented design.

The matrix is formalised in Figure 4-9 (Chapter 4, Section 4.2.3). Insights into the nature of sustainability performance evaluation methods applied in engineering design yielded by the matrix and its development supported identification of issue I2 in Chapter 5 by highlighting shortcomings in the literature.

K5. The S-Cycle guideline (Chapter 7, Section 7.1.1), detailing a six-step process for evaluating and improving the sustainability performance of a technical system (Figure 7-3) known as the S-Cycle Performance Improvement Process (S-CPIP). The guideline supported application of the S-Cycle model to technical systems during three case studies (discussed in Section 10.5). Additionally, elements of the guideline (namely, the E^2 performance model) supported application of the S-Cycle in the analytical study of performance indicators conducted during evaluation (Chapter 7, Section 7.3).

K6. The S-Cycle Performance Matrix (Figure 8-9, Chapter 8), a set of generic sustainability goals, SPI archetypes, and associated metrics and measures for technical systems. The matrix was the output of the analytical study of performance indicators, and provided support for the validity and utility of the S-Cycle model.

This chapter concludes the thesis by summarising the research approach (Section 10.1), the contributions and evaluation (Sections 10.2 – 10.5), the advantages and disadvantages of the work, and suggested future work (Section 10.6).

10.1 Research approach

The approach adopted to conduct the research was presented in Chapter 2. A critical realist worldview was adopted, owing to the involvement of both natural processes/systems and people in sustainability research (Section 2.3.1). Based on the ontological, epistemological, and axiological perspectives of critical realism, the adopted research methodology was largely qualitative, multi method, and triangulated. Triangulation was achieved in four aspects, i.e. data sources, investigators, theories, and methods (Section 2.3.2).

Data sources included samples of the sustainability literature, technical documentation describing systems in industry, and engineering designers in industry. Between-method triangulation was achieved through the application of five research methods: inductive literature investigation, worked examples, case study, expert appraisal through workshops, and an analytical study of performance indicators. Within-method triangulation was also achieved through two independent worked examples and three independent case studies. Investigator

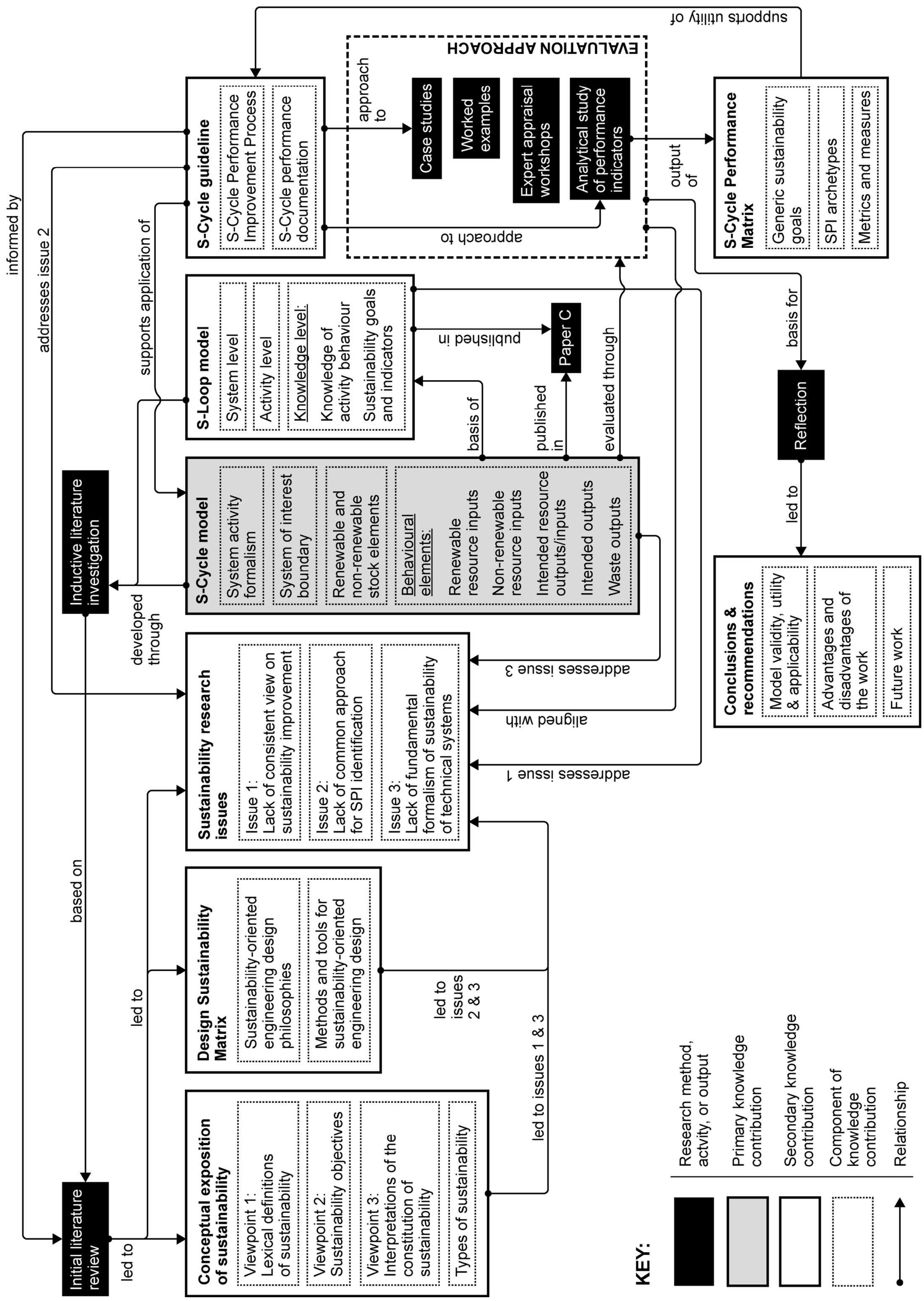


Figure 10-1: Summary of the work

Figure 10-1: Summary of the work

triangulation was achieved through the involvement of three independent researchers in the worked examples and case studies. The S-Cycle/S-Loop models were built through inferences based on observations gathered from the literature. Conclusions regarding the models' validity, utility, and applicability were then drawn from observations gathered using the remaining methods listed above. Thus, theory triangulation was achieved through the adoption of an inductive process to build the models, and a deductive process to evaluate them.

10.2 Review of sustainability research

Existing knowledge on sustainability in both a societal and a technical systems context was reviewed in Chapters 3 and 4. In Chapter 3, research on sustainability spanning nine societal sectors was considered. The meaning, value, and constitution of sustainability were firstly examined (Sections 3.1 to 3.3), followed by the activities through which sustainability is realised by humans (Sections 3.4 and 3.5). In Chapter 4, the nature and life cycle of technical systems was firstly examined (Section 4.1). Design was identified as a critical activity in terms of improving the sustainability of technical systems, and the literature on sustainability-oriented design was reviewed (Section 4.2, reported in Paper A, Appendix 1). Sustainability performance evaluation was found to receive significant attention during the design process, and the literature on this activity in a broader organisational context was subsequently reviewed (Section 4.3).

The literature reviews on sustainability in a societal and a technical systems context led to the identification of three issues to be tackled by the research, summarised in Section 10.3 below. Additionally, the reviews led to two secondary contributions:

- A conceptual exposition of sustainability (Chapter 3, Section 3.3.1), consisting of three viewpoints on the concept that may be used to characterise sustainability in different contexts. These are: (i) lexical definitions of sustainability; (ii) sustainability objectives, encapsulating what is to be sustained and for how long; and (iii) interpretations of the basic constitution of sustainability. Different perspectives that may be adopted in relation to each viewpoint were identified from the literature. The viewpoints were applied to describe and differentiate types of sustainability discussed by authors in different contexts (Table 3-1).
- The Design Sustainability Matrix (Chapter 4, Section 4.2.3), a classification of design philosophies, methods, and tools applied in sustainability-oriented design. Design methods and tools are categorised with respect to: (i) the sustainability-oriented design philosophy they are most commonly associated with in the literature, i.e. design for environment/ecodesign,

design for sustainability/sustainable design, or whole system design; and (ii) the type of design activity they support, i.e. creativity, decision making, evaluation and analysis, and modelling, simulation, and optimisation.

10.3 Issues for sustainability research

In Chapter 5, three salient issues for sustainability research were identified on the basis of the literature reviews summarised above. That is, the lack of a:

- I1. consistent view on how the sustainability of human activities and systems can be improved (Section 5.1);
- I2. common approach for identifying appropriate sustainability performance indicators (SPIs) for technical systems (Section 5.2); and
- I3. fundamental formalism to describe the constitution of sustainability generally and in turn, sustainability of technical systems (Section 5.3).

Firstly, a plethora of different types of sustainability, focusing on different activities and systems, and based on different perspectives regarding the meaning and constitution of sustainability, may be identified in the literature. A range of different sustainability objectives also exist, focusing on different entities and timescales. On this basis, I1 was defined. Secondly, a variety of different methods for evaluating the sustainability performance of technical systems are discussed in the literature, using different indicators and evaluation procedures. Environmental, economic, and social aspects of performance may all be measured, although the rationale for this is not always clear. Based on these observations, I2 was defined. Finally, four different interpretations of the basic constitution of sustainability may be identified in the literature on sustainability of society, i.e. sustainability as an ability, a property of an entity, a process of change, and a state of an entity. In contrast, the constitution of sustainability does not appear to have been extensively considered in the literature on sustainability of technical systems. On this basis, I3 was defined.

It was determined that issues I1, I2, and I3 could be addressed through modelling. Consequently, the research aim was defined: *to develop a generic model of technical system sustainability*, to address the lack of a: (i) consistent view on sustainability improvement, (ii) common approach to identifying appropriate SPIs, and (iii) fundamental formalism of sustainability (Section 5.5). In Chapter 7, three salient aspects to be considered during evaluation were defined on the basis of the identified issues, summarised in Section 10.5 below.

10.4 The S-Cycle and S-Loop models

To achieve the research aim, the S-Cycle and S-Loop models were developed through an inductive literature investigation (Chapter 6, also reported Paper C, Appendix 3). To develop generic models, this investigation was based on literature from the same nine sectors considered in the initial literature review.

Firstly, the constitution of "ability" generally was explored to gain insight into the basic constitution of sustainability (Section 6.1). It was found that sustainability may be viewed as *an ability*, which is in turn *a property of an entity*. It is manifested to humans as a particular *state of an entity* where its behaviour produces the effect of maintenance/continuation, either of the entity in question or some other entity. Achieving sustainability involves a *process of change* with respect to the behaviour of entities.

Next, three concepts found to emerge from the literature as significant given the aim of the research were examined:

- *Systems*, considered provide the context for human action towards sustainability (Section 6.2). The nature of systems in terms of their function, behaviour, and structure was explored, and the Earth system was characterised as the context for human efforts towards sustainability.
- *Activities*, defined as goal-directed physical or cognitive actions producing outputs within a system. The behaviour of activities operating in the Earth system was characterised as involving the following basic aspects: (i) use of renewable and non-renewable resources; (ii) production of intended yield[11]; (iii) production of waste; and (iv) production and use of intended resources. Activities were found to produce yield and resources that humans wish to sustain and therefore, represent fundamental entities to be sustained *per se*. It was determined that coupling relationships may exist between activities, and that sustainability may be viewed as an emergent property of a system supporting multiple interrelated activities. Consequently, activity relationships should be taken into account when defining and implementing goals to shift system behaviour towards sustainability.
- *Knowledge*, identified as a driver of human action towards sustainability (Section 6.4). Three notable components of sustainability knowledge were identified and discussed, namely knowledge of: (i) current activity

[11] Intended yield was changed to intended output in Chapter 7 (Section 7.2.1).

behaviour; (ii) sustainability goals and indicators; and (iii) activity behaviour in relation to goals.

The elements and relationships of the S-Cycle and S-Loop models were then inferred from the observations on systems, activities, and knowledge gathered during the literature investigation (Section 6.5):

- The S-Cycle model (Figure 6-5) formalises activity behaviour from a sustainability perspective, i.e. describes the aspects of activity behaviour through which the property of sustainability is manifested in the Earth system and its sub-systems. System activities transform input flows of renewable and non-renewable resources, ultimately originating from stocks, into output flows of intended resources, intended yield, and waste. The sustainability of system activities is dependent upon the availability of resources within the system, whilst the availability of resources is dependent upon the rate at which these activities consume and produce them.
- The S-Loop model (Figure 6-7) describes an iterative process of interpretation and action undertaken by humans striving for sustainability. Humans interpret activity behaviour within a particular system of interest (SoI) to produce knowledge, then take action on the basis of this knowledge to alter behaviour, before interpreting behaviour post-action to produce further knowledge that determines further action, and so on and so forth.

10.5 Evaluation

Evaluation focused largely upon the S-Cycle model owing to the time constraints of PhD research. The S-Cycle was evaluated using multiple methods (Chapter 7):

- two independent worked examples (WE1 and WE2), where the model was applied to a bioethanol production system (WE1) and a car engine (WE2) described in the literature by two researchers (Section 7.1.2);
- three independent case studies (CS1, CS2, and CS3), involving application of the model to sub-systems of a warship in industry by three researchers (Section 7.1.3), namely an heating, ventilation, and air conditioning (HVAC) system in CS1, a chilled water (CW) system in CS2, and a chilled water plant (CWP) system in CS3;
- two expert appraisal workshops (WS1 and WS2), where a practical exercise and questionnaire were delivered to a total of 27 engineering designers from industry, collectively holding over 425 years of experience (Section 7.2); and
- an analytical study of 324 indicators applied to evaluate the sustainability performance of technical systems (Section 7.3), associated with a range of

ad hoc and formal sustainability performance evaluation methods, and applied to a broad range of technical systems falling into seven categories.

Evaluation focused on three aspects of the model and its use (Chapter 7), aligned with the three issues identified in Chapter 5 (recapitulated in Section 10.3 above):

- *validity*, referring to the degree to which the S-Cycle's elements and relationships can be considered to model a technical system's behaviour from a sustainability perspective (aligned with issue I3);
- *utility*, referring to how effectively the model supports the identification of SPIs for technical systems, and whether it can be understood and applied by its intended users i.e. engineering designers (aligned with issue I2); and
- *applicability*, referring to the extent to which the model can be considered to be artefact and sector independent (aligned with both I2 and I3).

In addition to findings with respect to the above aspects (outlined below), the evaluation also led to two contributions:

- The S-Cycle guideline (Chapter 7, Section 7.1.1, and also Appendix 8A), developed to foster a consistent approach to the three case studies and to address issue I2 (see Section 10.3). The guideline details a six-step process for evaluating and improving the sustainability performance of a technical system, known as the S-Cycle Performance Improvement Process (S-CPIP). The format of the guideline is based on a performance management guide developed by Neely et al. (2002b). Guidance on the identification and evaluation of SPIs is largely drawn from the E^2 performance model (O'Donnell and Duffy, 2005), which describes performance in terms of efficiency and effectiveness.
- The S-Cycle Performance Matrix (Chapter 8, Section 8.2.3.2), comprised of three basic elements: a set of generic sustainability goals for technical systems; a corresponding set of SPI archetypes for measuring efficiency and effectiveness against the goals; and associated metrics and measures for each SPI archetype. The scale at which measures may be evaluated is also indicated, i.e. local, regional, or global. The matrix was developed through the analytical study of performance indicators (Chapter 7, Section 7.3), and is reported in Paper B (Appendix 2).

The evaluation findings were presented in Chapter 8 and discussed in depth in Chapter 9 (Section 9.1). A summary of the key findings with respect to validity (Section 8.1), utility (Section 8.2), and applicability (Section 8.3) is provided below.

Validity:

- All model elements and relationships were found to be supported, in varying degrees, across the findings from the different evaluation methods (Table 8-2, Section 8.1).
- One additional element and corresponding relationship that was not identified during the inductive literature investigation was revealed by CS2. Namely, a contaminant input originating from stocks in the wider system, i.e. an unintended input that is not a resource and may disrupt the functioning of a technical system (Figure 8-3, Section 8.1.3.1).
- During CS2, support was identified for coupling relationships between system activities. Specifically, instances where the intended output produced by one activity is used as a passive resource by another activity were observed (Figure 8-4 and Figure 8-5, Section 8.1.3.2).

Utility:

- Both the SoI boundary and the timescale over which system behaviour is interpreted were found to be basic aspects of the scope of application for the model during CS2 and the expert appraisal workshops (Section 8.2.1). Specifically, during CS2, it was observed that defining different SoI boundaries and timescales resulted in different interpretations regarding the renewability of the resources consumed by a technical system activity (illustrated in Table 8-9). Comments provided by participants in both WS1 and WS2 were also found to suggest that interpretation is affected by both SoI boundary and timescale.
- It was found during the expert appraisal workshops that the model can be both understood and applied by engineering designers. All participants in both WS1 and WS2 (i.e. 27 individuals) were able to apply the model to technical systems during the group-based practical exercise (Section 8.1). Furthermore, the majority of those who provided questionnaire responses (74% of the total participants, i.e. 20 individuals) rated the model positively (Section 8.2.2): 50% rated its effectiveness as an interpretation tool as *good*; 75% rated its ease of understanding as *good*, whilst 5% rated it as *excellent*; and 62.5% rated its effectiveness as a tool to explain sustainability as *good*, whilst 15% rated it as *excellent*.
- CS1 and CS3, along with the analytical study of performance indicators, demonstrated that the S-Cycle guideline provides a common approach for identifying SPIs for technical systems. The S-Cycle model was applied along with the guideline to identify SPIs for two different technical systems in industry, namely the HVAC system studied during CS1, and the CW plant system studied during CS2 (Chapter 7, Sections 7.1.3.1 and 7.1.3.3). Additionally, during the analytical study, the S-Cycle was applied alongside

elements of the guideline (i.e. the E2 model) to develop the S-Cycle Performance Matrix, comprising generic sustainability goals and SPI archetypes for technical systems (outlined above). It was found that 94.1% of the 324 indicators analysed during the study were classifiable with respect to the SPI archetypes proposed in the matrix (Chapter 8, Section 8.2.3.2).

Applicability:

- The worked examples, case studies, and practical exercises conducted at the appraisal workshops demonstrated that the S-Cycle model can be applied to different technical systems, with ten distinct systems studied during the evaluation (Table 8-12, Section 8.3). Comments provided by questionnaire respondents at the workshops also supported the broad applicability of the model (Section 8.3). The model may therefore be considered to be artefact independent.
- CS2 demonstrated that the S-Cycle can be applied to interpret activity behaviour, including coupling relationships, from a sustainability perspective at different system levels. The model was applied at five levels within the hierarchy of the CW system studied (Figure 8-10, Section 8.3). It may therefore be considered to provide a consistent basis for modelling both coupling and activity/sub-activity relationships throughout a technical system, although the nature of the latter was not investigated during the research.

The S-Loop model was applied alongside the S-Cycle model in WE1 to identify sustainability goals and indicators for a system described in the literature, as well as actions to potentially improve sustainability performance (Chapter 7, Section 7.1.2). WE1 underwent peer review by three independent reviewers as part of Paper C (Appendix 3), which was subsequently published in the Journal of Environmental Management. This endorsement of the work provides a degree of support for the validity of the model.

10.6 Advantages, disadvantages, and future work

The triangulated methodology adopted in the research meant that the S-Cycle model was built on the basis of the literature, and evaluated primarily through application to technical systems in industry and the elicitation of expert opinions (Chapter 2, Section 2.3.2). This facilitated the identification of a comprehensive set of model elements and relationships (Chapter 9, Section 9.3). The majority were identified through the inductive literature investigation (Chapter 6), with an additional element and corresponding relationship revealed by the evaluation using data from industry (Chapter 8, Section 8.1.3.1). Nonetheless, the majority of the technical systems studied in industry originated in the energy and marine (defence) sectors. Furthermore, those originating from the latter were all sub-systems of the same parent system, i.e. a warship. Thus, the applicability of the model is limited to these sectors unless more extensive evaluation is conducted (Chapter 9, Section 9.1.1.2). As stated in Section 10.5, the endorsement of the S-Loop model through peer review and subsequent publication provides a degree of confidence in its validity. Further research is needed to evaluate its use in industry (Section 9.1.2).

The evaluation findings summarised in Section 10.5 suggest that the S-Cycle model can be applied and understood by engineering designers (Chapter 9, Section 9.1.1.4). Participants in WS1 and WS2 were able to apply the model during the practical exercise, and the majority rated various aspects of its utility as good/excellent in the questionnaire (see Section 10.5 for a summary of percentages). However, certain comments provided by participants suggested that the model's abstract nature can make it difficult to understand (Chapter 8, Section 8.2.2.2). Owing to time constraints, the workshops were not conducive to the elicitation of in depth opinions on the model. Furthermore, participants applied the model under the controlled conditions of a structured workshop. Additional insights may have been obtained had participants been applying it in an uncontrolled industrial context over a period of time (Chapter 9, Section 9.2.4). Similarly, additional insights into the guideline may have been obtained if its use by engineering designers in industry had been observed. During evaluation, the guideline was applied by researchers only (Section 9.2.3).

Finally, multiple perspectives on the S-Cycle model and guideline were obtained through the involvement of three researchers in their evaluation, namely the author, Student A, and Student B. In comparison to the author, the students had less knowledge and experience of the model and guideline, which led to the identification of shortcomings that may have been missed by the author alone. The findings of both the inductive literature investigation conducted to build the S-Cycle and S-Loop, and the analytical study of indicators carried out to evaluate it, were necessarily affected by the author's interpretation. As such, investigator triangulation could have also been beneficial during this part of the research, to address any potential bias or misinterpretations. However, access to additional researchers was not available during these parts of the research and as such, investigator triangulation was not possible (Chapter 9, Section 9.3).

On the basis of both the research findings, and the advantages and disadvantages of the work summarised above, future research is recommended in the following areas:

- Further investigation of the nature of intended resources and contaminant inputs through application of the refined S-Cycle model presented in Chapter 8 (Figure 8-3).
- Further evaluation of the S-Cycle model and guideline through application to technical systems in additional sectors, and to other types of system e.g. organisations, businesses, and supply chains.
- Further evaluation of the use of the S-Cycle model and guideline by engineering designers in industry.
- Further investigation of the nature of the scope of application for the S-Cycle model, including the relationship between the SoI boundary and timescale, the impact of pre-existing boundaries (e.g. disciplinary and organisational) on the SoI boundary, and application across the full life cycle. Additionally, the development and evaluation of guidance on how to define the scope of application.
- Application of the S-Cycle model to investigate the activity relationships throughout a large-scale, complex technical system e.g. a warship. Additionally, the development and evaluation of guidance on modelling activity relationships.
- Further evaluation of the S-Loop model through industrial case studies focusing on sustainability performance improvement in organisations.

References

Abdel-Salam, A.H., Simonson, C.J., 2014. Annual evaluation of energy, environmental and economic performances of a membrane liquid desiccant air conditioning system with/without ERV. Appl. Energy 116, 134–148. doi:10.1016/j.apenergy.2013.11.047

Abukhader, S.M., 2008. Eco-efficiency in the era of electronic commerce – should "Eco-Effectiveness" approach be adopted? J. Clean. Prod. 16, 801–808.

Adams, P.W.R., McManus, M.C., 2014. Small-scale biomass gasification CHP utilisation in industry: Energy and environmental evaluation. Sustain. Energy Technol. Assessments 6, 129–140. doi:10.1016/j.seta.2014.02.002

Alfaris, A., Siddiqi, A., Rizk, C., de Weck, O., Svetinovic, D., 2010. Hierarchical Decomposition and Multidomain Formulation for the Design of Complex Sustainable Systems. J. Mech. Des. 132, 091003–1 – 091003–13.

Alfsen, K.H., Greaker, M., 2007. From natural resources and environmental accounting to construction of indicators for sustainable development. Ecol. Econ. 61, 600–610. doi:10.1016/j.ecolecon.2006.06.017

Antony, F., Grießhammer, R., Speck, T., Speck, O., 2014. Sustainability assessment of a lightweight biomimetic ceiling structure. Bioinspir. Biomim. 9, 1 – 15. doi:10.1088/1748-3182/9/1/016013

Aschehoug, S.H., Boks, C., Støren, S., 2012. Environmental information from stakeholders supporting product development. J. Clean. Prod. 31, 1–13. doi:10.1016/j.jclepro.2012.02.031

Asif, M., Muneer, T., 2014. Briefing: Sustainability assessment of super-insulated timber windows. Proc. ICE - Constr. Mater. 167, 3–7. doi:10.1680/coma.12.00034

Aydin, H., Turan, Ö., Karakoç, T.H., Midilli, A., 2013. Exergo-sustainability indicators of a turboprop aircraft for the phases of a flight. Energy 58, 550–560. doi:10.1016/j.energy.2013.04.076

Azkarate, A., Ricondo, I., Pérez, A., Martínez, P., 2011. An assessment method and design support system for designing sustainable machine tools. J. Eng. Des. 22, 165–179. doi:10.1080/09544820903153570

Babcock International Group PLC, 2014. Marine [WWW Document]. URL http://www.babcockinternational.com/about-us/divisions/marine-technology/marine/ (accessed 11.1.14).

BAE Systems Maritime, 2014. Products & services [WWW Document]. URL http://www.baesystems.com/our-company-rzz/our-businesses/maritime/products?xProductCategory=Product&_afrLoop=596538084181000&_afrWindowMode=0&_afrWindowId=esyj8k00q_1#!%40%40%3F_afrWindowId%3Desyj8k00q_1%26_afrLoop%3D596538084181000%26x

ProductCategory%3DProduct%26_afrWindowMode%3D0%26_adf.ctrl-state%3Desyj8k00q_93 (accessed 1.13.15).
Balta, M.T., Dincer, I., Hepbasli, A., 2010. Performance and sustainability assessment of energy options for building HVAC applications. Energy Build. 42, 1320–1328. doi:10.1016/j.enbuild.2010.02.026
Barbier, E.B., 1987. The Concept of Sustainable Economic Development. Environ. Conserv. 14, 101–110.
Barles, S., 2010. Society, energy and materials: the contribution of urban metabolism studies to sustainable urban development issues. J. Environ. Plan. Manag. 53, 439–455. doi:10.1080/09640561003703772
Baumgärtner, S., Quaas, M., 2010. What is sustainability economics? Ecol. Econ. 69, 445–450. doi:10.1016/j.ecolecon.2009.11.019
Beddoe, R., Costanza, R., Farley, J., Garza, E., Kent, J., Kubiszewski, I., Martinez, L., McCowen, T., Murphy, K., Myers, N., Ogden, Z., Stapleton, K., Woodward, J., 2009. Overcoming systemic roadblocks to sustainability: the evolutionary redesign of worldviews, institutions, and technologies. Proc. Natl. Acad. Sci. U. S. A. 106, 2483–2489. doi:10.1073/pnas.0812570106
Beder, S., 2011. Environmental economics and ecological economics: the contribution of interdisciplinarity to understanding, influence and effectiveness. Environ. Conserv. 38, 140–150. doi:10.1017/S037689291100021X
Bell, S., Morse, S., 2008. Sustainability indicators: measuring the immeasurable?, 2nd ed. Earthscan, London.
Bender, B., Reinicke, T., Wünsche, T., Blessing, L., 2002. Application of methods from social sciences in design research, in: International Design Conference - Design 2002, May 14-17. Dubrovnik, pp. 7–16.
Benoît, C., Mazjin, B., Andrews, E.S., Barthel, L.-P., Ciroth, A., Cucuzzella, C., Gensch, C.O., 2009. Guidelines for Social Life Cycle Assessment of Products. United Nations Environment Programme, Druk in de weer, Belgium.
Benoît, C., Norris, G.A., Valdivia, S., Ciroth, A., Moberg, A., Bos, U., Prakash, S., Ugaya, C., Beck, T., 2010. The guidelines for social life cycle assessment of products: just in time! Int. J. Life Cycle Assess. 15, 156–163. doi:10.1007/s11367-009-0147-8
Bettencourt, L.M.A., Kaur, J., 2011. Evolution and structure of sustainability science. Proc. Natl. Acad. Sci. U. S. A. 108, 19540–19545. doi:10.1073/pnas.1102712108
Bhamra, T., Lilley, D., Tang, T., 2011. Design for Sustainable Behaviour: Using Products to Change Consumer Behaviour. Des. J. 14, 427 – 445. doi:10.2752/175630611X13091688930453
Bhamra, T., Lofthouse, V., 2007. Design for Sustainability: A Practical Approach. Gower Publishing, Ltd., Aldershot.

Bhamra, T.A., Evans, S., McAloone, T.C., Simon, M., Poole, S., Sweatman, A., 1999. Integrating environmental decisions into the product development process. I. The early stages, in: Proceedings First International Symposium on Environmentally Conscious Design and Inverse Manufacturing. IEEE, pp. 329–333. doi:10.1109/ECODIM.1999.747633

Bhander, G.S., Hauschild, M., McAloone, T., 2003. Implementing life cycle assessment in product development. Environ. Prog. 22, 255–267. doi:10.1002/ep.670220414

Bianchi, M., Branchini, L., De Pascale, A., Peretto, A., 2014. Application of environmental performance assessment of CHP systems with local and global approaches. Appl. Energy. 130, 774 – 782. doi:10.1016/j.apenergy.2014.04.017

Blanchard, B.S., Fabrycky, W.J., 1981. Systems Engineering and Analysis. Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Blessing, L.T.M., Chakrabarti, A., 2009. A Design Research Methodology. Springer-Verlag London Limited, London; New York.

Blizzard, J.L., Klotz, L.E., 2012. A framework for sustainable whole systems design. Des. Stud. 33, 456–479. doi:10.1016/j.destud.2012.03.001

Bodini, A., 2012. Building a systemic environmental monitoring and indicators for sustainability: What has the ecological network approach to offer? Ecol. Indic. 15, 140–148. doi:10.1016/j.ecolind.2011.09.032

Boks, C., Stevels, A., 2007. Essential perspectives for design for environment. Experiences from the electronics industry. Int. J. Prod. Res. 45, 4021–4039. doi:10.1080/00207540701439909

Boks, C., Stevels, A., 2003. Theory and practice of environmental benchmarking in a major consumer electronics company. Benchmarking An Int. J. 10, 120–135. doi:10.1108/14635770310469653

Bovea, M.., Vidal, R., 2004. Increasing product value by integrating environmental impact, costs and customer valuation. Resour. Conserv. Recycl. 41, 133–145. doi:10.1016/j.resconrec.2003.09.004

Bovea, M.D., Pérez-Belis, V., 2012. A taxonomy of ecodesign tools for integrating environmental requirements into the product design process. J. Clean. Prod. 20, 61–71. doi:10.1016/j.jclepro.2011.07.012

Bovea, M.D., Wang, B., 2007. Redesign methodology for developing environmentally conscious products. Int. J. Prod. Res. 45, 4057–4072. doi:10.1080/00207540701472678

Boyle, I.M., Duffy, A.H.B., Whitfield, R.I., Liu, S., 2009. Towards an understanding of the impact of resources on the design process, in: 17th International Conference on Engineering Design (ICED `09), pp. 323 – 334. The Design Society, Stanford.

Braungart, M., McDonough, W., 2008. Cradle to Cradle: Re-making the Way We Make Things. Vintage, London.

Brown, B.J., Hanson, M.E., Liverman, D.M., Merideth, R.W., 1987. Global sustainability: Toward definition. Environ. Manage. 11, 713–719. doi:10.1007/BF01867238

Brown, M.., Ulgiati, S., 1997. Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation. Ecol. Eng. 9, 51–69. doi:10.1016/S0925-8574(97)00033-5

Brown, M.T., Odum, H.T., Jorgensen, S.., 2004. Energy hierarchy and transformity in the universe. Ecol. Modell. 178, 17–28. doi:10.1016/j.ecolmodel.2003.12.002

Brynolf, S., Fridell, E., Andersson, K., 2014. Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol. J. Clean. Prod. 74, 86–95. doi:10.1016/j.jclepro.2014.03.052

Buchanan, R., 1992. Wicked Problems in Design Thinking. Des. Issues 8, 5–21.

Buonocore, E., Franzese, P.P., Ulgiati, S., 2012. Assessing the environmental performance and sustainability of bioenergy production in Sweden: A life cycle assessment perspective. Energy 37, 69–78. doi:10.1016/j.energy.2011.07.032

Burger, P., Christen, M., 2011. Towards a capability approach of sustainability. J. Clean. Prod. 19, 787–795. doi:10.1016/j.jclepro.2010.06.019

Byggeth, S., Broman, G., Robèrt, K.-H., 2007. A method for sustainable product development based on a modular system of guiding questions. J. Clean. Prod. 15, 1–11. doi:10.1016/j.jclepro.2006.02.007

Byggeth, S.H., ., Ny, H., Wall, J., Broman, G., Robèrt, K.-H., 2007. Introductory procedure for sustainability-driven design optimization, in: International Conference on Engineering Design, ICED "07, 28-31 August, Cite Des Sciences et de L"Industrie, Paris, France. pp. 99–100.

Cabezas, H., Pawlowski, C.W., Mayer, A.L., Hoagland, N.T., 2005. Sustainable systems theory: ecological and other aspects. J. Clean. Prod. 13, 455–467. doi:10.1016/j.jclepro.2003.09.011

Caliskan, H., Dincer, I., Hepbasli, A., 2012. A comparative study on energetic, exergetic and environmental performance assessments of novel M-Cycle based air coolers for buildings. Energy Convers. Manag. 56, 69–79. doi:10.1016/j.enconman.2011.11.007

Caliskan, H., Dincer, I., Hepbasli, A., 2011a. Exergetic and sustainability performance comparison of novel and conventional air cooling systems for building applications. Energy Build. 43, 1461–1472. doi:10.1016/j.enbuild.2011.02.006

Caliskan, H., Hepbasli, A., Dincer, I., 2011b. Exergy Analysis and Sustainability Assessment of a Solar-Ground Based Heat Pump With Thermal Energy

Storage. J. Sol. Energy Eng. 133, 011005-1 – 011005-2. doi:10.1115/1.4003040

Campbell, D.E., Garmestani, A.S., 2012. An energy systems view of sustainability: emergy evaluation of the San Luis Basin, Colorado. J. Environ. Manage. 95, 72–97. doi:10.1016/j.jenvman.2011.07.028

Celino, A., Concilio, G., 2010. Explorative Nature of Negotiation in Participatory Decision Making for Sustainability. Gr. Decis. Negot. 20, 255–270. doi:10.1007/s10726-010-9197-3

Cellura, M., La Rocca, V., Longo, S., Mistretta, M., 2013. Energy and environmental impacts of energy related products (ErP): a case study of biomass-fuelled systems. J. Clean. Prod 85, 359 – 370. doi:10.1016/j.jclepro.2013.12.059

Çengel, Y.A., Turner, R.H., 2004. Fundamentals of thermal-fluid sciences, 2nd ed. McGraw-Hill, Boston, London.

Chandrasekaran, N., Guha, A., 2012. Development and optimization of a sustainable turbofan aeroengine for improved performance and emissions. Proc. Inst. Mech. Eng. Part G J. Aerosp. Eng. 227, 1701–1719. doi:10.1177/0954410012462183

Chapman, J., 2011. Emotionally Durable Design, 3rd ed. Earthscan, London, Washington DC.

Charnley, F., Lemon, M., Evans, S., 2011. Exploring the process of whole system design. Des. Stud. 32, 156–179. doi:10.1016/j.destud.2010.08.002

Charter, M., Tischner, U., 2001. Introduction, in: Sustainable Solutions: Developing Products and Services for the Future. Greenleaf Publishing Limited, Sheffield, pp. 17–22.

Chen, C., Zhu, J., Yu, J.-Y., Noori, H., 2012. A new methodology for evaluating sustainable product design performance with two-stage network data envelopment analysis. Eur. J. Oper. Res. 221, 348–359. doi:10.1016/j.ejor.2012.03.043

Chen, X., Frank, K.A., Dietz, T., Liu, J., 2012. Weak Ties, Labor Migration, and Environmental Impacts: Toward a Sociology of Sustainability. Organ. Environ. 25, 3–24. doi:10.1177/1086026611436216

Chiu, M.-C., Chu, C.-H., 2012. Review of Sustainable Product Design from Life Cycle Perspectives. Int. J. Precis. Eng. Manuf. 13, 1259–1272. doi:10.1007/s12541-012-0169-1

Choi, J.K., Nies, L.F., Ramani, K., 2008. A framework for the integration of environmental and business aspects toward sustainable product development. J. Eng. Des. 19, 431–446. doi:10.1080/09544820701749116

Churchman, C.W., 1967. Wicked Problems. Manage. Sci. 14, 141–146.

Clark, A.M., 1998. The qualitative-quantitative debate: moving from positivism and confrontation to post-positivism and reconciliation. J. Adv. Nurs. 27, 1242–1249. doi:10.1046/j.1365-2648.1998.00651.x

Clark, G., Kosoris, J., Nguyen Hong, L., Crul, M., 2009. Design for Sustainability: Current Trends in Sustainable Product Design and Development. Sustainability 1, 409–424.

Clark, W.C., Dickson, N.M., 2003. Sustainability science: the emerging research program. Proc. Natl. Acad. Sci. U. S. A. 100, 8059–8061. doi:10.1073/pnas.1231333100

Coelho, H.M.G., Lange, L.C., Coelho, L.M.G., 2012. Proposal of an environmental performance index to assess solid waste treatment technologies. Waste Manag. 32, 1473–1481. doi:10.1016/j.wasman.2012.03.001

Coley, F.J.S., Lemon, M., 2009. Exploring the design and perceived benefit of sustainable solutions: a review. J. Eng. Des. 20, 543–554. doi:10.1080/09544820802001276

Collado-Ruiz, D., Ostad-Ahmad-Ghorabi, H., 2010. Influence of environmental information on creativity. Des. Stud. 31, 479–498. doi:10.1016/j.destud.2010.06.005

Conway, G.R., 1986. Agroecosystem analysis for research and development. Winrock International, Bangkok.

Coppola, F., Bastianoni, S., Østergård, H., 2009. Sustainability of bioethanol production from wheat with recycled residues as evaluated by Emergy assessment. Biomass and Bioenergy 33, 1626–1642. doi:10.1016/j.biombioe.2009.08.003

Costanza, R., Daly, H.E., 1992. Natural Capital and Sustainable Development. Conserv. Biol. 6, 37–46. doi:10.1046/j.1523-1739.1992.610037.x

Costanza, R., Patten, B.C., 1995. Defining and predicting sustainability. Ecol. Econ. 15, 193–196. doi:10.1016/0921-8009(95)00048-8

Creswell, J.W., 2014. Research Design: Qualitative, Quantitative, and Mixed Methods Approaches, 4th ed. Sage Publications Ltd, London.

Cross, N., 2008. Engineering Design Methods, 4th ed. John Willey & Sons Ltd., Chichester.

Crossan, F., 2003. Research philosophy: towards an understanding. Nurse Res. 11, 46–55.

Dalal-Clayton, B., Bass, S., 2002. Sustainable Development Strategies - A Resource Book. Earthscan Publications Ltd., London.

Daly, H.E., 1992. Steady-state economics, 2nd ed. Earthscan, London.

Daly, H.E., 1990a. Toward some operational principles of sustainable development. Ecol. Econ. 2, 1–6. doi:10.1016/0921-8009(90)90010-R

Daly, H.E., 1990b. Sustainable Development: From Concept and Theory to Operational Principles. Popul. Dev. Rev. 16, 25–43.

Darnhofer, I., Fairweather, J., Moller, H., 2010. Assessing a farm's sustainability: insights from resilience thinking. Int. J. Agric. Sustain. 8, 186–198.

Dawson, T.P., Rounsevell, M.D.A., Kluvánková-Oravská, T., Chobotová, V., Stirling, A., 2010. Dynamic properties of complex adaptive ecosystems: implications for the sustainability of service provision. Biodivers. Conserv. 19, 2843–2853. doi:10.1007/s10531-010-9892-z

De Smedt, P., 2010. The Use of Impact Assessment Tools to Support Sustainable Policy Objectives in Europe. Ecol. Soc. 15.

Dempsey, N., Bramley, G., Power, S., Brown, C., 2011. The social dimension of sustainable development: Defining urban social sustainability. Sustain. Dev. 19, 289–300. doi:10.1002/sd.417

Denholm, P., Kulcinski, G.L., Holloway, T., 2005. Emissions and Energy Efficiency Assessment of Baseload Wind Energy Systems. Environ. Sci. Technol. 39, 1903–1911. doi:10.1021/es049946p

Denzin, N.K., 1970. The research act in sociology: a theoretical introduction to sociological research methods. Butterworths, London.

Derissen, S., Quaas, M.F., Baumgärtner, S., 2011. The relationship between resilience and sustainability of ecological-economic systems. Ecol. Econ. 70, 1121–1128. doi:10.1016/j.ecolecon.2011.01.003

Duffy, A., 2005. Design process and performance, in: Clarkson, J., Huhtala, M. (Eds.), Engineering Design - Theory and Practice, A Symposium in Honour of Ken Wallace. Engineering Design Centre, University Of Cambridge, pp. 76–85.

Duffy, A.H.B., O'Donnell, F.J., 1998. A Design Research Approach, in: Critical Enthusiasm - Contributions to Design Science. pp. 33–40.

Dyllick, T., Hockerts, K., 2002. Beyond the business case for corporate sustainability. Bus. Strateg. Environ. 11, 130–141.

Easterby-Smith, M., Thorpe, R., Lowe, A., 2012. Management research : an introduction, 4th ed. SAGE Publications, London.

Edeholt, H., 2012. Innovative Foresights in Sustainable Design and Architecture - How to Promote Seemingly Impossible, but Still Crucial, Radical Changes. Sustain. Dev. 20, 155–165. doi:10.1002/sd.1532

Eder, W.E., 2003. A typology of designs and designing, in: 14th International Conference on Engineering Design (ICED '03).

Ehrlich, P.R., Ehrlich, A.H., 2013. Can a collapse of global civilization be avoided? Proc. Biol. Sci. 280, 1 – 9. doi:10.1098/rspb.2012.2845

Ekins, P., 2011. Environmental sustainability: From environmental valuation to the sustainability gap. Prog. Phys. Geogr. 35, 629–651. doi:10.1177/0309133311423186

Ekins, P., Simon, S., Deutsch, L., Folke, C., De Groot, R., 2003. A framework for the practical application of the concepts of critical natural capital and strong sustainability. Ecol. Econ. 44, 165–185. doi:10.1016/S0921-8009(02)00272-0

Elkington, J., 1998. Cannibals with Forks: The Triple Bottom Line of 21st Century Business. New Society Publishers.
Ellen MacArthur Foundation, 2013. Towards the Circular Economy Vol. 1. URL https://emf-packs.s3-eu-west-1.amazonaws.com/Towards the Circular Economy vol 1/Ellen MacArthur Foundation Towards the Circular Economy vol.1.pdf (accessed 5.20.15)
Ernzer, M., Bey, N., 2003. The link between Life Cycle Design and innovation, in: Proceedings of EcoDesign 2003: Third International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokyo, Japan, December 8-11, 2003. Tokyo, pp. 559–566. doi:10.1109/ECODIM.2003.1322736
Ertesvag, I.S., 2005. Energy, exergy, and extended-exergy analysis of the Norwegian society 2000. Energy 30, 649–675. doi:10.1016/j.energy.2004.05.025
European Commission, 2009. Commission Impact Assessment Guidelines [WWW Document]. URL http://ec.europa.eu/governance/impact/commission_guidelines/commission_guidelines_en.htm (accessed 5.18.12).
Eurostat, 2013. Sustainable development in the European Union - 2013 monitoring report of the EU sustainable development strategy. Luxembourg. doi:10.2785/11549
Eurostat, 2011a. Sustainable development in the European Union - 2011 monitoring report of the EU sustainable development strategy. Publications Office of the European Union, Luxembourg. doi:10.2785/1538
Eurostat, 2011b. Material flow accounts - Statistics Explained [WWW Document]. URL http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Material_flow_accounts (accessed 5.25.12).
Eurostat, 2010. Eurostat Quality Profile - Gross Domestic Product (GDP) per capita in Purchasing Power Standards (PPS) [WWW Document]. URL http://epp.eurostat.ec.europa.eu/portal/page/portal/sdi/files/QP GDP per capita in PPS.pdf (accessed 7.18.12).
Evans, A., Strezov, V., Evans, T.J., 2009. Assessment of sustainability indicators for renewable energy technologies. Renew. Sustain. Energy Rev. 13, 1082–1088. doi:10.1016/j.rser.2008.03.008
Evbuomwan, N.F.O., Sivaloganathan, S., Jebb, A., 1996. A survey of design philosophies, models, methods and systems. Arch. Proc. Inst. Mech. Eng. Part B J. Eng. Manuf. 210, 301–320. doi:10.1243/PIME_PROC_1996_210_123_02
Fanuc, 2009. FANUC Leans on Automation to Keep Production At Home [WWW Document]. URL http://tr.fanucrobotics.eu/en/countries/frtr/customer-services/fanuc5000 (accessed 3.20.15).

Figge, F., Hahn, T., 2005. The Cost of Sustainability Capital and the Creation of Sustainable Value by Companies. J. Ind. Ecol. 9, 47–58.

Figge, F., Hahn, T., 2004. Sustainable Value Added—measuring corporate contributions to sustainability beyond eco-efficiency. Ecol. Econ. 48, 173–187.

Fiksel, J., 2003. Designing Resilient, Sustainable Systems. Environ. Sci. Technol. 37, 5330–5339. doi:10.1021/es0344819

Fthenakis, V., 2009. Sustainability of photovoltaics: The case for thin-film solar cells. Renew. Sustain. Energy Rev. 13, 2746–2750. doi:10.1016/j.rser.2009.05.001

Gagnon, B., Leduc, R., Savard, L., 2012. From a conventional to a sustainable engineering design process: different shades of sustainability. J. Eng. Des. 23, 49–74. doi:10.1080/09544828.2010.516246

Gaichas, S.K., 2008. A context for ecosystem-based fishery management: Developing concepts of ecosystems and sustainability. Mar. Policy 32, 393–401. doi:10.1016/j.marpol.2007.08.002

Galli, A., Kitzes, J., Niccolucci, V., Wackernagel, M., Wada, Y., Marchettini, N., 2012. Assessing the global environmental consequences of economic growth through the Ecological Footprint: A focus on China and India. Ecol. Indic. 17, 99–107. doi:10.1016/j.ecolind.2011.04.022

Gamage, A., Hyde, R., 2012. A model based on Biomimicry to enhance ecologically sustainable design. Archit. Sci. Rev. 55, 224–235. doi:10.1080/00038628.2012.709406

Garmendia, E., Prellezo, R., Murillas, A., Escapa, M., Gallastegui, M., 2010. Weak and strong sustainability assessment in fisheries. Ecol. Econ. 70, 106–96. doi:10.1016/j.ecolecon.2010.08.001

Garmendia, E., Stagl, S., 2010. Public participation for sustainability and social learning: Concepts and lessons from three case studies in Europe. Ecol. Econ. 69, 1712–1722. doi:10.1016/j.ecolecon.2010.03.027

Gasparatos, A., El-Haram, M., Horner, M., 2009a. Assessing the sustainability of the UK society using thermodynamic concepts: Part 1. Renew. Sustain. Energy Rev. 13, 1074–1081. doi:10.1016/j.rser.2008.03.004

Gasparatos, A., El-Haram, M., Horner, M., 2009b. Assessing the sustainability of the UK society using thermodynamic concepts: Part 2. Renew. Sustain. Energy Rev. 13, 956–970. doi:10.1016/j.rser.2008.03.005

Gasparatos, A., El-Haram, M., Horner, M., 2008. A critical review of reductionist approaches for assessing the progress towards sustainability. Environ. Impact Assess. Rev. 28, 286–311. doi:10.1016/j.eiar.2007.09.002

Gatto, M., 1995. Sustainability: Is it a well defined concept? Ecol. Appl. 5, 1181–1183.

Georgescu-Roegen, N., 1971. The entropy law and the economic process. Harvard University Press.

Gero, J.S., Kannengiesser, U., 2004. The situated function–behaviour–structure framework. Des. Stud. 25, 373–391. doi:10.1016/j.destud.2003.10.010

Global Reporting Initiative, 2013a. G4 Sustainability Reporting Guidelines - Reporting Principles and Standard Disclosures. Amsterdam.

Global Reporting Initiative, 2013b. G4 Sustainability Reporting Guidelines - Implementation Manual. Amsterdam.

Godfrey, P., 2010. Using systems thinking to learn to deliver sustainable built environments. Civ. Eng. Environ. Syst. 27, 219–230. doi:10.1080/10286608.2010.482656

Goerner, S.J., Lietaer, B., Ulanowicz, R.E., 2009. Quantifying economic sustainability: Implications for free-enterprise theory, policy and practice. Ecol. Econ. 69, 76–81. doi:10.1016/j.ecolecon.2009.07.018

Goodland, R., 1995. The concept of environmental sustainability. Annu. Rev. Ecol. Syst. 26, 1–24.

Gorod, A., White, B.E., Ireland, V., Gandhi, S.J., Sauser, B., 2015. Case Studies in System of Systems, Enterprise Systems, and Complex Systems Engineering. CRC Press, Hoboken.

Gould, D., 2011. 13 Inspirational Designers And Their Design Philosophies [WWW Document]. URL http://www.psfk.com/2011/05/13-inspirational-designers-and-their-design-philosophies.html (accessed 3.12.13).

Grinnell, R.M., Jr., Unrau, Y.A., 2010. Social Work Research and Evaluation: Foundations of Evidence-Based Practice. Oxford University Press, USA.

Gu, Y., Frazer, J., 2009. Complex Modelling of Open System Design for Sustainable Architecture, in: Zhou, J. (Ed.), Complex Sciences - Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 1898–1906. doi:10.1007/978-3-642-02469-6

Guba, E.G., Lincoln, Y.S., 1994. Competing Paradigms in Qualitative Research, in: Denzin, N.K., Lincoln, Y.S. (Eds.), Handbook of Qualitative Research. Sage, London, pp. 105–117.

Gurzenich, D., Wagner, H.-J., 2004. Cumulative energy demand and cumulative emissions of photovoltaics production in Europe. Energy 29, 2297–2303. doi:10.1016/j.energy.2004.03.037

Hahn, T., Figge, F., 2011. Beyond the Bounded Instrumentality in Current Corporate Sustainability Research: Toward an Inclusive Notion of Profitability. J. Bus. Ethics 104, 325–345. doi:10.1007/s10551-011-0911-0

Hahn, W.A., Knoke, T., 2010. Sustainable development and sustainable forestry: analogies, differences, and the role of flexibility. Eur. J. For. Res. 129, 787–801.

Hak, T., Kovanda, J., Weinzettel, J., 2012. A method to assess the relevance of sustainability indicators: Application to the indicator set of the Czech

Republic's Sustainable Development Strategy. Ecol. Indic. 17, 46–57. doi:10.1016/j.ecolind.2011.04.034

Hannon, A., Callaghan, E.G., 2011. Definitions and organizational practice of sustainability in the for-profit sector of Nova Scotia. J. Clean. Prod. 19, 877–884. doi:10.1016/j.jclepro.2010.11.003

Hansen, J.W., 1996. Is agricultural sustainability a useful concept? Agric. Syst. 50, 117–143.

Hardin, G., 1968. The tragedy of the commons. Science 162, 1243–12488. doi:10.1126/science.162.3859.1243

Hart, S.L., Milstein, M.B., 2003. Creating sustainable value. Acad. Manag. Exec. 17, 56–69.

Heal, G., 2012. Reflections - Defining and Measuring Sustainability. Rev. Environ. Econ. Policy 6, 147–163.

Heijungs, R., Huppes, G., Guinée, J.B., 2010. Life cycle assessment and sustainability analysis of products, materials and technologies. Toward a scientific framework for sustainability life cycle analysis. Polym. Degrad. Stab. 95, 422–428. doi:10.1016/j.polymdegradstab.2009.11.010

Hepbasli, A., 2008. A key review on exergetic analysis and assessment of renewable energy resources for a sustainable future. Renew. Sustain. Energy Rev. 12, 593–661. doi:10.1016/j.rser.2006.10.001

Hernandez, J., 2010. An Introduction to Design Methods. University of Strathclyde, Glasgow.

Hindle, T., 2009. Triple bottom line. The Economist. [WWW Document]. URL http://www.economist.com/node/14301663 (accessed 9.6.13).

Holan Fenwick Willan, 2013. Green Shipping Bulletin. London.

Holling, C.S., 2001. Understanding the Complexity of Economic, Ecological, and Social Systems. Ecosystems 4, 390–405. doi:10.1007/s10021-001-0101-5

Holling, C.S., Goldberg, M.A., 1971. Ecology and Planning. J. Am. Inst. Plann. 37, 221–230. doi:10.1080/01944367108977962

Hondo, H., 2005. Life cycle GHG emission analysis of power generation systems: Japanese case. Energy 30, 2042–2056. doi:10.1016/j.energy.2004.07.020

Hong, T., Ji, C., Park, H., 2012. Integrated model for assessing the cost and CO2 emission (IMACC) for sustainable structural design in ready-mix concrete. J. Environ. Manage. 103, 1–8. doi:10.1016/j.jenvman.2012.02.034

Horváth, I., Duhovnik, J., 2005. Towards a better understanding of the methodological characteristics of engineering design research, in: Proceedings of IDETC/CIE 2005 ASME 2005 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference September 24-28, 2005, pp.1 – 15. Long Beach, California.

Hossain, K.A., Khan, F., Hawboldt, K., 2010. SusDesign – An approach for a sustainable process system design and its application to a thermal power plant. Appl. Therm. Eng. 30, 1896–1913. doi:10.1016/j.applthermaleng.2010.04.011

Hubka, V., 1982. Principles of Engineering Design. Butterworth & Co Ltd., London, Boston.

Hubka, V., Eder, W.E., 1988. Theory of Technical Systems, 2nd ed. Springer-Verlag, Berlin, Heidelberg, New York.

Huisman, J., Boks, C., Stevels, A., 2000. Environmentally weighted recycling quotes-better justifiable and environmentally more correct, in: Proceedings of the 2000 IEEE International Symposium on Electronics and the Environment (Cat. No.00CH37082). IEEE, pp. 105–111. doi:10.1109/ISEE.2000.857633

Huisman, J., Boks, C.B., Stevels, A.L.N., 2003. Quotes for environmentally weighted recyclability (QWERTY): Concept of describing product recyclability in terms of environmental value. Int. J. Prod. Res. 41, 3649–3665. doi:10.1080/0020754031000120069

Hussey, D.M., Kirsop, P.L., Meissen, R.E., 2001. Global Reporting Initiative Guidelines: An Evaluation of Sustainable Development Metrics for Industry. Environ. Qual. Manag. 11, 1–20. doi:10.1002/tqem.1200

International Institute for Sustainable Development, 2013. Complete Bellagio Principles [WWW Document]. URL https://www.iisd.org/measure/principles/progress/bellagio_full.asp (accessed 7.5.13)

International Standards Organization, 1999. ISO 14031:1999 Environmental management - Environmental performance evaluation - Guidelines.

Jamieson, D., 1998. Sustainability and beyond. Ecol. Econ. 24, 183–192. doi:10.1016/S0921-8009(97)00142-0

Jones, J.C., 1991. Designing Designing. Architecture Design and Technology Press, London.

Jordan, S.J., Hayes, S.E., Yoskowitz, D., Smith, L.M., Summers, J.K., Russell, M., Benson, W.H., 2010. Accounting for natural resources and environmental sustainability: linking ecosystem services to human well-being. Environ. Sci. Technol. 44, 1530–1536. doi:10.1021/es902597u

Jørgensen, A., Finkbeiner, M., Jørgensen, M.S., Hauschild, M.Z., 2010. Defining the baseline in social life cycle assessment. Int. J. Life Cycle Assess. 15, 376–384. doi:10.1007/s11367-010-0176-3

Kajikawa, Y., 2008. Research core and framework of sustainability science. Sustain. Sci. 3, 215–239. doi:10.1007/s11625-008-0053-1

Kajikawa, Y., Ohno, J., Takeda, Y., Matsushima, K., Komiyama, H., 2007. Creating an academic landscape of sustainability science: an analysis of the citation network. Sustain. Sci. 2, 221–231. doi:10.1007/s11625-007-0027-8

Karlsson, R., Luttropp, C., 2006. EcoDesign: what's happening? An overview of the subject area of EcoDesign and of the papers in this special issue. J. Clean. Prod. 14, 1291–1298. doi:10.1016/j.jclepro.2005.11.010

Keitsch, M., 2012. Sustainable Design: A Brief Appraisal of its Main Concepts. Sustain. Dev. 20, 180–188. doi:10.1002/sd.1534

Kemp, R., Martens, P., 2007. Sustainable development: how to manage something that is subjective and never can be achieved? Sustain. Sci. Pract. Policy 3, 5–14.

Kemp, R., Parto, S., 2005. Governance for sustainable development: moving from theory to practice. Int. J. Sustain. Dev. 8, 12–30.

Keoleian, G.A., Menerey, D., 1994. Sustainable Development by Design: Review of Life Cycle Design and Related Approaches. Air Waste 44, 645–668. doi:10.1080/1073161X.1994.10467269

Kidd, C. V., 1992. The evolution of sustainability. J. Agric. Environ. Ethics 5, 1–26. doi:10.1007/BF01965413

Kim, B., Lee, J., Kim, K., Hur, T., 2014. Evaluation of the environmental performance of sc-Si and mc-Si PV systems in Korea. Sol. Energy 99, 100–114. doi:10.1016/j.solener.2013.10.038

Kim, J., Oki, T., 2011. Visioneering: an essential framework in sustainability science. Sustain. Sci. 6, 247–251. doi:10.1007/s11625-011-0130-8

Kloepffer, W., 2008. Life cycle sustainability assessment of products. Int. J. Life Cycle Assess. 13, 89–95. doi:10.1065/lca2008.02.376

Klöpffer, W., Ciroth, A., 2011. Is LCC relevant in a sustainability assessment? Int. J. Life Cycle Assess. 16, 99–101. doi:10.1007/s11367-011-0249-y

Knox, K., 2004. A Researcher's Dilemma-Philosophical and Methodological Pluralism. Electron. J. Bus. Res. Methods 2, 119 – 128.

Köhn, J., 1998. Thinking in terms of system hierarchies and velocities. What makes development sustainable? Ecol. Econ. 26, 173–187. doi:10.1016/S0921-8009(97)00102-X

Koller, M., Floh, A., Zauner, A., 2011. Further insights into perceived value and consumer loyalty: A "Green" perspective. Psychol. Mark. 28, 1154–1176.

Komiyama, H., Takeuchi, K., 2006. Sustainability science: building a new discipline. Sustain. Sci. 1, 1–6. doi:10.1007/s11625-006-0007-4

Kumar, R., 2011. Research methodology: a step-by-step guide for beginners, 3rd ed. Sage, Los Angeles; London.

Laitala, K., Boks, C., Klepp, I.G., 2011. Potential for environmental improvements in laundering. Int. J. Consum. Stud. 35, 254–264. doi:10.1111/j.1470-6431.2010.00968.x

Larkin, P.A., 1977. An Epitaph for the Concept of Maximum Sustained Yield. Trans. Am. Fish. Soc. 106, 1–11.

Laszlo, A., Laszlo, K.C., Dunsky, H., 2009. Redefining success: designing systemic sustainable strategies. Syst. Res. Behav. Sci. 27, 3–21. doi:10.1002/sres.982

Lele, S., Norgaard, R.B., 1996. Sustainability and the Scientist's Burden. Conserv. Biol. 10, 354–365. doi:10.1046/j.1523-1739.1996.10020354.x

Lenau, T., Bey, N., 2001. Design of environmentally friendly products using indicators. Proc. Inst. Mech. Eng. Part B J. Eng. Manuf. 215, 637–645. doi:10.1243/0954405011518575

Levine, L., Mohr, B.J., 1998. Whole System Design (WSD): The Shifting Focus of Attention and the Threshold Challenge. J. Appl. Behav. Sci. 34, 305–326. doi:10.1177/0021886398343005

Li, J., Wang, J., Ma, Z., Sun, L., 2012. Environmental Performance Assessment for Heterogeneous Azeotropic Distillation Partitioned Distillation Column. Adv. Mater. Res. 485, 229 – 232

Li, Y., Yang, Z.F., 2011. Quantifying the sustainability of water use systems: Calculating the balance between network efficiency and resilience. Ecol. Modell. 222, 1771–1780. doi:10.1016/j.ecolmodel.2011.03.001

Liao, W., Heijungs, R., Huppes, G., 2011. Is bioethanol a sustainable energy source? An energy-, exergy-, and emergy-based thermodynamic system analysis. Renew. Energy 36, 3487–3479. doi:10.1016/j.renene.2011.05.030

Lindahl, M., 2006. Engineering designers' experience of design for environment methods and tools – Requirement definitions from an interview study. J. Clean. Prod. 14, 487–496. doi:10.1016/j.jclepro.2005.02.003

Lindahl, M., 2001. Environmental effect analysis - how does the method stand in relation to lessons learned from the use of other design for environment methods, in: Proceedings Second International Symposium on Environmentally Conscious Design and Inverse Manufacturing. IEEE Comput. Soc, pp. 864–869. doi:10.1109/.2001.992482

Lindahl, M., 1999. E-FMEA-a new promising tool for efficient design for environment, in: Proceedings First International Symposium on Environmentally Conscious Design and Inverse Manufacturing. IEEE, pp. 734–739. doi:10.1109/ECODIM.1999.747707

Lindahl, M., Sundin, E., Sakao, T., Shimomura, Y., 2007. Integrated Product and Service Engineering versus Design for Environment - A Comparison and Evaluation of Advanatges and Disadvantages, in: Advances in Life Cycle Engineering for Sustainable Manufacturing Businesses. pp. 137–142.

Lindner, M., Suominen, T., Palosuo, T., Garcia-Gonzalo, J., Verweij, P., Zudin, S., Päivinen, R., 2010. ToSIA—A tool for sustainability impact assessment of forest-wood-chains. Ecol. Modell. 221, 2197–2205. doi:10.1016/j.ecolmodel.2009.08.006

Lindsey, T.C., 2011. Sustainable principles: common values for achieving sustainability. J. Clean. Prod. 19, 561–565. doi:10.1016/j.jclepro.2010.10.014

Liu, J., Lin, B.-L., Sagisaka, M., 2012. Sustainability assessment of bioethanol and petroleum fuel production in Japan based on emergy analysis. Energy Policy 44, 23–33. doi:10.1016/j.enpol.2011.12.022

Liu, S., Costanza, R., Farber, S., Troy, A., 2010. Valuing ecosystem services: theory, practice, and the need for a transdisciplinary synthesis. Ann. N. Y. Acad. Sci. 1185, 54–78. doi:10.1111/j.1749-6632.2009.05167.x

Lo, S.-F., 2010. Performance evaluation for sustainable business: a profitability and marketability framework. Corp. Soc. Responsib. Environ. Manag. 17, 311–319. doi:10.1002/csr.214

Lopes, A.M., Fam, D., Williams, J., 2012. Designing sustainable sanitation: Involving design in innovative, transdisciplinary research. Des. Stud. 33, 298–317. doi:10.1016/j.destud.2011.08.005

Lozano, R., Huisingh, D., 2011. Inter-linking issues and dimensions in sustainability reporting. J. Clean. Prod. 19, 99–107. doi:10.1016/j.jclepro.2010.01.004

Lu, B., Zhang, J., Xue, D., Gu, P., 2011. Systematic Lifecycle Design for Sustainable Product Development. Concurr. Eng. 19, 307–324. doi:10.1177/1063293X11424513

Lutter, S., Pirgmaler, E., Fruhmann, J., Burger, E., Mayr, M., Polzin, C., 2009. Measuring Performance towards Sustainable Consumption and Production - Types of Indicators and Indicator Sets. Sustainable Europe Research Institute.

M'Pherson, P.K., 1980. Systems Engineering: an approach to whole-system design. Radio Electron. Eng. 50, 545 – 558. doi:10.1049/ree.1980.0081

Maclaren, V.W., 1996. Urban Sustainability Reporting. J. Am. Plan. Assoc. 62, 184–202.

Manzini, E., 2006. Design, ethics and sustainability, in: Sotamaa, Y., Salmi, E., Anusionwu, L. (Eds.), Nantes Cumulus Working Papers Publication Series G. University of Art and Design, Helsinki, pp. 9–15.

Marchettini, N., Ridolfi, R., Rustici, M., 2007. An environmental analysis for comparing waste management options and strategies. Waste Manag. 27, 562–71.

Marcuse, P., 1998. Sustainability is not enough. Environ. Urban. 10, 103–112.

Marimon, F., Alonso-Almeida, M. del M., Rodríguez, M. del P., Cortez Alejandro, K.A., 2012. The worldwide diffusion of the global reporting initiative: what is the point? J. Clean. Prod. 33, 132–144. doi:10.1016/j.jclepro.2012.04.017

Marks, S., 2011. Valuing the future: Intergenerational discounting, its problems, and a modest proposal (No. 11-12). Boston University School of Law, Boston.

Mayyas, A., Qattawi, A., Omar, M., Shan, D., 2012. Design for sustainability in automotive industry: A comprehensive review. Renew. Sustain. Energy Rev. 16, 1845–1862. doi:10.1016/j.rser.2012.01.012

Mayyas, A.T., Qattawi, A., Mayyas, A.R., Omar, M.A., 2012. Life cycle assessment-based selection for a sustainable lightweight body-in-white design. Energy 39, 412–425. doi:10.1016/j.energy.2011.12.033

McAloone, T., 2001. Confronting product life thinking with product life cycle analysis, in: Proceedings Second International Symposium on Environmentally Conscious Design and Inverse Manufacturing. IEEE Comput. Soc, pp. 60–64. doi:10.1109/.2001.992315

McAloone, T.C., Andreasen, M.M., 2004. Design for Utility, Sustainability and Societal Virtues: Developing Product Service Systems, in: International Design Conference - Design 2004, Dubrovnik, May 18-21, 2004. Dubrovnik, pp. 1–8.

McCool, S.F., Stankey, G.H., 2004. Indicators of sustainability: challenges and opportunities at the interface of science and policy. Environ. Manage. 33, 294–305. doi:10.1007/s00267-003-0084-4

McDonough, W., Braungart, M., 2002. Design for the Triple Top Line: New Tools for Sustainable Commerce. Corp. Environ. Strateg. 9, 251–258.

Meadows, D., 1998. Indicators and information systems for sustainable development. The Sustainability Institute, Hartland.

Meadows, D.H., 2008. Thinking in Systems - A Primer. Earthcan, London.

Meadows, D.H., Club of Rome, 1972. The Limits to growth : a report for the Club of Rome's project on the predicament of mankind. Earth Island.

Metcalf, S.S., Widener, M.J., 2011. Growing Buffalo's capacity for local food: A systems framework for sustainable agriculture. Appl. Geogr. 31, 1242–1251. doi:10.1016/j.apgeog.2011.01.008

Ministry of Defence, 2000. MoD Defence Standard 02-102. Bristol.

Mitsch, W.J., 2012. What is ecological engineering? Ecol. Eng. 45, 5–12. doi:10.1016/j.ecoleng.2012.04.013

Mori, K., Christodoulou, A., 2012. Review of sustainability indices and indicators: Towards a new City Sustainability Index (CSI). Environ. Impact Assess. Rev. 32, 94–106. doi:10.1016/j.eiar.2011.06.001

Moss, A.R., Lansing, S.A., Tilley, D.R., Klavon, K.H., 2014. Assessing the sustainability of small-scale anaerobic digestion systems with the introduction of the emergy efficiency index (EEI) and adjusted yield ratio (AYR). Ecol. Eng. 64, 391–407. doi:10.1016/j.ecoleng.2013.12.008

Neely, A., Adams, C., Kennerley, M., 2002a. The Performance Prism: The Scorecard for Measuring and Managing Business Success. Pearson Education Limited, Harlow; London.

Neely, A., Bourne, M., Mills, J., Platts, K., Richards, H., 2002b. Getting the measure of your business. Cambridge University Press, Cambridge.

Ness, B., Urbel-Piirsalu, E., Anderberg, S., Olsson, L., 2007. Categorising tools for sustainability assessment. Ecol. Econ. 60, 498–508. doi:10.1016/j.ecolecon.2006.07.023

Neumayer, E., 2003. Weak versus strong sustainability : exploring the limits of two opposing paradigms, 2nd ed. Edward Elgar, Cheltenham, UK; Northampton, MA.

Newell, A., 1982. The knowledge level. Artif. Intell. 18, 87–127. doi:10.1016/0004-3702(82)90012-1

Niinimäki, K., Koskinen, I., 2011. I Love this Dress, It Makes Me Feel Beautiful! Empathic Knowledge in Sustainable Design. Des. J. 14, 22. doi: dx.doi.org/10.2752/175630611X12984592779962

NIST, 1993. Integration Definition for Function Modelling (IDEF0). Draft Federal Information Processing Standards Publication 183.

Norse, E.A., Brooke, S., Cheung, W.W.L., Clark, M.R., Ekeland, I., Froese, R., Gjerde, K.M., Haedrich, R.L., Heppell, S.S., Morato, T., Morgan, L.E., Pauly, D., Sumaila, R., Watson, R., 2012. Sustainability of deep-sea fisheries. Mar. Policy 36, 307–320. doi:10.1016/j.marpol.2011.06.008

Noss, R.F., 1993. Sustainable Forestry or Sustainable Forests?, in: Aplet, G.H., Johnson, N., Olson, J.T., Sample, V.A. (Eds.), Defining Sustainable Forestry. Island Press, Washington D.C., pp. 17–43.

Ny, H., Hallstedt, S., Robèrt, K.-H., Broman, G., 2008. Introducing Templates for Sustainable Product Development. J. Ind. Ecol. 12, 600–623. doi:10.1111/j.1530-9290.2008.00061.x

O'Donnell, F.J., Duffy, A.H.B., 2005. Design Performance. Springer-Verlag, London.

O'Donnell, F.J., Duffy, A.H.B., 2002. Modelling design development performance. Int. J. Oper. Prod. Manag. 22, 1198–1221. doi:10.1108/01443570210450301

Odum, H.T., 1994. The emergy of natural capital, in: Jansson, A., Hammer, M., Folke, C., Costanza, R. (Eds.), Investing in Natural Capital - The Ecological Economics Approach to Sustainability. Island Press, Washington D.C., pp. 200–214.

Ofori-Boateng, C., Lee, K.T., 2014. An oil palm-based biorefinery concept for cellulosic ethanol and phytochemicals production: Sustainability evaluation using exergetic life cycle assessment. Appl. Therm. Eng. 62, 90–104. doi:10.1016/j.applthermaleng.2013.09.022

Onat, N., Bayar, H., 2010. The sustainability indicators of power production systems. Renew. Sustain. Energy Rev. 14, 3108–3115. doi:10.1016/j.rser.2010.07.022

Oram, D., 2010. Designing for Sustainability: Negotiating Ethical Implications. IEEE Technol. Soc. Mag. 29, 31–36. doi:10.1109/MTS.2010.938107

Organisation for Economic Co-operation and Development, 1998. Eco-Efficiency. OCED Publications, Paris.

Organisation for Economic Co-operation and Development, 1997. Sustainable Consumption and Production - Clarifying the Concepts. OCED Publications, Paris.

Ostad-Ahmad-Ghorabi, H., Collado-Ruiz, D., 2011. Tool for the environmental assessment of cranes based on parameterization. Int. J. Life Cycle Assess. 16, 392–400. doi:10.1007/s11367-011-0280-z

Oxford English Dictionary, 2014. Oxford English Dictionary [WWW Document]. URL http://www.oed.com/

Pacca, S., Sivaraman, D., Keoleian, G.A., 2007. Parameters affecting the life cycle performance of PV technologies and systems. Energy Policy 35, 3316–3326. doi:10.1016/j.enpol.2006.10.003

Päivinen, R., Lindner, M., Rosén, K., Lexer, M.J., 2010. A concept for assessing sustainability impacts of forestry-wood chains. Eur. J. For. Res. 131, 7–19. doi:10.1007/s10342-010-0446-4

Papandreou, V., Shang, Z., 2008. A multi-criteria optimisation approach for the design of sustainable utility systems. Comput. Chem. Eng. 32, 1589–1602. doi:10.1016/j.compchemeng.2007.08.006

Papanek, V., 1972. Design for the Real World. Thames and Hudson Ltd., London.

Park, P.-J., Lee, K.-M., Wimmer, W., 2005. Development of an Environmental Assessment Method for Consumer Electronics by combining Top-down and Bottom-up Approaches. Int. J. Life Cycle Assess. 11, 254–264. doi:10.1065/lca2005.05.205

Parris, T.M., Kates, R.W., 2003. Characterizing a sustainability transition: goals, targets, trends, and driving forces. Proc. Natl. Acad. Sci. U. S. A. 100, 8068–8073. doi:10.1073/pnas.1231336100

Payne, G., 2006. The SAGE Dictionary of Social Research Methods [WWW Document]. URL http://srmo.sagepub.com/view/the-sage-dictionary-of-social-research-methods/n117.xml (accessed 3.20.15)

Pearce, D., Putz, F.E., Vanclay, J.K., 2003. Sustainable forestry in the tropics: panacea or folly? For. Ecol. Manage. 172, 229–247.

Phillis, Y.A., Kouikoglou, V.S., Manousiouthakis, V., 2010. A Review of Sustainability Assessment Models as System of Systems. IEEE Syst. J. 4, 15–25. doi:10.1109/JSYST.2009.2039734

Pidd, M., 2010. Why modelling and model use matter. J. Oper. Res. Soc. 61, 14–24.

Pigosso, D.C.A., McAloone, T.C., Rozenfield, H., 2014. Systematization of best practices for ecodesign implementation, in: International Design Conference - Design 2014. Dubrovnik, pp. 1651–1662.

Pigosso, D.C.A., Rozenfield, H., Seliger, G., 2011. Ecodesign Maturity Model: criteria for methods and tools classification, in: Seliger, G., Khraisheh, M.M.K., Jawahir, I.S. (Eds.), Advances in Sustainable Manufacturing: Proceedings of the 8th Global Conference. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 239–243. doi:10.1007/978-3-642-20183-7

Poole, S., Simon, M., Sweatman, A., Bhamra, T.A., Evans, S., McAloone, T.C., 1999. Integrating environmental decisions into the product development process. II.

The later stages, in: Proceedings First International Symposium on Environmentally Conscious Design and Inverse Manufacturing. IEEE, pp. 334–337. doi:10.1109/ECODIM.1999.747634

Popper, K.R., 1959. The logic of scientific discovery. Basic Books, New York.

Posner, S.M., Costanza, R., 2011. A summary of ISEW and GPI studies at multiple scales and new estimates for Baltimore City, Baltimore County, and the State of Maryland. Ecol. Econ. 70, 1972–1980. doi:10.1016/j.ecolecon.2011.05.004

Pretty, J., 2008. Agricultural sustainability: concepts, principles and evidence. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 363, 447–65.

Pugh, S., 1991. Total design: integrated methods for successful product engineering. Addison-Wesley, Wokingham.

Pülzl, H., Prokofieva, I., Berg, S., Rametsteiner, E., Aggestam, F., Wolfslehner, B., 2011. Indicator development in sustainability impact assessment: balancing theory and practice. Eur. J. For. Res. 131, 35–46. doi:10.1007/s10342-011-0547-8

Quental, N., Lourenço, J.M., 2011. References, authors, journals and scientific disciplines underlying the sustainable development literature: a citation analysis. Scientometrics 90, 361–381. doi:10.1007/s11192-011-0533-4

Quental, N., Lourenço, J.M., da Silva, F.N., 2011. Sustainable Development Policy: Goals, Targets and Political Cycles. Sustain. Dev. 19, 15–29. doi:10.1002/sd.416

Quental, N., Lourenço, J.M., da Silva, F.N., 2010. Sustainability: characteristics and scientific roots. Environ. Dev. Sustain. 13, 257–276. doi:10.1007/s10668-010-9260-x

Rahman, S.M.A., Masjuki, H.H., Kalam, M.A., Sanjid, A., Abedin, M.J., 2014. Assessment of emission and performance of compression ignition engine with varying injection timing. Renew. Sustain. Energy Rev. 35, 221–230. doi:10.1016/j.rser.2014.03.049

Rainey, D.L., 2006. Sustainable business development : inventing the future through strategy, innovation, and leadership. Cambridge University Press, Cambridge; New York.

Ramani, K., Ramanujan, D., Bernstein, W.Z., Zhao, F., Sutherland, J., Handwerker, C., Choi, J.-K., 2010. Integrated Sustainable Life Cycle Design: A Review. J. Mech. Des. 132, 091004-1 – 091004-15

Rametsteiner, E., Pülzl, H., Alkan-Olsson, J., Frederiksen, P., 2011. Sustainability indicator development—Science or political negotiation? Ecol. Indic. 11, 61–70. doi:10.1016/j.ecolind.2009.06.009

Ramos, T.B., Caeiro, S., 2010. Meta-performance evaluation of sustainability indicators. Ecol. Indic. 10, 157–166. doi:10.1016/j.ecolind.2009.04.008

Raugei, M., Bargigli, S., Ulgiati, S., 2005. A multi-criteria life cycle assessment of molten carbonate fuel cells (MCFC)?a comparison to natural gas turbines. Int. J. Hydrogen Energy 30, 123–130. doi:10.1016/j.ijhydene.2004.04.009

Raut, S.P., Ralegaonkar, R.V., Mandavgane, S.A., 2011. Development of sustainable construction material using industrial and agricultural solid waste: A review of waste-create bricks. Constr. Build. Mater. 25, 4037–4042.

Reber, M., 2011. A theory of value in design. PhD thesis. University of Strathclyde, Glasgow.

Reed, M.S., Fraser, E.D.G., Dougill, A.J., 2006. An adaptive learning process for developing and applying sustainability indicators with local communities. Ecol. Econ. 59, 406–418.

Reich, Y., 1994. Layered models of research methodologies. Artif. Intell. Eng. Des. Anal. Manuf. 8, 263–274.

Rittel, H.W.J., Webber, M.M., 1973. Dilemmas in a general theory of planning. Policy Sci. 4, 155–169. doi:10.1007/BF01405730

Robinson, J., Burch, S., Talwar, S., O'Shea, M., Walsh, M., 2011. Envisioning sustainability: Recent progress in the use of participatory backcasting approaches for sustainability research. Technol. Forecast. Soc. Change 78, 756–768. doi:10.1016/j.techfore.2010.12.006

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A., 2009. A safe operating space for humanity. Nature 461, 472–475. doi:10.1038/461472a

Rodriguez, E., Boks, C., 2005. How design of products affects user behaviour and vice versa: the environmental implications, in: 2005 4th International Symposium on Environmentally Conscious Design and Inverse Manufacturing. IEEE, pp. 54–61. doi:10.1109/ECODIM.2005.1619166

Rosato, A., Sibilio, S., Scorpio, M., 2014. Dynamic performance assessment of a residential building-integrated cogeneration system under different boundary conditions. Part II: Environmental and economic analyses. Energy Convers. Manag. 79, 749–770. doi:10.1016/j.enconman.2013.09.058

Rosen, M.A., Dincer, I., 2001. Exergy as the confluence of energy, environment and sustainable development. Exergy, An Int. J. 1, 3–13. doi:10.1016/S1164-0235(01)00004-8

Rosen, M.A., Dincer, I., Kanoglu, M., 2008. Role of exergy in increasing efficiency and sustainability and reducing environmental impact. Energy Policy 36, 128–137. doi:10.1016/j.enpol.2007.09.006

Rosen, M.A., Kishawy, H.A., 2012. Sustainable Manufacturing and Design: Concepts, Practices and Needs. Sustainability 4, 154–174. doi:10.3390/su4020154 OPEN

Rotella, G., Umbrello, D., Dillon Jr., O.W., Jawahir, I.S., 2012. Evaluation of Process Performance for Sustainable Hard Machining. J. Adv. Mech. Des. Syst. Manuf. 6, 989–998.

Russell-Smith, S. V., Lepech, M.D., Fruchter, R., Meyer, Y.B., 2014. Sustainable target value design: integrating life cycle assessment and target value design to improve building energy and environmental performance. J. Clean. Prod. 88, 43 – 51. doi:10.1016/j.jclepro.2014.03.025

Sage, A.P., 1992. Systems engineering. John Wiley, New York.

Saunders, M., Lewis, P., Thornhill, A., 2009. Research methods for business students, 5th ed. Pearson, Harlow.

Saunders, M., Tosey, P., 2012. The Layers of Research Design. Rapport 30, 58–59.

Scerri, A., James, P., 2009. Communities of citizens and “indicators” of sustainability. Community Dev. J. 45, 219–236. doi:10.1093/cdj/bsp013

Scientific Applications International Corporation, 2006. Life Cycle Impact Assessment, in: Life Cycle Assessment: Principles and Practice. National Risk Management Research Laboratory, Cincinnati, pp. 46–53.

SENSOR, 2009. Tools for Environmental, Social and Economic Effects of Multifunctional Land Use in European Regions [WWW Document]. URL http://www.sensor-ip.org/ (accessed 5.7.12).

Shah, V.P., Debella, D.C., Ries, R.J., 2008. Life cycle assessment of residential heating and cooling systems in four regions in the United States. Energy Build. 40, 503–513. doi:10.1016/j.enbuild.2007.04.004

Shahabi, M.P., McHugh, A., Anda, M., Ho, G., 2014. Environmental life cycle assessment of seawater reverse osmosis desalination plant powered by renewable energy. Renew. Energy 67, 53–58. doi:10.1016/j.renene.2013.11.050

Sharma, A., Saxena, A., Sethi, M., Shree, V., 2011. Life cycle assessment of buildings: A review. Renew. Sustain. Energy Rev. 15, 871–875. doi:10.1016/j.rser.2010.09.008

Shearman, R., 1990. The Meaning and Ethics of Sustainability. Environ. Manage. 14, 1–8.

Shedroff, N., 2009. Design is the Problem - The Future of Design Must be Sustainable. Rosenfield Media, New York.

Shih, F.-J., 1998. Triangulation in nursing research: issues of conceptual clarity and purpose. J. Adv. Nurs. 28, 631–641. doi:10.1046/j.1365-2648.1998.00716.x

Sim, S.K., 2000. Modelling Learning in Design. PhD thesis. University of Strathclyde, Glasgow.

Singh, G., Singh, A.P., Agarwal, A.K., 2014. Experimental investigations of combustion, performance and emission characterization of biodiesel fuelled HCCI engine using external mixture formation technique. Sustain. Energy Technol. Assessments 6, 116–128. doi:10.1016/j.seta.2014.01.002

Singh, R.K., Murty, H.R., Gupta, S.K., Dikshit, A.K., 2012. An overview of sustainability assessment methodologies. Ecol. Indic. 15, 281–299. doi:10.1016/j.ecolind.2011.01.007

Skjerven, A., 2012. Cultural Traditions for the Sake of Innovation: the Concept of Scandinavian Design as a Potential Tool in the Development of a Sustainable China. Sustain. Dev. 20, 230–238. doi:10.1002/sd.1539

Skyttner, L., 1996. General Systems Theory - An Introduction. Macmillan Press Ltd, Basingstoke; London.

Söğüt, Z., Oktay, Z., Karakoc, H., Hepbasli, A., 2012. Investigation of environmental and exergetic performance for coal-preparation units in cement production processes. Energy 46, 72–77. doi:10.1016/j.energy.2012.04.041

Solow, R., 1993. An almost practical step toward sustainability. Resour. Policy 19, 162–172.

Spangenberg, J.H., 2011. Sustainability science: a review, an analysis and some empirical lessons. Environ. Conserv. 38, 275–287. doi:10.1017/S0376892911000270

Spangenberg, J.H., Fuad-Luke, A., Blincoe, K., 2010. Design for Sustainability (DfS): the interface of sustainable production and consumption. J. Clean. Prod. 18, 1485–1493. doi:10.1016/j.jclepro.2010.06.002

Standal, D., Utne, I.B., 2011. The hard choices of sustainability. Mar. Policy 35, 519–527. doi:10.1016/j.marpol.2011.01.001

Stasinopoulos, P., Smith, M.H., Hargroves, K., Desha, C., 2009. Whole System Design. An Integrated Approach to Sustainable Engineering. Earthscan, London.

Strasser, C., Wimmer, W., 2003. Supporting customer driven eco-solutions - implementing ecodesign in the daily work of product developers, in: Proceedings of EcoDesign 2003: Third International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokyo, Japan, December 8-11, 2003, Tokyo, pp.757 – 762. doi:10.1109/ECODIM.2003.1322770

Stremke, S., van den Dobbelsteen, A., Koh, J., 2011. Exergy landscapes: exploration of second-law thinking towards sustainable landscape design. Int. J. Exergy 8, 148–174.

Student A, 2013. Assessing the suitability of air-cycle based HVAC systems for marine applications. Master’s dissertation. University of Strathclyde, Glasgow.

Student B, 2014. Assessing sustainability performance in a complex technical system. Master’s dissertation. University of Strathclyde, Glasgow.

Stupak, I., Lattimore, B., Titus, B.D., Tattersall Smith, C., 2011. Criteria and indicators for sustainable forest fuel production and harvesting: A review of current standards for sustainable forest management. Biomass and Bioenergy 35, 3287–3308. doi:10.1016/j.biombioe.2010.11.032

Swarr, T.E., Hunkeler, D., Klöpffer, W., Pesonen, H.-L., Ciroth, A., Brent, A.C., Pagan, R., 2011. Environmental life-cycle costing: a code of practice. Int. J. Life Cycle Assess. 16, 389–391. doi:10.1007/s11367-011-0287-5

Taras, S., Woinaroschy, A., 2012. An interactive multi-objective optimization framework for sustainable design of bioprocesses. Comput. Chem. Eng. 43, 10–22. doi:10.1016/j.compchemeng.2012.04.011

Tharp, B.M., Tharp, S.M., n.d. Discursive Design: Beyond Purely Commerical Notions of Industrial and Product Design. Industrial Designers Society of America. URL http://www.idsa.org/discursive-design (accessed 2.14.13)

The Royal Society, 2012. People and the planet. The Royal Society Science Policy Centre, London.

Thiers, S., Peuportier, B., 2012. Energy and environmental assessment of two high energy performance residential buildings. Build. Environ. 51, 276–284. doi:10.1016/j.buildenv.2011.11.018

Thomé, B., 1993. Definition and Scope of Systems Engineering, in: Thomé, B. (Ed.), Systems Engineering: Principles and Practice of Computer-Based Systems Engineering. John Wiley & Sons Ltd., Chichester, pp. 1–23.

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418, 671–7.

Tischner, U., Charter, M., 2001. Sustainable product design, in: Sustainable Solutions: Developing Products and Services for the Future. Greenleaf Publishing Limited, Sheffield, pp. 118–138. doi:http://dx.doi.org/10.9774/GLEAF.978-1-907643-21-7_8

Todorov, V., Marinova, D., 2011. Modelling sustainability. Math. Comput. Simul. 81, 1397–1408. doi:10.1016/j.matcom.2010.05.022

Tokos, H., Pintarič, Z.N., Krajnc, D., 2011. An integrated sustainability performance assessment and benchmarking of breweries. Clean Technol. Environ. Policy 14, 173–193. doi:10.1007/s10098-011-0390-0

Trochim, W., 2006. Research methods knowledge base [WWW Document]. URL http://www.socialresearchmethods.net/kb/ (accessed 7.30.13)

Trotta, M.G., 2010. Product Lifecycle Management: Sustainability and knowledge management as keys in a complex system of product development. J. Ind. Eng. Manag. 3, 309–322. doi:10.3926/jiem..v3n2.p309-322

Tully, C., 1993. System Development Activity, in: Thomé, B. (Ed.), Systems Engineering: Principles and Practice of Computer-Based Systems Engineering. John Wiley & Sons Ltd., Chichester, pp. 45–80.

Turner, B.L., 2010. Vulnerability and resilience: Coalescing or paralleling approaches for sustainability science? Glob. Environ. Chang. 20, 570–576. doi:10.1016/j.gloenvcha.2010.07.003

Turner, B.L., Kasperson, R.E., Matson, P.A., McCarthy, J.J., Corell, R.W., Christensen, L., Eckley, N., Kasperson, J.X., Luers, A., Martello, M.L., Polsky, C., Pulsipher, A., Schiller, A., 2003. A framework for vulnerability analysis in sustainability science. Proc. Natl. Acad. Sci. U. S. A. 100, 8074–8079. doi:10.1073/pnas.1231335100

Uddin, M.S., Kumar, S., 2014. Energy, emissions and environmental impact analysis of wind turbine using life cycle assessment technique. J. Clean. Prod. 69, 153–164. doi:10.1016/j.jclepro.2014.01.073

Ulanowicz, R., Goerner, S., Lietaer, B., Gomez, R., 2009. Quantifying sustainability: Resilience, efficiency and the return of information theory. Ecol. Complex. 6, 27–36. doi:10.1016/j.ecocom.2008.10.005

Ulanowicz, R.E., 1980. An Hypothesis on the Development of Natural Communities. J. Theor. Biol. 85, 223–245.

Ulgiati, S., Ascione, M., Bargigli, S., Cherubini, F., Franzese, P.P., Raugei, M., Viglia, S., Zucaro, A., 2011. Material, energy and environmental performance of technological and social systems under a Life Cycle Assessment perspective. Ecol. Modell. 222, 176–189. doi:10.1016/j.ecolmodel.2010.09.005

Ulgiati, S., Raugei, M., Bargigli, S., 2006. Overcoming the inadequacy of single-criterion approaches to Life Cycle Assessment. Ecol. Modell. 190, 432–442. doi:10.1016/j.ecolmodel.2005.03.022

Ulrich, K.T., Eppinger, S.D., 2008. Product Design and Development, 4th ed. McGraw-Hill/Irwin, New York.

Unger, N., Schneider, F., Salhofer, S., 2008. A review of ecodesign and environmental assessment tools and their appropriateness for electrical and electronic equipment. Prog. Ind. Ecol. 5, 13–29.

United Nations, 2007. Indicators of Sustainable Development: Guidelines and Methodologies. United Nations, New York.

United Nations, 1992. Agenda 21. United Nations, Rio de Janerio.

United Nations Development Programme, 2011. Human Development Report 2011. Palgrave Macmillan, Basingstoke.

United Nations Environment Programme, 2012. GEO5 - Environment for the future we want. United Nations Environment Programme, Valletta, Malta.

Urban, R.A., Bakshi, B.R., Grubb, G.F., Baral, A., Mitsch, W.J., 2010. Towards sustainability of engineered processes: Designing self-reliant networks of technological–ecological systems. Comput. Chem. Eng. 34, 1413–1420. doi:10.1016/j.compchemeng.2010.02.026

Van Zeijl-Rozema, A., Martens, P., 2010. An adaptive indicator framework for monitoring regional sustainable development - a case study of the INSURE project in Limburg, The Netherlands. Sustain. Sci. Pract. Policy 6, 6–17.

Vinodh, S., Rathod, G., 2010. Integration of ECQFD and LCA for sustainable product design. J. Clean. Prod. 18, 833–842. doi:10.1016/j.jclepro.2009.12.024

Viva Labs Inc., 2015. Oil: Not Exactly Dead Dinosaurs [WWW Document]. URL http://krilloil.com/research/oil-not-exactly-dead-dinosaurs/ (accessed 14.2.13)

Voinov, A., 2007. Understanding and communicating sustainability: global versus regional perspectives. Environ. Dev. Sustain. 10, 487–501. doi:10.1007/s10668-006-9076-x

Vos, R.O., 2007. Defining sustainability: a conceptual orientation. J. Chem. Technol. Biotechnol. 82, 334–339. doi:10.1002/jctb.1675

Vucetich, J.A., Nelson, M.P., 2010. Sustainability: Virtuous or Vulgar? Bioscience 60, 539–544. doi:10.1525/bio.2010.60.7.9

Waage, S.A., 2007. Re-considering product design: a practical "road-map" for integration of sustainability issues. J. Clean. Prod. 15, 638–649. doi:10.1016/j.jclepro.2005.11.026

Wackernagel, M., Rees, W.E., 1997. Perceptual and structural barriers to investing in natural capital: Economics from an ecological footprint perspective. Ecol. Econ. 20, 3–24. doi:10.1016/S0921-8009(96)00077-8

Wackernagel, M., Yount, D.J., 1998. The Ecological Footprint: an Indicator of Progress Toward Regional Sustainability. Environ. Monit. Assess. 51, 511–529.

Waheed, M.A., Oni, A.O., Adejuyigbe, S.B., Adewumi, B.A., 2014. Thermoeconomic and environmental assessment of a crude oil distillation unit of a Nigerian refinery. Appl. Therm. Eng. 66, 191–205. doi:10.1016/j.applthermaleng.2014.02.007

Wahl, D.C., 2012. Scale-linking design for systemic health: sustainable communities and cities in context, in: Ecodynamics - The Prigogine Legacy. WIT Press, Southampton, Billerica, pp. 233–248.

Wahl, D.C., Baxter, S., 2008. The Designer's Role in Facilitating Sustainable Solutions. Des. Issues 24, 72–83.

Wahyuni, D., 2012. The Research Design Maze: Understanding Paradigms, Cases, Methods and Methodologies. J. App. Manage. Account. R. 10, 69 – 80.

Walter, C., Stützel, H., 2009. A new method for assessing the sustainability of land-use systems (I): Identifying the relevant issues. Ecol. Econ. 68, 1275–1287. doi:10.1016/j.ecolecon.2008.11.016

Wang, G., Côté, R., 2011. Integrating eco-efficiency and eco-effectiveness into the design of sustainable industrial systems in China. Int. J. Sustain. Dev. World Ecol. 18, 65–77. doi:10.1080/13504509.2010.527459

Wang, W., 2008. The nature of evolutionary artefact and design process knowledge coupling. PhD thesis. University of Strathclyde, Glasgow.
Wang, W., Duffy, A., Boyle, I., Whitfield, R.I., 2013. A critical realism view of design artefact knowledge. J. Des. Res. 11, 243–262.
Wang, W., Duffy, A., Whitfield, I., Liu, S., Boyle, I., 2008. A design view of capability, in: Realising Network Enabled Capability Conference 2008, 13-14 October 2008, Leeds, UK. Leeds, pp.1 – 9.
Wang, W., Duffy, A.H.B., 2009. A triangulation approach for design research, in: Proceedings of ICED'09. The Design Society, Stanford, pp. 275–286.
Web of Science, 2014. Web of Science - Search [WWW Document]. URL http://apps.webofknowledge.com/UA_GeneralSearch_input.do?product=UA&search_mode=GeneralSearch&SID=V1aRs3HEYrackiiNeFd&preferencesSaved= (accessed 9.15.14).
Werhahn-Mees, W., Palosuo, T., Garcia-Gonzalo, J., Roser, D., Lindner, M., 2011. Sustainability impact assessment of increasing resource use intensity in forest bioenergy production chains. GCB Bioenergy 3, 91–106. doi:10.1111/j.1757-1707.2010.01068.x
Wiersum, K.F., 1995. 200 Years of Sustainability in Forestry : Lessons from History. Environ. Manage. 19, 321–329.
Wigum, K.S., Zachrisson, J., Boks, C., 2011. The role of product and system interfaces in designing zero emission buildings, in: Proceedings of the 2011 IEEE International Symposium on Sustainable Systems and Technology. IEEE, pp. 1–6. doi:10.1109/ISSST.2011.5936844
Williams, C.C., Millington, A.C., 2004. The diverse and contested meanings of sustainable development. Geogr. J. 170, 99–104.
Wimmer, W., 1999. The ECODESIGN checklist method: a redesign tool for environmental product improvements, in: Proceedings First International Symposium on Environmentally Conscious Design and Inverse Manufacturing. IEEE, pp. 685–688. doi:10.1109/ECODIM.1999.747698
Wimmer, W., Judmaier, P., 2003. Learning and understanding ECODESIGN - preparing the complex environmental relations of products for straightforward application in companies, in: Proceedings of EcoDesign 2003: Third International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokyo, Japan, December 8-11, 2003. Tokyo, pp. 404 – 408. doi:10.1109/ECODIM.2003.1322702
World Bank, 2010. Environmental Economics and Indicators - Adjusted Net Saving [WWW Document]. URL http://web.worldbank.org/WBSITE/EXTERNAL/TOPICS/ENVIRONMENT/EXTEEI/0,,contentMDK:20502388~menuPK:1187778~pagePK:148956~piPK:216618~theSitePK:408050,00.html (accessed 6.6.12).

World Commission on Environment and Development, 1987. Our common future. Oxford University Press, Oxford, New York.

Yang, C.-M., Li, J.-J., Chiang, H.-C., 2011. Stakeholders' perspective on the sustainable utilization of marine protected areas in Green Island, Taiwan. Ocean Coast. Manag. 54, 771–780. doi:10.1016/j.ocecoaman.2011.08.006

Yang, H., Li, Y., Shen, J., Hu, S., 2003. Evaluating waste treatment, recycle and reuse in industrial system: an application of the eMergy approach. Ecol. Modell. 160, 13–21.

Yin, R., Xiang, Q., 2009. An integrative approach to modeling land-use changes: multiple facets of agriculture in the Upper Yangtze basin. Sustain. Sci. 5, 9–18. doi:10.1007/s11625-009-0093-1

Yin, R.K., 2003. Applications of case study research. Sage Publications, Thousand Oaks.

Yoshikawa, H., 1989. Design Philosophy: The State of the Art. CIRP Ann. - Manuf. Technol. 38, 579–586. doi:10.1016/S0007-8506(07)61126-3

Zachrisson, J., Boks, C., 2011. A framework for selecting sustainable behavior design strategies, in: Proceedings of the 2011 IEEE International Symposium on Sustainable Systems and Technology. IEEE, pp. 1. doi:10.1109/ISSST.2011.5936877

Zhang, X., Deng, S., Zhang, Y., Yang, G., Li, L., Qi, H., Xiao, H., Wu, J., Wang, Y., Shen, F., 2011. Emergy evaluation of the impact of waste exchanges on the sustainability of industrial systems. Ecol. Eng. 37, 206–216. doi:10.1016/j.ecoleng.2010.10.001

Zhang, Y., Singh, S., Bakshi, B.R., 2010. Accounting for ecosystem services in life cycle assessment, Part I: a critical review. Environ. Sci. Technol. 44, 2232–2242. doi:10.1021/es9021156

Appendices

Appendix 1: Paper A

This appendix contains Paper A, which presents the findings of a literature review on sustainability-oriented design. The paper has been submitted to the Journal of Engineering Design, and is currently under revision for resubmission in response to reviewer feedback. As such, the ideas and concepts discussed are in a state of evolution. For instance, owing to changes in the interpretation of certain design philosophies, methods, and tools, certain statistics presented here have also changed since submission of the paper and as such, may not directly align with those presented in the main body of the thesis. As stated in Chapter 4, the analysis leading to the (revised) statistics is presented in Appendix 6. With respect to references and styles, the paper is presented here largely as it is formatted for the journal.

Section 4.2 of Chapter 4 of the thesis presents a summary of key points and observations from this paper. Note that owing to space limitations, certain tables and figures presented elsewhere in the thesis have been removed from the following paper. Where this is the case, readers are referred to the appropriate section of the thesis.

The Design Sustainability Matrix

Laura Hay, Alex Duffy, R. I. Whitfield

Abstract

This paper presents the results of a critical literature investigation on sustainability-oriented design. Sixteen sustainability-oriented design philosophies (S-philosophies) were identified, the major ones being: sustainable design (SD); ecodesign (ED); design for environment (DfE); design for sustainability (DfS); and whole system design (WSD). These philosophies were found to focus on different dimensions of sustainability: ED and DfE focus on environmental sustainability; DfS and SD focus on environmental, economic, and social sustainability; and WSD focuses on environmental, economic, and social sustainability at the system level. One hundred and seventy three methods and tools were identified. These were found to be discussed by authors in the context of different S-philosophies, and reflected certain perspectives expounded by the philosophies. In comparison, relatively few efforts to integrate sustainability into the design process as a whole were observed. On the basis of these findings, the Design Sustainability Matrix (DSM) was created to serve three purposes: (i) visually position research on sustainability-oriented design; (ii) identify shortcomings in current knowledge on sustainability-oriented design; and (iii) guide designers with respect to methods and tools that may be most appropriate given their sustainability aims and perspectives. Finally, observations are made regarding the state of knowledge and challenges in the field.

Keywords: design for the environment; eco-design; sustainability; sustainable design

1. Introduction

Papanek (1972, 3) remarks that, "All men are designers. All that we do, almost all the time, is design, for design is basic to human activity." From this perspective, design has been cited as a key driver behind the socio-technical change required to shift human activity towards sustainability (Kemp and Parto 2005; Lopes, Fam, and Williams 2012; Shedroff 2009). However, design itself is argued to be a root cause of the sustainability and environmental problems that it is now expected to solve (Shedroff 2009). Jones (1991, xi) remarks that, "Designing, if it is to survive as an activity through which we transform our lives, on earth, and beyond, has itself to be redesigned, continuously." Along these lines, authors suggest that to effectively tackle sustainability issues, we must redesign designing (Wahl and Baxter 2008). That is, both the "way we think about design," and our "practices" (Wahl and Baxter 2008, 72). On a conceptual level, a number of sustainability-oriented design philosophies have emerged over the decades (Chapman 2011; Skjerven 2012). For example, Bhamra and Lofthouse (2007, 39) outline an evolution in such philosophies, from green design to ecodesign, through to design for sustainability. With respect to design practice, a plethora of methods and tools are positioned as effective means to address sustainability issues in design (Bovea and Pérez-Belis 2012; Gagnon, Leduc, and Savard 2012). For instance, Waage (2007, 638) writes of a "proliferation" in the "sustainability assessment principles, strategies, actions, and tools" available to designers and managers who wish to integrate sustainability considerations into the design process. Certain authors suggest that the literature on sustainability-oriented design has expanded to such a degree that something of a saturation point has been reached. For example, from a practical perspective, Byggeth, Broman, and Robert (2007a, 1) highlight the work of Baumann et al. (2000), who claim that "there is too much tool development and too few studies and evaluations of existing tools." Regarding design philosophies focusing on sustainability, Chapman (2011, 172) remarks that, "Large amounts of time and energy are spent attempting to define whether what you do is design for environment, ecodesign, sustainable design, design for sustainability, low-impact design, green design, clean design, and so on, and so on." They argue that, "The way in which we both discuss and name our practice [...] needs resolving, and fast."

In spite of the considerable research output generated on how to think about and carry out design in the context of sustainability, authors argue that the achievement of sustainability in design remains shrouded in confusion. For instance, Coley and Lemon (2009, 544) write that there is "confusion surrounding the multiple approaches to the design of more sustainable solutions due to the numerous definitions and interpretations currently being used within the relevant literature." Blizzard and Klotz (2012, 457) position "whole system design" as "one approach to sustainable design offering great potential." However, echoing the sentiments of Coley and Lemon (2009), they remark that "the processes, principles, and methods guiding the whole systems approach are not clearly defined or understood by practicing designers or design educators." More generally, Waage (2007, 638) suggests that the proliferation of methods discussed above "has created confusion about pathways forward for companies." They remark that it is "unclear how existing approaches are complementary or distinct." In this respect, a lack of clarity may be perceived with respect to the differentiation of sustainability-oriented design philosophies. For instance, Bhamra and Lofthouse (2007, 39) position "ecodesign" and "design for sustainability" as distinct philosophies in an evolution of "environmental design philosophies." In contrast, Clark et al. (2009, 409) refer to "Design for Sustainability" as an "ecodesign methodology" rather than a philosophy in its own right. As discussed above, Chapman (2011, 172) draws out a number of high-level terms, including: "design for environment, eco-design, sustainable design, design for sustainability, low-impact design, green design, [and] clean design." In contrast with Bhamra and Lofthouse (2007) above, they suggest that this patchwork of terms may simply be reduced to "a matter of opinion." In certain cases, authors may discuss what are potentially distinct philosophies, but conflate different terminologies. For instance, Ramani et al. (2010, 3) describe "eco-design tools" in the context of an overarching "sustainable product development" concept. Similarly, Strasser and Wimmer (2003, 757) refer to the "ECODESIGN PILOT" as a "Design for Environment" tool, whilst Bovea and Pérez-Belis (2012, 63) include the same tool in a "taxonomy of ecodesign tools." Reflecting upon this research landscape, Coley and Lemon (2009, 544) remark that terminology employed to describe different sustainability-oriented approaches is "manifold."

From the above, it can be seen that there is a lack of clarity regarding the means and mindsets that may be adopted to effectively tackle sustainability issues in design. In order to arrive at a clear and informed view in this respect, it seems reasonable to suggest that an examination of the relevant literature from a neutral perspective is required. That is, a perspective that is free from bias towards any single design philosophy or domain. However, review papers on sustainability and the environment in design tend to examine research output from the viewpoint of a single philosophy such as e.g. ecodesign (M.D. Bovea and Pérez-Belis 2012) or sustainable design (Chiu and Chu 2012), or focus on a single design domain such as e.g. engineering design (Gagnon, Leduc, and Savard 2012) or product design (Waage 2007). Further, they tend to employ different terms with such a lack of rigour so as to hinder understanding of the basic concepts involved. For example, Ramani et al. (2010) provide a review entitled, "Integrated Sustainable Life Cycle Design: A Review." However, the term "sustainable product development" is employed throughout much of the work, with "sustainable life cycle design" not mentioned at all in the body of the article. Additionally, during the course of the article the authors discuss "eco-design tools" and the "practice" of "Design for Environment," without explaining how these concepts described by a mixture of terminology are related to sustainable product development.

To address the perceived shortcomings in current literature outlined above, this paper presents the results of a critical literature investigation on sustainability in design, spanning multiple design domains. The investigation clarifies the range of philosophies, methods, and tools developed to guide and support designing with sustainability in mind. The Design Sustainability Matrix (DSM), a taxonomy of major design philosophies, methods, and tools provides guidance and a means for tackling sustainability issues in design. The DSM serves three major purposes: (i) it visually positions research on sustainability-oriented design, i.e. clarifies the range of philosophies, methods, and tools developed to guide and support designing with sustainability in mind; (ii) it identifies shortcomings in current knowledge on sustainability-oriented design, i.e. the challenges in the field; and (iii) it can guide designers with respect to the methods and tools that may be most appropriate given their sustainability aims and perspectives.

The remainder of this paper is organised as follows. In section 2, the sample of literature that was considered during the investigation is outlined. In section 3, definitions of design and sustainability are examined. To ensure consistency throughout the paper and transparency in the results of the investigation, concrete definitions of each concept as they are considered are provided. In section 4, design philosophies oriented towards sustainability are identified. The aims and key perspectives of different philosophies are examined, and any similarities are highlighted. In section 5, methods and tools positioned as effective means for tackling sustainability issues in design are discussed. Further, efforts to integrate sustainability with the design process as a whole are considered. In section 6, the Design Sustainability Matrix is created on the basis of the investigation findings. In turn, a number of observations regarding the current state of knowledge and challenges in the field are made. The paper concludes with a summary of the work in section 7.

2. Methods

As mentioned in Section 1, the investigation was conducted from a neutral perspective. That is, the literature was viewed from a general standpoint as opposed to the perspective of a single philosophy or design domain. Literature was gathered from a range of different design areas, including: architecture and building design (e.g. Gamage and Hyde, 2012; Wigum et al., 2011); electrical/ electronic design (e.g. Boks and Stevels 2003; Unger, Schneider, and Salhofer 2008); engineering design (e.g. Gagnon, Leduc, and Savard 2012; Mayyas et al. 2012a); industrial design (e.g. Bhamra and Lofthouse 2007; Rodriguez and Boks 2005); process design (e.g. Hossain, Khan, and Hawboldt 2010; Taras and Woinaroschy 2012); product design and development (e.g. Byggeth et al. 2007a; Chapman 2011); service design (e.g. McAloone and Andreasen 2004); and systems design (e.g. Alfaris et al. 2010; Papandreou and Shang 2008). Additionally, sources considering design in relation to manufacturing were included (e.g. Lindahl et al. 2005; Rosen and Kishawy 2012). In total, eighty three sources were included in the literature sample examined, as shown in Table 1. In cases where the concepts described in a particular source were unclear, additional literature was consulted, also shown in Table 1. For instance, Bovea and Pérez-Beliz (2012) provide a review of ecodesign tools. In certain cases, the source indicated by the authors as originally defining a particular concept was consulted for further clarification. Three main aspects were considered in selecting specific sources for inclusion in the sample. In no particular order, these were as follows:

- The *focus* of the source: a mixture of sources reporting the development of concepts, the practical application of concepts, and the analysis of concepts was included. Note that "concepts" is employed here to refer to e.g. philosophies, methods, and tools. The inclusion of sources with a range of different focuses ensured that theoretical and practical perspectives were represented in the literature sample. Further, literature reviews focusing on design philosophies, methods, and tools from the perspective of sustainability were included to maximise the number of such entities uncovered by the investigation.

- The *content* of the source: all sources included in the sample were explicitly focused on some aspect of sustainability in design. A definition of sustainability, as it is considered in the context of this paper, is provided in section 3.2. As shown in section 3.2, sustainability may be considered from different perspectives, including environmental, economic, and social. A mixture of sources considering multiple and single dimensions of sustainability was included in the sample, in order to capture a broad spectrum of different viewpoints on design and sustainability.
- The relative *quality* and *impact* of the source: sources deemed to be of higher quality and impact were given precedence for inclusion in the sample. With respect to impact, the number of times each source was cited in wider literature was considered. However, this measure could not be relied upon blindly. For instance, a paper published in 1980 may reasonably be expected to have been cited more often than a paper of the same quality published in 2012. As such, qualitative judgements were also made by the authors regarding the quality and impact of each source (on the basis of wider literature wherever possible).

Table 1. Literature sample and additional sources consulted

Source	Context[a]	Main focus[b]	Additional clarifying sources
Alfaris et al., 2010	SysD	App; Dev	-------------------------
Aschehoug et al., 2012	PDD	A; App	-------------------------
Azkarate et al., 2011	EngD	Dev; App	-------------------------
Bazmi and Zahedi, 2011	SysD	A; LR	-------------------------
Bhamra and Lofthouse, 2007	PDD	A; App; LR	-------------------------
Bhamra et al., 1999	PDD	A; LR	-------------------------
Bhamra et al., 2011	ID	A; App	-------------------------
Bhander et al., 2003	PDD	A; Dev	-------------------------
Blizzard and Klotz, 2012	SysD	A; LR	-------------------------
Boks and Diehl, 2005	Multiple	A; App	-------------------------
Boks and Stevels, 2003	EED	A; App	-------------------------
Boks and Stevels, 2007	PDD	A; LR	-------------------------
Bovea and Pérez-Belis, 2012	PDD	A; LR	Bovea and Wang, 2007; De Benedetto and Klemeš, 2009; Luttropp and Lagerstedt, 2006; Sakao, 2009
Bovea and Vidal, 2004	PDD	App; Dev	-------------------------
Byggeth et al., 2007a	PDD	App; Dev	Byggeth et al., 2007b; Ny et al., 2005; Ny et al., 2008a; Ny et al., 2008b
Chapman, 2011	PDD	A; Dev	-------------------------
Charnley et al., 2011	PDD	A; App	-------------------------
Chen et al., 2012	PDD	App; Dev	-------------------------
Chiu and Chu, 2012	PDD	A; LR	Belaziz et al., 2000; Bonanni et al., 2010; Fargnoli and Kimura, 2006; Harun and Cheng, 2011; Santana et al., 2010; Spangenberg et al., 2010
Choi et al., 2008	PDD	App; Dev	-------------------------
Clark et al., 2009	PDD	App; LR	-------------------------
Coley and Lemon, 2009	PDD/SD	A; LR	-------------------------
Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010	Multiple	A	-------------------------
Edeholt, 2012	Multiple	A; App; LR	-------------------------
Ernzer and Bey, 2003	PDD	A; Dev	-------------------------
Ernzer and Wimmer, 2002	PDD	A; App	-------------------------
Fiksel, 2003	SysD	A; Dev	-------------------------
Gagnon et al., 2012	EngD	A; LR; Dev	Barron and Barrett, 1996; Belaziz et al., 2000
Gamage and Hyde, 2012	ABD	A; Dev; LR	-------------------------

Gu and Frazer, 2009	SysD	A; Dev	-------------------------
Han et al., 2012	SysD	App; Dev	-------------------------
Hong et al., 2012	EngD	App; Dev	-------------------------
Hossain et al., 2010	PrcD	App; Dev	-------------------------
Huisman et al., 2000	PDD	App; Dev	-------------------------
Huisman et al., 2003	PDD	App; Dev	-------------------------
Karlsson and Luttropp, 2006	PDD	A; App; Dev	Bhamra and Lofthouse, 2007; Luttropp and Lagerstedt, 2006
Keitsch, 2012a	ID	A; LR	-------------------------
Laitala et al., 2011	PDD	A	-------------------------
Laszlo et al., 2009	SysD	A; Dev	-------------------------
Latham, 2009	SysD	A; LR	-------------------------
Lenau and Bey, 2001	PDD	App	-------------------------
Lindahl, 1999	PDD	App; Dev	-------------------------
Lindahl, 2001	M	App; Dev	-------------------------
Lindahl, 2006	EngD	A; App	-------------------------
Lindahl et al., 2005	M	A; App	-------------------------
Lindahl et al., 2007	EngD	A	-------------------------
Lopes et al., 2012	PDD	A; App	-------------------------
Lu et al., 2011	PDD	App; Dev; LR	-------------------------
Luchs et al., 2012	PDD	A	-------------------------
Manesh and Tadi, 2011	SysD	A; App	-------------------------
Mayyas et al., 2012a	EngD	A; LR	-------------------------
Mayyas et al., 2012b	EngD	App; LR	-------------------------
McAloone, 2001	PDD	App	-------------------------
McAloone and Andreasen, 2004	PDD/SD	A	-------------------------
McDonough and Braungart, 2002	PDD	App; Dev	-------------------------
Niinimäki and Koskinen, 2011	ID	A	-------------------------
Oram, 2010	Multiple	A; Dev	-------------------------
Ostad-Ahmad-Ghorabi and Collado-Ruiz, 2011	SysD	App; Dev	-------------------------
Papandreou and Shang, 2008	SysD	App; Dev	IChemE, n.d.
Park et al., 2005	PDD	App; Dev	-------------------------
Pérez-Fortes et al., 2012	SysD	App	-------------------------
Poole et al., 1999	PDD	A; LR	-------------------------
Ramani et al., 2010	PDD	A; LR	-------------------------
Rodriguez and Boks, 2005	ID	A	-------------------------
Rosen and Kishawy, 2012	M	A; LR	Dreher et al., 2009; European Environment Agency, n.d.; Ford, n.d. OECD Environment Directorate, 2008; United Nations, 2007
Skjerven, 2012	ID	A; LR	-------------------------
Spangenberg et al., 2010	PDD	A; LR	-------------------------
Stasinopoulos et al., 2009	EngD/SysD	App; Dev	-------------------------
Strasser and Wimmer, 2003	PDD	App; Dev	-------------------------
Taras and Woinaroschy, 2012	PrcD	App; Dev	-------------------------
Trotta, 2010	PDD	A; LR	-------------------------
Unger et al., 2008	EED	A; App; LR	-------------------------
Urban et al., 2010	SysD	A; App; Dev	-------------------------
Urken et al., 2012	SysD	A; LR	-------------------------
Vinodh and Rathod, 2010	PDD	App; Dev	-------------------------
Waage, 2007	PDD	A; LR	-------------------------
Wahl, 2012	SysD	A; Dev	-------------------------
Wahl and Baxter, 2008	Multiple	A; LR	-------------------------
Wang and Côté, 2011	SysD	A; App	-------------------------
Wever et al., 2005	PDD	A	Boks and Stevels, 2003
Wigum et al., 2011	ABD	A	-------------------------
Wimmer and Judmaier, 2003	PDD	App; Dev	-------------------------
Yeo and Gabbai, 2011	EngD	A; App	-------------------------
Zachrisson and Boks, 2011	PDD	Dev	-------------------------

[a] Please see Section 8 (Nomenclature) for context abbreviations.
[b] Focus abbreviations: A = analysis of concepts; App = application of concepts; Dev = development of concepts; LR = literature review.

3. Defining design and sustainability

Clearly, interpretations of design may vary between design domains, and even individual designers within a single domain (Hubka 1982; Jones 1992). Thus, to ensure some degree of consistency and objectivity, a broad interpretation of design that is applicable across multiple contexts was adopted and is outlined in Section 3.1. With respect to sustainability, Vos (2007, 335) suggests that definitions "must number in the hundreds." As such, a similarly broad interpretation of sustainability is provided in Section 3.2, and positioned relative to design.

3.1 What is design?

Design has undergone considerable evolution over the years (Duffy 2005), from early craft based design (Hubka 1982; Jones 1991), through to design-by-drawing, system designing (Jones 1991), and finally, the notion that design is a fundamental process of human life. That is, as human individuals existing in a society, we are all designers to some extent (Jones 1991; Papanek 1972; Wahl and Baxter 2008). From this perspective, design may be viewed as a driver of socio-technical change (Lopes, Fam, and Williams 2012), defined by Jones (1991, 32) as "the fitting of products and systems to newly emerging forms of society." Horvath (2004, 155) remarks that design has progressed to such a point that it "could be identified as a discipline in its own right, independent of the various areas in which it is applied." Accordingly, the notion of "design research" has been outlined as a specific undertaking with its own distinctive features (Horváth and Duhovnik 2005).

Considering the research output produced on design in different contexts reveals a multitude of different interpretations and definitions of design. For instance, in the context of engineering design, Hubka (1982, 27) writes that, "Design engineering is primarily a mental activity, an activity of thinking." As such, it is "critically dependent on many other areas of knowledge." In the same context, Andreasen et al. (2002, 1) suggest that "designing may be seen as a transformation system, in which an operand is being transformed into a desired state by a set of operators. The operand is primarily the artefact to be designed, based upon an intention and observation of a need and transformed into a specification of the design, which satisfies the need. The system of operators is the "machinery" performing the design process, i.e. humans, technical means, information, goals and management systems used here." In the context of industrial design, Papanek (1972, 17) writes that the "planning and patterning of any act towards a desired, foreseeable end constitutes the design process." According to the author, "All men are designers. All that we do, almost all the time, is design, for design is basic to all human activity." Against the backdrop of product design and development, O'Donnell and Duffy (2005, 56) position design as "the processing of knowledge." That is, "knowledge is continuously evolved as a result of specific activities between extremes of abstract versus concrete and general versus specific." In a more general context, Jones (1992, 6) defines designing as "the initiation of change in man-made things." Further, they position design as "an activity through which we transform our lives, on earth, and beyond" Jones (1991, xi). Likewise, Mayall (1979, 121) remarks that, "Design above all things is the agent of change." They further interpret design as a "distinct and distinguished human activity," suggesting that "we cannot have good design unless we have good designers to do it!"

From the above, it may be seen that at least two features emerge as common among interpretations and definitions of design provided by authors in different contexts: (i) design is carried out by humans, or at least some intelligent entity; and (ii) design involves the transformation of entities that are physical (e.g. physical objects) or cognitive (e.g. knowledge) in nature. Additionally, it may be seen in the above paragraphs that design is frequently described as an "activity" (Hubka 1982; Jones 1991; Papanek 1972). In other words, a goal-directed physical or cognitive action (I.M. Boyle et al. 2009). In this vein, Archer (1965, in Jones 1992, 3) defines design as a "goal-directed problem-solving activity." Likewise, O'Donnell and Duffy (2005, 11) suggest that design "may be seen as a process of goal-directed reasoning." O'Donnell and Duffy (2005, 56) remark that "activities are the fundamental elements that transform input to output and are the basic components of processes, phases, projects, etc." Thus, it may be seen that considering design as an activity logically aligns with the notion that design involves the transformation of physical or cognitive entities as discussed above. It is therefore concluded that on a basic level, design may be viewed as an activity (Hubka 1982; Jones 1991; Papanek 1972), carried out by humans or some intelligent entity (Hubka 1982; Mayall 1979; Papanek 1972), that involves the transformation of physical and/or cognitive entities (Andreasen, Wognum, and McAloone 2002; Jones 1992; O'Donnell and Duffy 2005) according to design goals (Archer 1965, in Jones 1992; Boyle et al. 2009).

3.2 What is sustainability?

As is the case with design, different interpretations and definitions of the concept exist. Major interpretations of the meaning of sustainability include: the ability to sustain (Kajikawa 2008), the ability to maintain something (Lele and Norgaard 1996; Marcuse 1998), the ability to be maintained by something (Chapman 2011; Kajikawa 2008), and the ability to continue (Dempsey et al. 2011; Shearman 1990). However, from the perspective of dictionary entries at least, these interpretations may be viewed as closely related if not identical (OED 2012). Thus, they will be employed synonymously throughout this paper. To move from these abstract interpretations of sustainability to a more concrete definition, humans in a particular context must make value judgements regarding what is to be sustained, and for how long (Lele and Norgaard 1996). A range of different targets to be sustained may be identified, such as: the Earth system's natural resource base (Gagnon, Leduc, and Savard 2012); the function of a system (Urken, Nimz, and Schuck 2012); the value of a product for a user (Chapman 2011); and the relationship between a product and a user (Chapman 2011). Given a chosen target to be sustained over a period of time (which may be finite (e.g. Neumayer 2003) or indefinite (e.g. Larkin 1977)), humans may formulate contextual definitions of sustainability (Lele and Norgaard 1996; Vos 2007). For example, in the context of engineering design, Gagnon, Leduc, and Savard (2012, 50) define "sustainable engineering projects" as those that "preserve the sound functioning of ecosystems and social systems." In other words, sustainability is the ability of an engineering project to maintain the sound functioning of ecosystems and social systems indefinitely.

As touched upon in Section 1, it is now generally understood that the Earth system provides the basis for all human activities (UNEP 2012), including design (Gagnon, Leduc, and Savard 2012). However, UNEP (2012, xviii) highlight that "the 7 billion humans alive today are collectively exploiting the Earth's resources at accelerating rates and intensities that surpass the capacity of its systems to absorb wastes and neutralize the adverse effects on the environment." As discussed in section 3.1, design is interpreted in this paper as an activity (Hubka 1982; Jones 1991; Papanek 1972), carried out by humans or some intelligent entity (Hubka 1982; Mayall 1979; Papanek 1972), that involves the transformation of physical and/or cognitive entities (Andreasen, Wognum, and McAloone 2002; Jones 1992; O'Donnell and Duffy 2005) according to design goals (Archer 1965, in Jones 1992; Boyle et al. 2009). From this perspective, the crux of the sustainability problem for design may be described thus: design has a physical impact on the Earth system that may be detrimental to the system's resource base and waste processing capacity (Bhamra and Lofthouse 2007; Chapman 2011; Papanek 1972), which in turn may be compromising the continued operation (i.e. sustainability) of design and human activity as a whole (Papanek 1972; UNEP 2012).

From a human perspective at least, it is not sufficient for the behaviour of activities in the Earth system to be environmentally sustainable, as outlined above. This behaviour must also be socially and economically sustainable (Kajikawa 2008; Spangenberg, Fuad-Luke, and Blincoe 2010) – in other words, it should be socially acceptable and desirable, and economically viable (Brown et al. 1987; Goerner, Lietaer, and Ulanowicz 2009; Vucetich and Nelson 2010). Horvath (2004, 155) highlights that design "is destined to sustain human existence and well being by […] creation of artifacts and services for the society." Further, as discussed in Section 3.1, design may be viewed as a driver of socio-technical change (Lopes, Fam, and Williams 2012). As such, it may be seen that in addition to having a physical impact upon the Earth system, design also has a profound socio-economic impact on human life and civilisation within the system (Bhamra, Lilley, and Tang 2011; Papanek 1972). Accordingly, efforts to redesign design to include sustainability considerations, in the manner suggested by Wahl and Baxter (2008), typically centre on ameliorating the environmental, economic, and social impacts of design upon the Earth system (Bhamra et al. 2011; Spangenberg, Fuad-Luke, and Blincoe 2010). In the following sections of this paper, the outcomes of these efforts are examined. In Section 4, sustainability-oriented design philosophies are discussed, to provide a view on how we think about design in the context of sustainability. That is, the aims and perspectives that govern the actions taken when designing with sustainability in mind. To provide a complementary view on how we actually carry out design when considering sustainability, design methods and tools positioned by authors as effective means for tackling sustainability issues are discussed in Section 5.

4. Sustainability-oriented design philosophies

A design philosophy may be viewed as an overarching design concept, that expresses certain values and perspectives on design held by an individual (e.g. a lone designer) or a group of individuals (e.g. the design department of an organisation) (Evbuomwan, Sivaloganathan, and Jebb 1996; Hernandez 2010; Yoshikawa 1989). Typically, a design philosophy may be expressed in terms of broad aims and basic principles for design (Bhamra and Lofthouse 2007; Gould 2011; Hernandez 2010; Yoshikawa 1989). Essentially, such a philosophy may be considered to represent a designer's frame of reference. That is, a "set of standards, beliefs, or assumptions governing perceptual or logical evaluation or social behaviour" (OED 2013). From this perspective, it may be seen that the adoption of a particular design philosophy determines, at least to some extent, the way that we think about design (Evbuomwan, Sivaloganathan, and Jebb 1996). As discussed in section 1, a range of design philosophies focusing on sustainability have emerged over the years (Bhamra and Lofthouse 2007; Chapman 2011; Skjerven 2012). We may term these "sustainability-oriented philosophies," or "S-philosophies" hereafter. Following the definition of a design philosophy outlined above, an S-philosophy may be considered to be an overarching design concept that expresses values and perspectives on design with respect to sustainability.

In total, sixteen S-philosophies were identified, as presented in Table 2. Aims were detectable for all identified S-philosophies. Certain philosophies are discussed in wider design literature, but were presented by authors as suitable for tackling sustainability challenges. For instance, Edeholt (2012, 160) suggests that the "ultimate goal" for society is to address sustainability issues "by utilizing design and some of its tools to spur a creative public debate of our coming future," through "what sometimes is labeled 'discursive design.'" However, discursive design is also discussed in the general context of industrial and product design by Tharp and Tharp (n.d.), who make no reference to sustainability. Similarly, Blizzard and Klotz (2012) suggest that "more widespread application of whole systems design in practice […] will lead to more sustainable designs." However, whole system design is also discussed in the context of organisational redesign by Levine and Mohr (1998), and systems engineering by M'Pherson (1980), with neither author making reference to sustainability.

As discussed in Section 3.2, efforts to integrate sustainability considerations into design typically focus on ameliorating the environmental, economic, and social impacts of design upon the Earth system (Bhamra, Lilley, and Tang 2011; Spangenberg, Fuad-Luke, and Blincoe 2010). This focus may be seen to be reflected in the aims of the identified S-philosophies, with the majority aiming to address the environmental, economic, and/or social impacts of design in varying degrees. Further, the aims of certain S-philosophies were seen to express an intention to balance sustainability issues against traditional design issues during the design process. For instance, design for environment (Ramani et al. 2010), ecodesign (Park, Lee, and Wimmer 2005), and life cycle engineering (Ernzer and Bey 2003) were all found to aim at the reduction of major negative environmental impacts throughout the life cycle of a design, whilst simultaneously fulfilling traditional design requirements with respect to aspects such as performance, function, and quality.

It can be seen in Table 2 that some S-philosophies appear to be discussed by more authors than others. For example, significantly more references are associated with design for environment, design for sustainability, ecodesign, and sustainable design than other philosophies in the table. Overall the following conclusions can be reached (Figure 1):

- Sustainable design was discussed in twenty four distinct sources, i.e. 29% of those included in the sample (Azkarate et al. 2011; Bazmi and Zahedi 2011; Bhamra, Lilley, and Tang 2011; Byggeth et al. 2007a; Chapman 2011; Chen et al. 2012; Chiu and Chu 2012; Gagnon, Leduc, Savard 2012; Gamage and Hyde 2012; Hong et al. 2012; Hossain, Khan, and Hawboldt 2010; Karlsson and Luttropp 2006; Keitsch 2012a; Lopes, Fam, and Williams 2012; Lu et al. 2011; Manesh and Tadi 2011; McDonough and Braungart 2002; Rosen and Kishawy 2012; Skjerven 2012; Stasinopoulos et al. 2009; Taras and Woinaroschy 2012; Vinodh and Rathod 2010; Waage 2007; Yeo and Gabbai 2011);
- ecodesign was discussed in nineteen distinct sources, i.e. 23% of those included in the sample (Aschehoug, Boks, and Storen 2012; Bhamra et al. 1999; Boks and Diehl 2005; Bovea and Pérez-Belis 2012; Bovea and Vidal 2004; Collado-Ruiz and Ostad-Ahmad-Ghorabi 2010; Huisman, Boks, and Stevels 2000, 2003; Karlsson and Luttropp 2006; McAloone 2001; McAloone and Andreasen 2004; Ostad-Ahmad-Ghorabi and Collado-Ruiz 2011; Park, Lee, and Wimmer 2005; Poole et al. 1999; Ramani et al. 2010; Strasser and Wimmer 2003; Unger, Schneider, and Salhofer 2008; Wever et al. 2005; Wimmer and Judmaier 2003);
- design for environment was discussed in sixteen distinct sources, i.e. 19% of those included in the sample (Bhander, Hauschild, and McAloone 2003; Boks and Stevels 2007; Choi, Nies, and Ramani 2008; Ernzer and Wimmer 2002; Lenau and Bey 2001; Lindahl 1999; Lindahl 2001; Lindahl 2006; Lindahl et al. 2005; Lindahl et al. 2007; McAloone and Andreasen 2004; Poole et al. 1999; Ramani et al. 2010; Rosen and Kishawy 2012; Trotta 2010; Wigum, Zachrisson, and Boks 2011);
- design for sustainability was discussed in ten distinct sources, i.e. 12% of those included in the sample (Rodriguez and Boks 2005; Bhamra and Lofthouse 2007; Wahl and Baxter 2008; Clark et al. 2009; Alfaris et al. 2010; Oram 2010; Spangenberg, Fuad-Luke, and Blincoe 2010; Mayyas et al. 2012a; Mayyas et al. 2012b; Rosen and Kishawy 2012); and
- whole system design was discussed in five distinct sources, i.e. 6% of those included in the sample (Blizzard and Klotz 2012; Charnley, Lemon, and Evans 2011; Coley and Lemon 2009; Gagnon, Leduc, and Savard 2012; Stasinopoulos et al. 2009)

Figure 1. Percentage of authors discussing different S-philosophies (see Figure 4-5, Section 4.2.2, Chapter 4 of thesis)

Table 2. Overview of S-philosophies (see Table 4-2, Section 4.2.2, Chapter 4 of thesis)

4.1 Design for environment (DfE) and ecodesign (ED)

Authors position DfE and ED as equivalent philosophies (Boks and Stevels 2007; Collado-Ruiz and Ostad-Ahmad-Ghorabi 2010; Ostad-Ahmad-Ghorabi and Collado-Ruiz 2011). For instance, Unger, Schneider, and Salhofer (2008, 14) remark that, "Ecodesign is often also referred to as green design, ecological design, environmentally sound or environmentally sensitive design, Design for the Environment (DfE), environmentally responsible design or others." Similarly, Poole et al. (1999, 334) consider "ecodesign as synonymous with Design for Environment" (DfE) and "Environmentally Conscious Design" (ECD)." They claim that "the field of study has developed such that all these names refer to the process of designing products and processes with attention to the environmental impact throughout their life-cycle." Indeed, authors discussing DfE and ED may be seen to describe essentially the same aim for each philosophy (as shown in Table 2 above), which may be recapitulated as: to reduce the negative environmental impacts of a design throughout its life cycle, whilst simultaneously fulfilling traditional design requirements with respect to aspects such as performance, function, and quality (Bhander, Hauschild, and McAloone 2003; Boks and Stevels 2007; Bovea and Pérez-Belis 2012; Choi, Nies, and Ramani 2008; Poole et al. 1999; Spangenberg, Fuad-Luke, and Blincoe 2010). For example, Ramani et al. (2010, 2) suggest that

"DFE practices are meant to develop environmentally compatible products and processes while maintaining product, price, performance, and quality standards." Similarly, Park, Lee, and Wimmer (2005, 254) remark that the "ultimate aim of ecodesign is to improve a product's environmental performance. Basic characteristics of a product, such as cost, functionality, performance, and reliability, must be considered simultaneously in the ecodesign process."

From the above, it may be seen that both DfE and ED seek to achieve environmental sustainability in design (Ramani et al. 2010; Rosen and Kishawy 2012). That is, to preserve the Earth system's resource base and waste processing capacity by ameliorating the environmental impacts of design on the system (Bhamra and Lofthouse 2007; Spangenberg, Fuad-Luke, and Blincoe 2010). However, in the context of DfE and ED, environmental sustainability should not be achieved at the expense of design and business success – that is, environmental sustainability should not be pursued at the expense of, for instance, design and business performance goals (Ramani et al. 2010). DfE and ED share a number of perspectives, which can be summarised as:

- the challenges involved in reducing the environmental impacts of design may be viewed as business opportunities (Boks and Stevels 2007; Ramani et al. 2010; Unger, Schneider, and Salhofer 2008);
- environmental considerations should be integrated into all stages of the design process (Ramani et al. 2010; Rosen and Kishawy 2012), especially the early phases where the design is most flexible (Bovea and Pérez-Belis 2012; Lindahl 2001; Park, Lee, and Wimmer 2005), and viewed in a balanced manner alongside traditional design requirements for aspects such as cost, quality, and technical performance (Park, Lee, and Wimmer 2005; Ramani et al. 2010);
- the environmental impacts of designed artefacts are addressed at various stages throughout their life cycle (Bhander, Hauschild, and McAloone 2003; Bovea and Pérez-Belis 2012; Choi, Nies, and Ramani 2008; Lindahl 2001; McAloone 2001), with a particular focus on the end-of-life stage (Choi, Nies, and Ramani 2008; Huisman, Boks, and Stevels 2000; Wigum, Zachrisson, and Boks 2011);
- in certain cases, life cycle stages with the greatest potential for negative impacts may be targeted as opposed to the full life cycle, in order to maintain acceptable performance with respect to the time and resources consumed by design activities (Bovea and Vidal 2004; Choi, Nies, and Ramani 2008; Park, Lee, and Wimmer 2005); and
- reductions in the material and energy consumption of design and designed artefacts are sought (Choi, Nies, and Ramani 2008; Wigum, Zachrisson, and Boks 2011), often through efficiency improvements (Boks and Stevels 2007; Choi, Nies, and Ramani 2008; Spangenberg, Fuad-Luke, and Blincoe 2010).

4.2 Design for sustainability (DfS) and sustainable design (SD)

Whilst not explicitly equated by authors, DfS and SD may be seen to share essentially the same aim and perspectives on design with respect to sustainability (Table 2). With respect to aims, both philosophies seek to improve environmental, economic, and social impacts throughout the life cycle of a design (Bhamra, Lilley, and Tang 2011; Chiu and Chu 2012; Mayyas et al. 2012; Spangenberg, Fuad-Luke, and Blincoe 2010). This improvement may involve either minimising negative (Bhamra and Lofthouse 2007; Chapman 2011) or creating positive (McDonough and Braungart 2002; Spangenberg, Fuad-Luke, and Blincoe 2010) impacts. For instance, Bhamra, Lilley, and Tang (2011, 428) remark that sustainable design "takes into account environmental, economic and social impacts enacted throughout the product lifecycle," and that the "application of sustainable design can greatly reduce the environmental and social impacts of [...] products and services." With respect to the creation of positive impacts, McDonough and Braungart (2002, 254) write that the "goal of an effective company," in the context of SD, "is to stay in business as it transforms, providing shareholder value as it discovers ways to generate positive social and environmental effects." In the context of DfS, Bhamra and Lofthouse (2007, 40) discuss the need for designers to "reduce the environmental and social impact [of design] across the life cycle." With respect to the creation of positive impacts in the context of DfS, Spangenberg, Fuad-Luke, and Blincoe (2010, 1490) write that DfS involves "minimising the negative and maximising the positive impacts on nature, humans and society." Therefore, it may be concluded that like DfE and ED, DfS and SD represent the same design philosophy.

It may be seen from the above that both DfS and SD seek to achieve environmental, economic, and social sustainability in design (Gagnon, Leduc, and Savard 2012; Spangenberg, Fuad-Luke, and Blincoe 2010). That is, to (i) preserve the Earth system's resource base and waste processing capacity by ameliorating the environmental impacts of design on the system, and (ii) ensure that design is economically viable, and socially acceptable and desirable, by ameliorating the economic and social impacts of design on the system (Bhamra and Lofthouse 2007; Bhamra, Lilley, and Tang 2011; Chiu and Chu 2012; Hossain, Kahn, and Hawboldt 2010; Spangenberg, Fuad-Luke, and Blincoe 2010). In the case of DfE and ED as discussed in section 4.1, it was shown that environmental sustainability considerations must be balanced against traditional design requirements (Park, Lee, and Wimmer 2005; Ramani et al. 2010). Certain authors in the context of DfS and SD may be seen to adopt a similar perspective. For instance, Mayyas et al. (2012, 1846) highlight the work of Curtis and Walker (2001), who suggest that "designing for sustainability involves balancing social, ethical and environmental issues alongside economic factors within the product or service development process." However, from other perspectives, sustainability considerations may be seen to drive evolution in what may be considered to be "traditional" design requirements. For instance, in the context of SD, McDonough and Braungart (2002, 252) argue that the creation of "a sustaining industrial system" requires "a new definition of quality in product, process and facility design." They write that "quality is embodied in designs that allow industry to enhance the well being of nature and culture while generating economic value." In other words, a traditional design requirement for "quality" has been redefined to account for sustainability considerations.

DfS and SD share a number of perspectives, which may be summarised as:

- environmental, economic, and social considerations should be integrated into all stages of the design process (Bhamra and Lofthouse 2007; Gagnon, Leduc, and Savard 2012; Spangenberg, Fuad-Luke, and Blincoe 2010; Waage 2007), and considered in a balanced and holistic manner (Keitsch 2012; Mayyas et al. 2012a; McDonough and Braungart 2002; Spangenberg, Fuad-Luke, and Blincoe 2010);
- the environmental, economic, and social impacts of designed artefacts should be addressed throughout their full life cycle (Bhamra and Lofthouse 2007; Bhamra, Lilley, and Tang 2011; Gagnon, Leduc, and Savard 2012; Mayyas et al. 2012a; Spangenberg, Fuad-Luke, and Blincoe 2010) – however, in certain cases, a specific stage in the life cycle may be targeted, such as the use phase (Bhamra, Lilley, and Tang 2011; Rodriguez and Boks 2005);
- the complexity and multiple scales of the Earth's sub-systems and in turn, design problems, are acknowledged (Gagnon, Leduc, and Savard 2012; Gamage and Hyde 2012; Spangenberg, Fuad-Luke, and Blincoe 2010; Wahl and Baxter 2008);
- the ethical aspects of design should be considered (Bhamra, Lilley, and Tang 2011; Chapman 2011; Spangenberg, Fuad-Luke, and Blincoe 2010; Mayyas et al. 2012), and the designer should recognise their ethical responsibilities towards society (Bhamra and Lofthouse 2007; Chapman 2011);
- human values and behaviour are viewed as underpinning the sustainability of design, production, and consumption (Bhamra and Lofthouse 2007; Bhamra, Lilley, and Tang 2011; Chapman 2011; Spangenberg, Fuad-Luke, and Blincoe 2010);
- to ensure that multiple (and potentially competing) values and perspectives are considered during design, a greater number of stakeholders (e.g. the general public (Daniel Christian Wahl and Baxter 2008), and product users (T. Bhamra, Lilley, and Tang 2011)) should participate in design than has conventionally been the case (Gagnon, Leduc, and Savard 2012; Keitsch 2012; Spangenberg, Fuad-Luke, and Blincoe 2011); and
- to tackle multidisciplinary challenges, cross-disciplinary collaboration should occur during design (Gagnon, Leduc, and Savard 2012; Keitsch 2012; Spangenberg, Fuad-Luke, and Blincoe 2010; Wahl and Baxter 2008).

4.3 Whole system design (WSD)

In sections 4.1 and 4.2, it was shown that (i) DfE and ED aim to achieve environmental sustainability (Ramani et al. 2010; Rosen and Kishawy 2012), and (ii) DfS and SD aim to achieve environmental, economic, and social sustainability (Gagnon, Leduc, and Savard 2012; Spangenberg, Fuad-Luke, and Blincoe 2010), by integrating environmental, economic, and/or social considerations into design. In other words, these philosophies are explicitly oriented towards sustainability (albeit in varying dimensions). WSD, on the other hand, may not necessarily be conducive to the achievement of sustainability. For instance, Blizzard and Klotz (2012, 458) remark that WSD "does not guarantee sustainable design outcomes. It may, however, offer more opportunity than traditional design approaches for designers to create sustainable solutions to our most pressing issues." Further, as discussed in the introduction to section 4, WSD may be seen to be discussed in wider design literature, with no relation to sustainability (e.g. Levine and Mohr 1998; M'Pherson 1980). However, the philosophy is positioned by certain authors as effective in tackling sustainability challenges (Blizzard and Klotz 2012; Charnley, Lemon, and Evans 2011; Coley and Lemon 2009; Gagnon, Leduc, and Savard 2012; Stasinopoulos et al. 2009). Upon examination of the research output produced by these authors, it may be seen that when applied in a sustainability context, the aim of WSD is similar to that of DfS and SD (Stasinopoulos et al. 2009) discussed in section 4.3. However, WSD may be considered to be founded in a systems view of the world (Coley and Lemon 2009) – that is, a view where "the interconnections between sub-systems and systems are actively considered" (Stasinopoulos et al. 2009, 3). As such, from the perspective of sustainability at least, the aim of WSD may be stated as: to improve (i.e. minimise negative or create positive) environmental, economic, and social impacts throughout the life cycle of a system (Blizzard and Klotz 2012; Charnley, Lemon, and Evans 2011; Stasinopoulos et al. 2009). Thus, it can be seen that WSD may result in the achievement of environmental, economic, and social sustainability as is the case with DfS and SD, but in the context of whole systems (Blizzard and Klotz 2012; Stasinopoulos et al. 2009). A number of key perspectives emerge from the literature on WSD in the context of sustainability, which can be summarised as:

- design problems are viewed as embedded within a wider system (Coley and Lemon 2009), where design requirements are interrelated with solutions (Blizzard and Klotz 2012) – as such, limits with respect to the sustainability of a particular design solution may be averted by redefining the problem (Coley and Lemon 2009);
- the environmental, economic, and social performance of whole systems should be optimised during design, as opposed to isolated entities (Stasinopoulos et al. 2009);
- the environmental, economic, and social impacts of systems should be addressed throughout their full life cycle – in particular, synergies among sub-systems should be sought out to increase positive and reduce negative impacts throughout the life cycle of the overall system (Blizzard and Klotz 2012; Charnley, Lemon, and Evans 2011; Coley and Lemon 2009; Stasinopoulos et al. 2009);
- throughout the design process, designers should adopt a systems view and rely more heavily upon ingenuity and intuition, as opposed to checklists and guidelines (Blizzard and Klotz 2012; Coley and Lemon 2009);
- the complexity and multiple scales of the Earth system, and in turn design problems, are acknowledged (Charnley, Lemon, and Evans 2011; Coley and Lemon 2009; Stasinopoulos et al. 2009);
- to tackle multidisciplinary challenges, cross-disciplinary collaboration should occur during design (Blizzard and Klotz 2012; Charnley, Lemon, and Evans 2011; Coley and Lemon 2009; Stasinopoulos et al. 2009); and
- to ensure that multiple (and potentially competing) values and perspectives are considered during design, a greater number of stakeholders should participate in design than has conventionally been the case (Charnley, Lemon, and Evans 2011; Coley and Lemon 2009).

5. Sustainability-oriented design practice

A design philosophy essentially provides a frame of reference within which to carry out design. With respect to the "doing" of design, design methods and tools may be seen to provide guidance

(Cross 2008; Jones 1992). A number of methods and tools are positioned here as effective means for tackling sustainability issues in design (Bovea and Pérez-Belis 2012; Gagnon, Leduc, and Savard 2012; Waage 2007), as shown in the following sections.

A design method may be interpreted as an identifiable way of working that supports a designer in meeting design goals or finding a solution to a problem (Cross 2008; Lindahl 2006). Closely related to the notion of a design method is a design tool. A design tool may be considered as a physical or intangible means that supports a designer in meeting design goals or finding a solution to a problem (Mattias Lindahl 2006). Generally speaking, a design tool may be used to support the application of a particular design method (Cross 2008). For instance, the House of Quality may be viewed as a tool to support the application of the Quality Function Deployment method (M. D. Bovea and Wang 2007). In section 5.1, the range of methods and tools for tackling sustainability issues is explored in the context of certain categories, and related to the key perspectives of the major S-philosophies outlined in section 4.

In striving to deliver a final design solution, a designer may undertake a particular sequence of activities that may be aggregated into stages or phases (O'Donnell and Duffy 2005; Pugh 1991). Holistically, these activities and stages may be termed the design process (O'Donnell and Duffy 2005). For instance, Ulrich and Eppinger (2008, 15) outline a "generic product development process," consisting of six phases comprised of various activities: 0. Planning, involving market research and technology assessment activities; 1. Concept development, involving needs analysis and idea generation activities; 2. System-level design, involving planning and target setting activities; 3. Detail design, involving planning and decision making activities; 4. Testing and refinement, involving testing and prototyping activities; and 5. Production ramp-up, involving evaluation and manufacturing activities. In section 5.2, sustainability and the design process as a whole is considered, to explore the degree to which sustainability issues and sustainability-focused methods and tools have been integrated with this process. Note that throughout the following sections, abbreviations are adopted for certain common design methods and tools. Readers are referred to Section 8 for a full list of these abbreviations.

5.1 Methods and tools

The major types of method and tool discussed by authors are presented in Table 3. In total, one hundred and seventy three distinct methods and tools were identified. Certain methods and tools presented in Table 3 represent generalisations of groups of individual methods and tools, owing to the number of specific examples uncovered. Namely, the following may all be decomposed into specific examples developed and applied by different authors: benchmarking methods; design for/to X methods; design guidelines; design principles; environmental evaluation methods; failure mode and effects analysis (FMEA) and FMEA-based methods; formal optimisation methods; idea generations methods; life cycle assessment (LCA) and LCA-based methods; life cycle costing (LCC) and LCC-based methods; multi criteria decision analysis (MCDA) methods; quality function deployment (QFD) and QFD-based methods; socio-economic evaluation methods; strategic evaluation methods; Theory of Inventive Problem Solving (TRIZ) and TRIZ-based methods; and user-centred design methods. The specific methods and tools are explored in greater detail in subsequent sub-sections.

Methods and tools were categorised according to the kinds of activities in which they are intended to support designers, with the categories listed below adopted throughout this paper. These categories are not intended to constitute an exhaustive representation of all types of method and tool. Rather, they may be viewed as the categories that emerged most prominently from the range of methods and tools identified through the investigation documented in this paper:

- *creativity*: includes methods and tools considered to support designers in creative activities, e.g. the generation and development of design concepts (Collado-Ruiz and Ostad-Ahmad-Ghorabi 2010);

- *decision making*: includes methods and tools considered to support designers in the various decision making activities that must be executed during design, e.g. key decisions to be made with respect to the life cycle of a design (Mayyas et al. 2012a);
- *evaluating and analysing*: includes methods and tools considered to support designers in evaluative and analytical activities, e.g. evaluating the sustainability performance of designs (Chen et al. 2012), and analysing user requirements (M.D. Bovea and Pérez-Belis 2012);
- *modelling and simulating*: includes methods and tools considered to support designers in activities focused on representing and studying behaviour and structure, e.g. developing a parametric model of a design (Ostad-Ahmad-Ghorabi and Collado-Ruiz 2011), or testing a process design by simulating its behaviour (Hossain, Khan, and Hawboldt 2010); and
- *optimising*: includes methods and tools considered to support designers in efforts to optimise designs, e.g. finding the best configuration for a designed system given a set of competing objectives (Papandreou and Shang 2008).

Additionally, the following distinctions are made between different types of evaluation method in the context of this paper:

- *benchmarking methods* are viewed as methods for evaluating the environmental, economic, and/or social performance of a design or design process relative to the performance of another such entity (Wever et al. 2005);
- *environmental evaluation methods* are viewed as methods for evaluating environmental performance that do not adopt a life cycle perspective;
- *impact assessment methods* are viewed as methods for evaluating environmental, economic, and/or social performance that attempt to evaluate the “actual significance” of the effects measured (Fiksel 2003, 5337);
- *integrated environmental and socio-economic evaluation methods* are viewed as methods for the holistic evaluation of environmental, economic, and social performance (Gagnon, Leduc, and Savard 2012);
- *life cycle assessment (LCA) and LCA-based methods* are viewed as methods for the evaluation of environmental performance, that adopt a life cycle perspective (Fiksel 2003);
- *life cycle costing (LCC) and LCC-based methods* are viewed as methods for evaluating costs (i.e. economic performance) from a life cycle perspective (M.D Bovea and Vidal 2004);
- *socio-economic evaluation methods* are viewed as methods for evaluating social and/or economic performance that do not adopt a life cycle perspective; and
- *strategic evaluation methods* are viewed as methods for evaluating environmental, economic, and/or social performance that “provide a quick way of identifying which areas [of a design] are most important to focus [on]” (Bhamra and Lofthouse, 2007, 71).

A tool may be used to support the application of a particular method (Cross 2008). As such, it was assumed during the investigation that a method and a tool that are seen to be used in direct conjunction will always belong to the same category from the first list provided above. Therefore, in cases where a tool is clearly associated with a method, only the method is included in Table 3. Conversely, in cases where a tool is discussed in isolation from any particular method, then the tool is included in Table 3.

Table 3. Overview of major methods and tools (see Table 4-3, Section 4.2.3, Chapter 4 of thesis)

It would be beyond the scope of this paper to provide detailed descriptions of each method and tool. Rather, the intention in the following paragraphs is to provide an overview of the different kinds of methods and tools relating to sustainability in design. Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010, 479) suggest that in the development of means for tackling sustainability issues in design, “Many design methods were “environmentalized,” as well as new ones generated.” Along these lines, the following classifications are highlighted in the proceeding discussion: new methods and tools, i.e. those newly developed with the explicit purpose of tackling sustainability issues (e.g. the Templates for Sustainable Development tool developed by Ny et al. (2008)); modified methods and tools, i.e. those developed by modifying conventional methods and tools to be more effective in tackling sustainability issues (e.g. the Environmental Effect Analysis method developed by Lindahl (2001)); and conventional methods and tools, i.e. those that may be applied in design conventionally, but are presented as effective in tackling sustainability issues in their original, unmodified form (e.g. the brainstorming method presented by Gagnon, Leduc, and Savard (2012) and Stasinopoulos et al. (2009)).

5.1.1 Methods and tools for creativity

Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010, 480) write that creativity "is already a key aspect in design, and sustainable products, more than any other sector, will need groundbreaking ideas." Along these lines, Gagnon, Leduc, and Savard (2012, 63) position the generation of "at least one alternative concept radically different from conventional ones" as a key task involved in designing in the context of sustainability. However, the authors highlight a need to "increase the importance of creativity tools" in sustainability-oriented design. Indeed, a relatively low number of creativity-focused methods and tools were identified during the investigation (eighteen in total), as shown in Table 4.

Table 4. Methods and tools for creativity

Method/tool description[a]	**Sources**	**S-phil.**[b]	**Context**[b]
TRIZ and TRIZ-based methods/tools:			
Bio-TRIZ[b] (M)	Gamage and Hyde, 2012	SD	ABD
TRIZ (M)	Strasser and Wimmer, 2003;	ED;	PDD
	Trotta, 2010	DfE	
TRIZ laws of evolution (T)	Chiu and Chu, 2012	SD	PDD
Other methods/tools:			
Backcasting (M)	Bhamra and Lofthouse, 2007;	DfS;	ID;
	Byggeth et al., 2007a,b;	SD;	PDD;
	Gagnon et al., 2012		
		SD	EngD
Brainstorming (M)	Gagnon et al., 2012;	SD;	EngD;
	Stasinopoulos et al., 2009	WSD	SysD
Brainwriting (M)	Gagnon et al., 2012	SD	EngD
Design spiral (M)	Gamage and Hyde, 2012	SD	ABD
Flowmaker (M)	Bhamra and Lofthouse, 2007	DfS	ID
Forced relationships (M)	Bhamra and Lofthouse, 2007;	DfS;	ID;
	Gagnon et al., 2012	SD	EngD
Information/Inspiration (T)	Bhamra and Lofthouse, 2007;	DfS;	ID;
	Karlsson and Luttropp, 2006	ED	PDD
Layered games (M)	Bhamra and Lofthouse, 2007	DfS	ID
Mood boards (M)			
Random words (M)			
Real People (T)			
SCAMPER[c] (M)	Gagnon et al., 2012	SD	EngD
Synectics (M)			
Templates for Sustainable Development (T)	Byggeth et al., 2007a,b	SD	PDD
What if? (M)	Bhamra and Lofthouse, 2007	DfS	EngD

[a] "M" designates a method; "T" designates a tool.
[b] Please see Section 8 (Nomenclature) for abbreviations.
[c] SCAMPER = Substitute, Combine, Adapt, Modify, Put to another use, Eliminate, Reverse

It may be seen in Table 4 that the majority of the identified methods and tools for creativity were discussed in the context of DfS and SD. Lindahl et al. (2007, 138) remark that when DfE is applied, often "the focus is on environmental redesign of products instead of the development of new products." Similarly, redesign is frequently discussed by authors in the context of ED (Boks and Diehl 2005; Bovea and Pérez-Belis 2012; Bovea and Wang 2007; Ostad-Ahmad-Ghorabi and Collado-Ruiz 2011; Poole et al. 1999; Strasser and Wimmer 2003). In contrast, authors discussing DfS and SD may be seen to place considerable importance upon the development of new and radical concepts. For instance, in the context of SD, Gagnon, Leduc, and Savard (2012, 61) suggest that the generation of new ideas should be a key task, writing that "incremental innovation is unlikely to provide the level of performance expected from sustainable solutions." Spangenberg, Fuad-Luke, and Blincoe (2010, 1489) remark that DfS attempts to satisfy needs "in an innovative, more sustainable fashion," and requires "thinking out of the box." As such, it may be expected to some degree that a greater number of methods and tools focusing on creativity are discussed in the context of DfS and SD.

Two of the tools shown in Table 4 are presented by authors as new methods, specially developed to tackle sustainability issues – namely, Information/Inspiration (Bhamra and Lofthouse 2007; Karlsson and Luttropp 2006); and Templates for Sustainable Development (Byggeth et al. 2007a). With respect to modified versions of conventional methods, Gamage and Hyde (2012, 229) describe bio-TRIZ as "a systematically developed version of TRIZ," that may be used for "transferring biology into technology." The remainder of the methods and tools presented in Table 4 may be viewed as conventional, representing the majority of the identified methods and tools for creativity.

5.1.2 Methods and tools for decision making

Waage (2007, 638) suggests that the range of "details and decisions" to be addressed by designers who wish to integrate sustainability into the design process is "immense." Accordingly, a relatively high number of methods and tools for decision making was identified (forty one in total) as shown in Table 5.

Table 5. Methods and tools for decision making identified

Method/tool description[a]	Sources	S-phil.[b]	Context[b]
Checklists:			
AT&T checklist (M)	Bovea and Pérez-Belis, 2012	ED	PDD
Checklist method (M)	Park et al., 2005	ED	PDD
Checklists generally (M)	Lindahl, 1999; Lindahl, 2001	DfE	PDD; M
Eco-Design Checklist Method (M)	Bovea and Pérez-Belis, 2012	ED	PDD
Fast Five (M)	Bhamra and Lofthouse, 2007; Bovea and Pérez-Belis, 2012	DfS; ED	ID; PDD
Design for/to X methods:			
Design for disassembly (M)	Karlsson and Luttropp, 2006	SD	PDD
Design for disassembly and recycling (M)	Byggeth et al., 2007b	SD	PDD
Design for durability (M)	Mayyas et al., 2012a	DfS	EngD
Design for end-of-life (M)	Huisman et al., 2000	ED	PDD
Design for energy efficiency (M)	Mayyas et al., 2012a	DfS	EngD
Design for Manufacture and Assembly (M)	Ramani et al., 2010	DfE/ED	PDD
Design for manufacturing (M)	Mayyas et al., 2012a	DfS	EngD
Design for recyclability (M)	Huisman et al., 2000; Mayyas et al., 2012a	ED; DfS	PDD; EngD
Design for recycling (M)	Bhander et al., 2003; Wigum et al., 2011	DfE	PDD; ABD
Design for remanufacture (M)	Bhander et al., 2003; Chiu and Chu, 2012	DfE; SD	PDD
Design for re-use (M) Design for waste treatment (M)	Bhander et al., 2003	DfE	PDD
Design to minimize material usage (M)	Mayyas et al., 2012a	DfS	EngD
Design for Sustainable Behaviour (M)	Bhamra et al., 2011; Laitala et al., 2011; Zachrisson and Boks, 2011	SD	PDD
Design guidelines:			
Guidelines generally (M)	Lindahl, 1999; Lindahl, 2001	DfE	PDD; M
Environmental reporting guidelines (M)	Mayyas et al., 2012a	DfS	EngD
Guideline-based reference information system for sustainable design (T)	Chiu and Chu, 2012	SD	PDD
Kodak Guidelines (M)	Bovea and Pérez-Belis, 2012	ED	PDD
Material selection guidelines (M)	Mayyas et al., 2012a	DfS	EngD

Six Rules of Thumb (T)	Bhamra and Lofthouse, 2007	DfS	ID
Ten Golden Rules (T)	Bovea and Pérez-Belis, 2012; Karlsson and Luttropp, 2006	ED	PDD
Design principles:			
Factor 10 Engineering (10xE) principles (T)	Blizzard and Klotz, 2012	WSD	SysD
Generic DfE principles (T)	Boks and Stevels, 2007	DfE	PDD
SCALES[c] principles (T)	Chiu and Chu, 2012; Spangenberg et al., 2010	SD; DfS	PDD
Multi criteria decision analysis methods/tools:			
Analytic hierarchy process (M)	Choi et al., 2008; Gagnon et al., 2012	DfE; SD	PDD; EngD
Douglas hierarchical decision procedure (M)	Hossain et al., 2010	SD	PrcD
ELECTRE[d] (M)	Gagnon et al., 2012	SD	EngD
Hopfield network (T)	Chiu and Chu, 2012	SD	PDD
Multi criteria decision analysis (M)	Azkarate et al., 2011	SD	EngD
PROMETHEE[e] (M)	Gagnon et al., 2012	SD	EngD
Simple multi attribute rating technique (M)			
TOPSIS[f] (M)			
Other methods/tools:			
A framework for ethical decision-making in design - the "culturally negotiated ethical triangle" (T)	Oram, 2010	DfS	Multiple
Fractal triangle (T)	McDonough and Braungart, 2002	SD	PDD
Typological analysis (M)	Gamage and Hyde, 2012	SD	ABD
User-centred design methods (M)	Wigum et al., 2011	DfE	ABD

[a] "M" designates a method; "T" designates a tool.
[b] Please see Section 8 (Nomenclature) for abbreviations.
[c] SCALES = Special skills, Creating change agents, Awareness, Learning together, Ethical responsibilities, Synergy & co-creating
[d] ELECTRE = ELimination and Choice Expressing Reality
[e] PROMETHEE = Preference Ranking Organization Method for Enrichment of Evaluations
[f] TOPSIS = Technique for Order of Preference by Similarity to Ideal Situation

It may be seen in Table 5 that considerable numbers of methods and tools for decision making were identified in the context of all major S-philosophies discussed in section 4, with the exception of WSD, where the only decision making tool uncovered was a set of "Factor 10" engineering principles (Blizzard and Klotz 2012). On the one hand, this observation may be seen to reflect the notion that decision making is ubiquitous in design and represents a fundamental activity (Iain M. Boyle et al. 2012). On the other hand, it may be seen to reflect one of the key perspectives of WSD identified in section 4: that throughout the design process, designers should adopt a systems view and rely more heavily upon ingenuity and intuition, as opposed to guidelines and checklists (Blizzard and Klotz 2012; Coley and Lemon 2009). As shown in Table 5, the majority of MCDA methods and tools identified were discussed by authors in the context of SD. According to Boggia and Cortina (2010, 2302), MCDA methods are "multidimensional in nature," and thus allow multiple aspects to be considered during decision making. As discussed in section 4.2, SD, along with DfS, may be viewed as oriented towards the achievement of environmental, economic, and social sustainability (Gagnon, Leduc, and Savard 2012; Spangenberg, Fuad-Luke, and Blincoe 2010). In contrast, in section 4.1 DfE and ED were shown to be oriented towards the achievement of environmental sustainability (Ramani et al. 2010; Rosen and Kishawy 2012). Thus, it may be expected that MCDA methods are employed to a greater extent in the context of SD than DfE/ED.

A mixture of new and conventional methods may be identified in Table 5. To the best of the authors' knowledge, none of the methods and tools presented in Table 5 represent modified versions of conventional tools. Generally speaking, the checklists (Bhamra and Lofthouse 2007; Bovea and Pérez-Belis 2012; Lindahl 1999; Lindahl 2001; Park, Lee, and Wimmer 2005), guidelines (Bhamra and Lofthouse 2007; Bovea and Pérez-Belis 2012; Chiu and Chu 2012; Karlsson and Luttropp 2006; Mayyas et al. 2012a), and design principles (Blizzard and Klotz 2012; Boks and Stevels 2007; Chiu and Chu 2012; Spangenberg, Fuad-Luke, and Blincoe 2010) in Table 5 may be viewed as new methods, developed for the explicit purpose of tackling sustainability challenges. Similarly, the "culturally negotiated ethical triangle" (Oram 2010, 32) and the fractal triangle (McDonough and Braungart 2002) may be viewed as new methods. Design for/to X methods, of which a considerable number were identified, may be viewed as conventional methods (Holt and Barnes 2009; Poole et al. 1999). An exception is Design for Sustainable Behaviour (DfSB), described by Bhamra, Lilley, and Tang (2011, 427) as an "emerging activity under the banner of sustainable design." They write that DfSB "aims to reduce products' environmental and social impact by moderating how users interact with them." Thus, the application of DfSB in the context of SD may be seen to reflect the philosophy's perspective that human values and behaviour underpin the sustainability of production, consumption, and design (Bhamra and Lofthouse 2007; Bhamra, Lilley, and Tang 2011; Chapman 2011; Spangenberg, Fuad-Luke, and Blincoe 2010) as discussed in section 4.2. Additionally, Mayyas et al. (2012a, 1847) highlight the work of Jawahir et al. (2007), who established a framework for DfS based around "design-for-X (DfX) principles." MCDA methods may also be viewed as conventional methods (Baharudin et al. 2012), whose use extends beyond the boundaries of design and into the realm of sustainability assessment and management generally (Boggia and Cortina 2010; Ness et al. 2007).

5.1.3 Methods and tools for evaluating and analysing

As shown in Gagnon, Leduc, and Savard (2012, 52), evaluation and analysis represent key activities in conventional design. The high number of evaluation and analysis tools identified (ninety in total), as shown in Table 6, suggests that their importance is no less in sustainability-oriented design.

Table 6. Methods and tools for evaluating and analysing

Method/tool description[a]	Sources	S-phil.[b]	Context[b]
Benchmarking methods:			
Benchmarking generally (M)	Huisman et al., 2000; Stasinopoulos et al., 2009	ED; WSD	PDD; SysD
EcoBenchmarking method (M)	Boks and Diehl, 2005	ED	Multiple
Environmental Benchmarking Method (M)	Boks and Stevels, 2003	ED	PDD
Multiple Environmental Benchmarking Data Analysis (M)			
Environmental evaluation methods/tools:			
Assistant environmental assessment tool (T)	Wimmer and Judmaier, 2003	ED	PDD
Cumulated Energy Demand (M)	Ostad-Ahmad-Ghorabi and Collado-Ruiz 2011; Unger et al. 2008	ED	SysD; EED
Eco effectiveness (M)	Wang and Côté 2011	OP	SysD
Eco efficiency (M)	Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010; Hong et al., 2012; McAloone and Andreasen, 2004; Unger et al., 2008	ED; SD ED; ED;	EED; EngD PDD/SD; Multiple;
Ecological footprinting (M)	Gagnon et al., 2012; Unger et al., 2008	SD; ED	EngD; EED
Ecological indicators (T)	Stasinopoulos et al., 2009	WSD	SysD
Emergy analysis (M)	Gagnon et al., 2012	SD	EngD
Energy analysis (M)	Hossain et al., 2010	SD	PrcD
Environmental product declaration (M)	Mayyas et al., 2012a	DfS	EngD
Environmental valuation (M)	Gagnon et al., 2012	SD	EngD
Exergy analysis (M)	Hossain et al., 2010; Gagnon et al., 2012	SD	PrcD; EngD
Footprinting (M)	Bovea and Pérez-Belis, 2012	ED	PDD
Material Flow Analysis (M)	Unger et al., 2008	ED	EED
Material Intensity per Unit of Service (M)			
Material Recycling Efficiency calculations (M)	Huisman et al., 2000; Huisman et al., 2003	ED	PDD

Materials, Energy & Toxicity matrix (T)	Bovea and Pérez-Belis, 2012;	ED;	PDD
	Chiu and Chu, 2012	SD	
Oil Point Method (M)	Bovea and Pérez-Belis, 2012;	ED;	PDD
	Chiu and Chu, 2012;	SD;	
	Lenau and Bey, 2001	DfE	
Recyclability assessment (M)	Huisman et al., 2000	ED	PDD
Toxicity assessment (M)			
FMEA[b] and FMEA-based methods:			
Eco-FMEA (M)	Bovea and Pérez-Belis, 2012	ED	PDD
Environmental Effect Analysis (M)	Lindahl, 2001	DfE	M
Environmental FMEA (M)	Bovea and Pérez-Belis, 2012	ED	PDD
Failure Mode and Effect Analysis (M)	Byggeth et al., 2007a,b	SD	PDD
Impact assessment methods:			
Economic impact analysis (M)	Gagnon et al., 2012	SD	EngD
Environmental Impact and Factor Analysis (M)	Bovea and Pérez-Belis, 2012	ED	PDD
Environmental impact assessment (M)	Gagnon et al., 2012	SD	EngD
Integrated impact assessment (M)			
Social impact assessment (M)			
Integrated environmental and socio-economic evaluation methods/tools:			
Eco Value Analysis (M)	Bovea and Pérez-Belis, 2012	ED	PDD
Integrated tools (T)	Ramani et al., 2010	ED	PDD
Requirements matrix (T)	Bovea and Pérez-Belis, 2012	ED	PDD
Two-stage network data envelopment analysis (M)	Chen et al., 2012	SD	PDD
LCA[b] and LCA-based methods/tools:			
DfE[b] matrix (T)	Bovea and Pérez-Belis, 2012	ED	PDD
Eco-Indicator 95 (M)	Huisman et al., 2000;	ED;	PDD
	Huisman et al., 2003;		
	Lenau and Bey, 2001	DfE	
Eco-Indicator 99 (M)	Bhamra and Lofthouse, 2007;	DfS;	ID;
	Huisman et al., 2003		
		ED	PDD
Environmental Priority Strategies (M)	Huisman et al., 2003;	ED;	PDD
	Lenau and Bey, 2001	DfE	
Environmental Product Life Cycle matrix (T)	Bovea and Pérez-Belis, 2012	ED	PDD
Life cycle assessment (M)	Bhamra and Lofthouse, 2007;	DfS;	ID;
	Hossain et al., 2010;		
	McAloone, 2001;	SD;	PrcD;
	Park et al., 2005;	ED;	PDD;
	Stasinopoulos et al., 2009	ED;	PDD;
		WSD	SysD
Life cycle check (M)	McAloone, 2001	ED	PDD
Life Cycle Planning (M)	Bovea and Pérez-Belis, 2012	ED	PDD
Life Cycle Sustainability Assessment (M)	Chiu and Chu, 2012	SD	PDD
Okala method (M)			
Simplified life cycle assessment (M)	Chiu and Chu, 2012;	SD	PDD
	Lu et al., 2011		
Social life cycle assessment (M)	Gagnon et al., 2012	SD	EngD
Strategic Life Cycle Management (M)	Byggeth et al., 2007b	SD	PDD
Streamlined life cycle assessment (M)	Bovea and Pérez-Belis, 2012;	ED	PDD;
	Unger et al., 2008		EED
LCC[b] and LCC-based methods:			
Life cycle costing (M)	Mayyas et al., 2012b;	DfS;	PDD;
	Lu et al., 2011;	SD;	EngD;
	Bovea and Vidal, 2004;	ED;	PDD;
	Bovea and Pérez-Belis, 2012;	ED;	PDD;
	Azkarate et al., 2011	SD	EngD
Life Cycle Environmental Cost Analysis (M)	Bovea and Pérez-Belis, 2012	ED	PDD
Life cycle quality evaluation (M)	Lu et al., 2011	SD	PDD

QFD[b] and QFD-based methods:			
Environmental Objective Deployment (M)	Bovea and Pérez-Belis, 2012	ED	PDD
Environmental QFD (M)			
Environmentally Conscious QFD (M)	Bovea and Pérez-Belis, 2012; Vinodh and Rathod, 2010	ED; SD	PDD
Green QFD (M)	Bovea and Pérez-Belis, 2012	ED	PDD
Life cycle QFD (M)			
QFD for Environment (M)			
Quality Function Deployment (M)	Aschehoug et al., 2012; Bovea and Pérez-Belis, 2012; Ramani et al., 2010; Strasser and Wimmer, 2003	ED	PDD
Socio-economic evaluation methods:			
Contingent valuation (M)	Bovea and Vidal, 2004	ED	PDD
Cost-benefit analysis (M)	Gagnon et al., 2012	SD	EngD
Quality Engineering for Early Stage of Environmentally Conscious Design (M)	Bovea and Pérez-Belis, 2012	ED	PDD
Strategic evaluation methods/tools:			
Design abacus (M)	Bhamra and Lofthouse, 2007	DfS	ID
Ecodesign web (M)			
Environmentally Responsible Product Assessment (M)	Chiu and Chu, 2012	SD	PDD
Environmentally Responsible Product/Process Assessment Matrix (T)	Bovea and Pérez-Belis, 2012	ED	PDD
Product life thinking (M)	McAloone, 2001	ED	PDD
RAILS[c] (M)	Bovea and Pérez-Belis, 2012	ED	PDD
Strategic environmental assessment (M)	Gagnon et al., 2012	SD	EngD
Strategic wheel (T)	Unger et al., 2008	ED	EED
User-centred design methods:			
Ethnographic fieldwork (M)	Bhamra et al., 2011	SD	PDD
Participant observation (M)	Bhamra and Lofthouse, 2007	DfS	ID
Product-in-use (M)	Bhamra and Lofthouse, 2007; Bhamra et al., 2011	DfS; SD	ID; PDD
Questionnaire (M)	Bhamra et al., 2011	SD	PDD
Scenario-of-use (M)	Bhamra and Lofthouse, 2007	DfS	ID
Semi-structured interview (M)	Bhamra et al., 2011	SD	PDD
User diaries (M)			
User trials (M)	Bhamra and Lofthouse, 2007	DfS	ID
Other methods:			
ABCD analysis (M)	Byggeth et al., 2007a,b; Unger et al., 2008	SD; ED	PDD; EED
Functional analysis (M)	Stasinopoulos et al., 2009	WSD	EngD
Hierarchical design decomposition (M)	Alfaris et al., 2010	DfS	SysD
Inequality and equity analysis (M)	Gagnon et al., 2012	SD	EngD
Morphological analysis (M)	Chiu and Chu, 2012; Gagnon et al., 2012	SD	PDD; EngD
Nature studies analysis (M)	Gamage and Hyde, 2012	SD	ABD
Scenario analysis (M)	Huisman et al., 2000	ED	PDD
System analysis (M)	Stasinopoulos et al., 2009	WSD	SysD

[a] "M" designates a method; "T" designates a tool.
[b] Please see Section 8 (Nomenclature) for abbreviations.
[c] RAILS = Readiness Assessment for Implementing DfE Strategies

Quite an eclectic mix of new, modified, and conventional methods may be identified in Table 6. Thus, to highlight each and every instance is beyond the scope of this section given the necessary space limitations. However, a number of observations may be made on the basis of the methods and tools presented in Table 6. Firstly, it may be seen that authors have modified a number of conventional methods focusing on traditional design requirements to additionally account for environmental aspects. For instance, environmentally-oriented versions of FMEA (Bovea and Pérez-Belis 2012; Lindahl 2001), LCC (M.D. Bovea and Pérez-Belis 2012), and QFD (Bovea and Pérez-Belis 2012; Vinodh and Rathod 2010) were all identified. As shown in Table 6, these methods are discussed more frequently in literature on ED than DfS, SD or WSD. This may be seen to reflect a key perspective of ED (and also DfE): that environmental aspects should be considered in a balanced manner alongside traditional design requirements for aspects such as cost, quality, and technical performance (Park, Lee, and Wimmer 2005; Ramani et al. 2010).

As outlined in the introduction to section 5.1, both environmental evaluation methods and LCA/LCA-based methods focus solely upon environmental aspects. In contrast, certain impact assessment methods (e.g. economic impact assessment, integrated impact assessment, and social impact assessment (Gagnon, Leduc, and Savard 2012)), integrated environmental and socio-economic evaluation methods (e.g. Eco Value Analysis (M.D. Bovea and Pérez-Belis 2012) and two-stage network data envelopment analysis (Chen et al. 2012)), and LCC (Azkarate et al. 2011; Bovea and Pérez-Belis 2012; Bovea and Vidal 2004; Lu et al. 2011; Mayyas et al. 2012b) along with certain LCC-based methods (e.g. Life Cycle Environmental Cost Analysis (M.D. Bovea and Pérez-Belis 2012)) focus upon the broader spectrum of environmental, economic, and social aspects. Additionally, socio-economic evaluation methods (e.g. contingent valuation (M.D Bovea and Vidal 2004), cost-benefit analysis (Gagnon, Leduc, and Savard 2012), and Quality Engineering for Early Stage of Environmentally Conscious Design (M.D. Bovea and Pérez-Belis 2012)) focus on social and economic aspects. It may be seen in Table 6 that a considerably higher number of the former type of method were identified than the latter two. As discussed in sections 4.2 and 4.3, the following may be viewed as a key perspective of DfS, SD, and WSD: the environmental, economic, and social impacts of designed artefacts/systems should be addressed throughout their full life cycle (Bhamra and Lofthouse 2007; Bhamra, Lilley, and Tang 2011; Gagnon, Leduc, and Savard 2012; Mayyas et al. 2012a; Spangenberg, Fuad-Luke, and Blincoe 2010; Stasinopoulos et al. 2009). Thus, the aforementioned observation suggests something of a lack of support with regards to evaluating the full spectrum of impacts that require to be addressed in DfS, SD, and WSD.

As shown in Table 6, user-centred design methods were found to be discussed by authors in the literature on DfS and SD exclusively. According to Bhamra and Lofthouse (2007, 87), user-centred design methods "are useful for gaining information about 'actual' user practices, habits, behaviours, or needs to inform the design of a product, service, or system." The insight that they provide "helps designers better understand how people use and misuse products, which can in turn reduce the impact of product use." In addition to providing insight into behaviour, certain user-centred design methods, such as participant observation, can provide designers with information on "thoughts [and] beliefs." As such, the use of this kind of method in the context of DfS and SD may be seen to reflect a key perspective of these philosophies that was outlined in section 4.2: that human values and behaviour are viewed as underpinning the sustainability of design, production, and consumption (Bhamra and Lofthouse 2007; Bhamra, Lilley, and Tang 2011; Chapman 2011; Spangenberg, Fuad-Luke, and Blincoe 2010). Further, the majority of the user-centred design methods presented in Table 6 involve the actual participation of users (Bhamra and Lofthouse 2007; Bhamra, Lilley, and Tang 2011). For instance, in user trials, "subjects are asked to fulfil specified tasks in an experimental setting, using a product or product simulation" (Bhamra and Lofthouse 2007, 89). Bhamra, Lilley, and Tang (2011, 433) employ participant observation coupled with semi-structured interviews and questionnaires to investigate user behaviour, writing that the latter methods "provided a chance for participants to explain their behaviour in the observation sections." Therefore, the use of user-centred design methods in the context of DfS and SD may be seen to reflect another of their key perspectives outlined in section 4.2: to ensure that multiple values and perspectives are considered during design, a greater number of stakeholders (e.g. the general public (Daniel Christian Wahl and Baxter 2008), and product users (T. Bhamra, Lilley, and Tang 2011)) should participate in design than has conventionally been the case (Gagnon, Leduc, and Savard 2012; Keitsch 2012; Spangenberg, Fuad-Luke, and Blinco 2010).

A relatively high number of authors were observed to discuss LCA and LCA-based methods (twenty three, Table 6). This may be seen to reflect the well-established nature of this method (Heijungs, Huppes, and Guinee 2010; Ness et al. 2007; Ulgiati et al. 011). For instance, Bhander, Hauschild, and McAloone (2003, 256) suggest that "LCA is recognized as one of the most frequently used techniques for systematically evaluating environmental performance of a product throughout its life cycle." They highlight that an "international standard posing formalized requirements to the LCA methodology has been developed by the International Standard Organization (ISO) and practiced worldwide since 1997." Further, like MCDA methods discussed in section 5.1.2, the application of LCA extends beyond the boundaries of design and into the realm of sustainability assessment and management generally (Ness et al. 2007). LCA was also observed to be discussed in the literature on all major S-philosophies, i.e. DfE (e.g. McAloone 2001), ED (e.g. Park, Lee, and Wimmre 2005), DfS (e.g. Bhamra and Lofthouse 2007), SD (e.g. Hossain, Khan, and Hawboldt 2010), and WSD (e.g. Stasinopoulos et al. 2009). In section 4, it was shown that all of these philosophies adopt a life cycle perspective on the impacts of designed artefacts (Bhamra and Lofthouse 2007; Bhamra, Lilley, and Tang 2011; Bhander, Hauschild, and McAloone 2003; Bovea and Pérez-Belis 2012; Choi et al. 2008; Gagnon, Leduc, and Savard 2012; Lindahl 2001; Mayyas et al. 2012a; McAloone 2001; Spangenberg, Fuad-Luke, and Blincoe 2010; Stasinopoulos et al. 2009). Thus, it may be expected that life cycle assessment is discussed in the context of each.

Finally, as indicated in Table 6, references to evaluation and analysis methods were found to be particularly sparse in the literature on WSD. However, as shown in the introduction to section 4, just five authors were observed to discuss WSD (Blizzard and Klotz 2012; Charnley, Lemon, and Evans 2011; Coley and Lemon 2009; Gagnon, Leduc, and Savard 2012; Stasinopoulos et al. 2009). This may be contrasted with the most frequently discussed S-philosophy (SD), which was found to be discussed by twenty four authors in the sample. Thus, the seeming lack of discussion on evaluation and analysis tools in the literature on WSD may reflect the scant literature available on the philosophy, as opposed to any methodological difference between WSD and the other major philosophies discussed in section 4 (i.e. DfE/ED, and DfS/SD).

5.1.4 Methods and tools for modelling, simulating, and optimising

As indicated in the introduction to section 5.1, modelling and simulating is considered to represent a category of methods and tools distinct from optimising in the context of this paper. However, as may be seen in Table 7, few methods and tools were identified in each category: twelve for modelling and simulating, and twelve for optimising. Thus, they are considered together here.

Table 7. Methods and tools for modelling, simulating, and optimising

Method/tool description[a]	Sources	S-phil.[b]	Context[b]
Formal optimisation methods:			
Interactive multi objective optimisation (M)	Taras and Woinaroschy, 2012	SD	PrcD
Interval mathematical programming (M)	Han et al., 2012	SD	SysD
Lexicographic method (M)	Gagnon et al., 2012	SD	EngD
Maximin method (M)			
Multi objective optimisation (M)	Bazmi and Zahedi, 2011; Han et al., 2012; Papandreou and Shang, 2008; Pérez-Fortes et al., 2012	SD	SysD
Optimisation under uncertainty (M)	Bazmi and Zahedi, 2011	SD	SysD
Stochastic mathematical programming (M)	Han et al., 2012	SD	SysD
Structural optimisation (M)	Yeo and Gabbai, 2011	SD	EngD
Weighted sum (M)	Gagnon et al., 2012	SD	EngD
Modelling methods/tools:			
CAD[c] software (T)	Byggeth et al., 2007a,b	SD	PDD
Causal loop diagrams (T)	Byggeth et al., 2007b	SD	PDD
Computer models (T)	Stasinopoulos et al., 2009	WSD	SysD
Mathematical models (T)			
Multi domain formulation (M)	Alfaris et al., 2010	DfS	SysD

Physical models (T)	Stasinopoulos et al., 2009	WSD	SysD
Screening Life Cycle Modelling (M)	Chiu and Chu, 2012	SD	PDD
Systems Modeling within Sustainability Constraints (M)	Byggeth et al., 2007b	SD	PDD
Simulation:			
Life cycle simulation (M)	Chiu and Chu, 2012; Harun and Cheng, 2011	SD	PDD
Multi disciplinary simulation (M)	Byggeth et al., 2007b	SD	PDD
Process simulation (M)	Hossain et al., 2010	SD	PrcD
Virtual reality (T)	Byggeth et al., 2007a,b	SD	PDD
Other methods:			
Life cycle optimisation (M)	Mayyas et al., 2012b	DfS	EngD
PILOT[d] (T)	Bovea and Pérez-Belis, 2012; Strasser and Wimmer, 2003; Wimmer and Judmaier, 2003	ED	PDD
System optimisation (M)	Stasinopoulos et al., 2009	WSD	SysD

[a] "M" designates a method; "T" designates a tool.
[b] Please see Section 8 (Nomenclature) for abbreviations.
[c] CAD = computer aided design
[d] PILOT = Product Investigation, Learning and Optimization Tool

An initial observation that may be made with respect to Table 7 is that with the exception of PILOT (Strasser and Wimmer 2003; Wimmer and Judmaier 2003), all methods and tools for modelling, simulating, and optimising were found to be discussed by authors in the literature on DfS, SD, and WSD. These types of method and tool may all be positioned as effective means for coping with complexity during design. For instance, Byggeth et al. (2007b) discuss the method, Systems Modelling within Sustainability Constraints. The originators of the method position it as a means to cope with the "complexities of […] ecological and social systems and their interrelationships" (Ny et al. 2005). In a similar vein, Stasinopoulos et al. (2009, 57) remark that, "Mathematical, computer and physical models are valuable for addressing relatively complex engineering systems." With respect to simulation, Harun and Cheng (2011) present life cycle simulation as capable of representing complexity in the life cycle of a production process. Considering optimisation, Taras and Woinaroschy (2012, 10) position multi objective optimisation as a method for dealing with the "complex nature of the real world applications." Likewise, Bazmi and Zahedi (2011, 3495) remark that optimisation methods can provide support in finding "optimal and sustainable solutions [to] the complex problems associated with power generation and supply scenarios." A key perspective that was found to be shared by DfS/SD and WSD is the following, as discussed in sections 4.2 and 4.3: the complexity and multiple scales of the Earth system, and in turn design problems, are acknowledged (Charnley, Lemon, and Evans 2011; Coley and Lemon 2009; Gagnon, Leduc, and Savard 2012; Gamage and Hyde 2012; Spangenberg, Fuad-Luke, and Blincoe 2010; Stasinopoulos et al. 2009; Wahl and Baxter 2008). Thus, it may be expected to a certain degree that modelling, simulation, and optimisation methods are discussed more frequently in the literature on DfS, SD, and WSD than that on DfE and ED.

In addition to supporting designers in dealing with complexity, authors also describe optimisation as an effective method for overcoming conflict among competing aspects during design. For example, Taras and Woinaroschy (2012, 10) position optimisation as an effective method in the context of problems involving "consideration of several objectives" that are "conflicting." Similarly, Papandreou and Shang (2008, 1591) discuss the application of multi objective optimisation to problems involving "conflicting design objectives." Therefore, the use of optimisation methods in the context of SD, as shown in Table 7, may be seen to reflect the SD perspective, discussed in section 4.2, that environmental, economic, and social considerations should be considered in a balanced manner (McDonough and Braungart 2002). That is, recognising the trade-offs that arise between competing aspects. As shown in section 4.3, WSD adopts the perspective that the environmental, economic, and social performance of whole systems should be optimised during design, as opposed to isolated entities (Stasinopoulos et al. 2009). Thus, it is perhaps somewhat surprising that no formal optimisation methods were identified in the literature on WSD (Table 7).

Finally, a number of methods for modelling, simulating, and optimising that were found to be discussed in the context of DfS and SD may be seen to support multi-disciplinary working. For instance, in the context of SD, Byggeth et al. (2007b, 7) discuss the use of multi-disciplinary simulation in solving a "multi-disciplinary design problem." Also in the context of SD, Taras and Woinaroschy (2012, 11) describe multi objective optimisation as a "multi-disciplinary field." In the context of DfS, Alfaris et al. (2010, 1) outline the application of multi domain formulation as part of an "integrated, multidomain design approach." As discussed in section 4.2, a key perspective adopted by DfS and SD is that cross-disciplinary collaboration should occur during design (Gagnon, Leduc, and Savard 2012; Keitsch 2012; Spangenberg, Fuad-Luke, and Blincoe 2010; Wahl and Baxter 2008). The use of the aforementioned methods may be seen to reflect this perspective, at least to some extent.

A mixture of new, modified and conventional methods may be identified in Table 7. Formal optimisation methods may be viewed as relatively well established methods in certain design domains, particularly engineering design (Diwekar 2008; Eschenauer, Koski, and Osyczka 1990; Marler and Arora 2004). Similarly, certain modelling and simulation methods and tools may be seen to be applied in a wider design context, such as CAD software (Byggeth et al. 2007a; Whitfield et al. 2012), causal loop diagrams (Byggeth et al., 2007b; Gong et al., 2004), and process simulation (Hossain, Khan, and Hawboldt 2010; Kimita, Tateyama, and Shimomura 2012). Systems Modeling within Sustainability Constraints, discussed by Byggeth et al. (2007b) in the context of SD, may be viewed as a modified version of system dynamics modelling (Ny et al. 2005). With respect to new methods and tools, PILOT (the Product Investigation, Learning, and Optimization Tool) is described as a "basic tool" that has been developed "to help engineers to make environmental decisions in product development" (Strasser and Wimmer 2003, 757).

5.2 Sustainability and the design process

In section 4, an S-philosophy was defined as an overarching design concept, which expresses values and perspectives on design with respect to sustainability. In turn, the aims and key perspectives of a number of S-philosophies were outlined. In section 5.1, it was shown that a plethora of methods and tools are positioned by authors as effective means for tackling sustainability issues. In essence, the S-philosophies, methods, and tools discussed in preceding sections may be viewed as the means by which sustainability considerations are introduced into designing (Bhamra and Lofthouse 2007; Byggeth et al. 2007b). Chapman (2011, 173) highlights that, "Many practitioners are beginning to believe that there should be no such thing as sustainable design, claiming that it is wrong to departmentalize environmentally aware design practice as it should simply be integrated with conventional design practice without ceremony." In other words, the aims and perspectives of S-philosophies, along with methods and tools for tackling sustainability issues, should form integral elements of the design process as opposed to being applied in isolation (Gagnon, Leduc, and Savard 2012; Waage 2007). Along these lines, the following paragraphs examine the degree to which sustainability issues and sustainability-focused methods and tools have been integrated into the design process.

As shown in Table 8, efforts to integrate sustainability into the design process may be broadly split into two categories: (i) authors who outline design processes, and then provide some indication of the major sustainability issues for each stage and the methods/tools that should be employed (included in Table 8 under the heading, "Design processes"); and (ii) authors who outline methodologies, which are considered here to constitute integrated sets of methods and/or tools to be applied during the design process (Evbuomwan, Sivaloganathan, and Jebb 1996; Hernandez 2010; OED 2013) (included in Table 8 under the heading, "Methodologies"). An initial observation that may be made with respect to Table 8 is that in comparison to the number of individual methods and tools (as shown in Tables 4 to 7 in section 5.1), relatively few efforts to integrate sustainability into the design process as a whole were uncovered.

5.2.1 Design processes

Let us first consider those research efforts falling into category (i), included under the heading, "Design processes" in Table 8. Certain authors in this category may be seen to examine existing design processes, and discuss the major sustainability issues that should be considered at each stage (Byggeth et al. 2007a; Gagnon, Leduc, and Savard 2012; Stasinopoulos et al. 2009; Waage 2007). For example, in the context of SD, Waage (2007, 639) considers the product development process in relation to sustainability. They outline a "sustainability process" that when followed, "infuses the standard design process with clear pathways for considering ecological, social, and financial issues throughout the design process." Although sustainability considerations for each stage are explored, the author does not suggest any specific methods and tools to be employed. In the context of WSD, Stasinopoulos et al. (2009, 49) consider the traditional systems engineering process, and explore how this process may be developed so that it "incorporates an emphasis on sustainability." In the resulting "Whole System Approach to Sustainable Design," key sustainability issues are highlighted for consideration during each stage. Additionally, the authors suggest the use of several methods at different stages, as shown in Table 8. In the context of SD, Gagnon, Leduc, and Savard (2012, 49) review both conventional and sustainable engineering design processes, before outlining a "novel integrated sustainable engineering design process." Like Stasinopoulos et al. (2009), they highlight key sustainability issues to be considered at each stage. They do not suggest the use of any specific methods and tools, although a range of methods and tools are explored in isolation from the developed process. Finally, also in the context of SD, Byggeth et al. (2007a, 2) outline a "model of a product development process." To integrate sustainability into the process, they develop a series of "Sustainability Product Assessment modules," containing questions "concerning sustainability aspects" that should be asked by designers at each stage of the process

Table 8. Sustainability and the design process

Description	**Stages/steps involved**	**Sustainability issues for each stage discussed?**	**Sources**	**S-phil.[a]**	**Context[a]**
Design processes:					
A 5-step process derived by generalising existing ecodesign methods	1. Product planning 2. Environmental assessment of a product 3. Generation of ecodesign ideas 4. Evaluation of ecodesign ideas 5. Application	Only for stage 2	Park et al., 2005	ED	PDD
A "Sustainability Process for Designers"	1. Establish sustainability context 2. Define sustainability issues 3. Assess 4. Act and receive feedback	Yes	Waage, 2007	SD	PDD
A "Whole System Approach to Sustainable Design"	1. Need definition 2. Conceptual design 3. Preliminary design 4. Detail design	Yes	Stasinopoulos et al., 2009	WSD	SysD
An "Integrated Sustainable Engineering Design Process"	1. Planning and problem definition 2. Conceptual analysis 3. Preliminary design 4. Detailed design	Yes	Gagnon et al., 2012	SD	EngD
Biomimicry theoretical model & theoretical	1. Categorisation 2. Functional integration 3. Environmental	Yes	Gamage and Hyde, 2012	SD	ABD

framework	adaptation 4. Innovation of form				
The "Method for Sustainable Product Development"	1. Investigation of need 2. Principle product 3. Primary product 4. Production process 5. Launching	Yes	Byggeth et al., 2007a	SD	PDD
Methodologies:					
An "integration model" to add value for the customer in ecodesign	1. Initial analysis of the product 2. Generation of alternatives 3. Analysis of alternatives 4. Selection of ecological alternatives	Yes	Bovea and Vidal, 2004	ED	PDD
A methodology for the design of complex systems	1. Multilevel abstraction 2. Identification of form and behaviour parameters 3. Identification of dependency between parameters 4. Design cycle identification 5. Decision structuring and scoping of design cycles	No	Alfaris et al., 2010	DfS	SysD
SusDesign, a "structured process design approach"	1. Process conceptualisation 2. Flowsheet synthesis 3. Flowsheet optimization	Yes	Hossain et al., 2010	SD	PrcD

[a] Please see Section 8 (Nomenclature) for abbreviations.

Other authors included in category (i) may be seen to define new sustainability-oriented processes to be followed by designers during design. For instance, in the context of ED, Park, Lee, and Wimmer (2005, 255) derive a five-step process by generalising "existing ecodesign methods." They highlight that a "generic model of product design and development" consisting of six stages is relatively well established. However, they argue that "from an environmental perspective, it is more efficient to divide the process into different stages, considering that the purpose of ecodesign is to improve the environmental performance of a product by integrating environmental concerns into product design and development." As shown in Table 8, the authors explore key sustainability considerations for a single stage of their proposed process, and suggest several methods to be employed during this stage. As part of a biomimicry framework, also developed in the context of SD, Gamage and Hyde (2012, 224) outline a design process that is eventually intended to enhance "ecological sustainability by increasing the applicability of Biomimicry theory into architectural practice." The authors do not associate any specific methods and tools with this process, but do explore sustainability considerations for each stage to some extent.

In spite of obvious differences among the design processes presented in Table 8, a particular commonality may be seen to emerge. Namely, that they all (with the exception of the process delineated by Gamage and Hyde (2012)) include at least one stage involving the evaluation of environmental, economic, and/or social performance. For example:

- the five-step process presented by Park, Lee, and Wimmer (2005, 255) in the context of ED includes a stage focusing on "environmental assessment of a product";
- the Integrated Sustainable Engineering Design Process, presented by Gagnon, Leduc, and Savard (2012, 63) in the context of SD, includes the following task during the preliminary

design stage: "Assess the performance of alternative concepts according to the sustainability criteria or indicators";

- the Method for Sustainable Product Development, presented by Byggeth et al. (2007a, 4) in the context of SD, prescribes the use of "Sustainability Product Assessment modules" during each stage;
- the Sustainability Process for Designers, presented by Waage (2007, 643) in the context of SD, includes a stage called "Assess," where designers must ask themselves the question, "What is the most sustainable solution?"; and
- the Whole System Approach to Sustainable Design, presented by Stasinopoulos et al. (2009, 70) in the context of WSD, prescribes the use of "ecological indicators" to assess performance.

5.2.2 Methodologies

Research efforts falling into category (ii) outlined above are included under the heading, "Methodologies" in Table 8. A methodology is considered here to constitute an integrated set of methods and/or tools to be applied during the design process (Evbuomwan, Sivaloganathan, and Jebb 1996; Hernandez 2010; OED 2013). It may be seen in Table 8 that three examples of methodologies were identified, and were found to be applied at a particular stage in the design process or to tackle a particular kind of design problem (Alfaris et al. 2010; Bovea and Vidal 2004; Hossain, Kahn, and Hawboldt 2010). For example, Bovea and Vidal (2004, 137) present an "integration model" that is "mainly applicable to the last stages of the product design process, embodiment design and detail design." The model combines three methods – life cycle assessment, life cycle costing, and contingent valuation. Alfaris et al. (2010, 2) propose a methodology for "systematically addressing a complex, multidomain design problem," consisting of multi domain formulation, and hierarchical design decomposition. The write that the methodology may be viewed as "a precursor before a formal design optimization formulation can be set up" (Alfaris et al. 2010, 12). Finally, Hossain, Kahn, and Hawboldt (2010, 1897) develop a "systematic process design and synthesis" methodology known as SusDesign, consisting of three steps involving the application of a range of different methods and tools. They remark that the methodology "is designed to provide a preliminary process design solution by incorporating environmental and economic issues from the initial stage of process design."

As is the case with the design processes discussed above, something of a commonality may be seen to emerge among the methodologies presented in Table 8 in that two of three identified include at least one step involving the evaluation of environmental, economic, and/or social performance. For example:

- SusDesign, presented by Hossain, Kahn, and Hawboldt (2010, 1898) in the context of SD, involves the use of several environmental evaluation methods during the "process conceptualization" and "flowsheet optimization" steps; and
- the "integration model," presented by Bovea and Vidal (2004, 138) in the context of ED, includes two stages focusing on the evaluation and analysis of environmental and economic performance: the first focuses on "initial analysis of the product," and the second on "analysis of alternatives."

6. Discussion

In section 3, it was shown that design may be viewed as an activity (Hubka 1982; Jones 1991; Papanek 1972), carried out by humans or some intelligent entity (Hubka 1982; Mayall 1979; Papanek 1972), that involves the transformation of physical and/or cognitive entities (Andreasen, Wognum, and McAloon 2002; Jones 1992; O'Donnell and Duffy 2005) according to design goals (Archer 1965, in Jones 1992; Boyle et al. 2009). As is the case with all human activities, design is physically reliant upon the Earth system's natural resource base and waste processing capacity for its continued operation (Gagnon, Leduc, and Savard 2012; UNEP 2012), i.e. its environmental sustainability (Kajikawa 2008). Additionally, human activities such as design should be economically and socially sustainable (Kajikawa 2008; Spangenberg, Fuad-Luke, and Blincoe 2010), i.e. economically viable, and socially acceptable and desirable (Brown et al. 1987; Goerner, Lietaer, and Ulanowicz 2009; Vucetich and Nelson 2010). Thus, efforts to integrate sustainability considerations into design through the development of methods, tools, and philosophies typically centre on ameliorating the environmental, economic, and social impacts of design on the Earth system (Bhamra, Lilley, and Tang 2011; Spangenberg, Fuad-Luke, and Blincoe 2010). However, as discussed in section 1, there is a lack of clarity regarding the means and mindsets that may be adopted to effectively tackle sustainability issues in design. According to Coley and Lemon (2009, 544), there is "confusion surrounding the multiple approaches to the design of more sustainable solutions due to the numerous definitions and interpretations currently being used within the relevant literature." Similarly, Waage (2007, 638) remarks that there is "confusion about pathways forward for companies" owing to the proliferation of methods and tools, and that it is "unclear how existing approaches are complementary or distinct."

To address the above shortcomings in current research, the investigation documented in this paper aimed to clarify the range of philosophies, methods, and tools developed to guide and support designing with sustainability in mind. Accordingly, in sections 4 and 5, a sample of the literature on sustainability-oriented design was examined to provide a view on current knowledge with respect to: (i) sustainability-oriented design philosophies (S-philosophies), i.e. how we think about design in the context of sustainability; and (ii) methods and tools positioned as effective means for tackling sustainability issues in design, i.e. how we carry out design when considering sustainability. In section 6.1, the Design Sustainability Matrix (DSM) is presented. Constructed on the basis of the major findings of the investigation, the DSM provides a visual summary of the state of the art in sustainability-oriented design. In section 6.2, a number of observations are made regarding the state of the art and challenges in the field.

6.1 The Design Sustainability Matrix (DSM)

On the basis of the major findings of the investigation, documented in sections 4 and 5, a taxonomy of design philosophies, methods, and tools for tackling sustainability issues in design may be constructed. As shown in section 4, sixteen S-philosophies were identified in total: design for environment (e.g. Boks and Stevels 2007; Lindahl 1999); design for sustainability (e.g. Bhamra and Lofthouse 2007; Mayyas et al. 2012a); discursive design (Edeholt 2012); ecodesign (e.g. Bovea and Pérez-Belis 2012; Park, Lee, and Wimmer 2005); ecological engineering (Gagnon, Leduc, and Savard 2012); emotionally durable design (Chapman 2011); empathic design (Niinimäki and Koskinen 2011); environmentally conscious design (Poole et al. 1999); evolutionary systems design (Laszlo, Laszlo, and Dunsky 2009); industrial ecology (Wang and Côté 2011); life cycle design (Ernzer and Bey 2003); life cycle engineering (T. C. McAloone and Andreasen 2004); restorative design (Gu and Frazer 2009); scale-linking design (D. C. Wahl 2012); sustainable design (e.g. Bhamra, Lilley, and Tang 2011; Keitsch 2012); and whole system design (e.g. Blizzard and Klotz 2012; Stasinopoulos et al. 2009). However, five S-philosophies were identified as the major S-philosophies, on the basis that they were found to be discussed considerably more frequently: sustainable design (SD, discussed in twenty four sources, i.e. 29% of the sample); ecodesign (ED, discussed in nineteen sources, i.e. 23% of the sample); design for environment (DfE, discussed in sixteen sources, i.e. 19% of the sample); design for sustainability (DfS, discussed in ten sources, i.e. 12% of the sample); and whole system design (WSD, discussed in seven sources, i.e. 6% of the sample). The literature on each of these five major S-philosophies was examined in greater depth in sections 4.1.1 to 4.1.3, revealing the key perspectives of each philosophy and leading to the following observations:

- DfE and ED tend to be equated by authors (Boks and Stevels 2007; Collado-Ruiz and Ostad-Ahmad-Ghorabi 2010; Ostad-Ahmad-Ghorabi and Collado-Ruiz 2011; Poole et al. 1999; Unger, Scheider, and Salhofer 2008), and were found to share the same aim and perspectives as shown in section 4.1.1. This aim may be stated as: to reduce the negative environmental impacts of a design throughout its life cycle, whilst simultaneously fulfilling traditional design requirements with respect to aspects such as performance, function, and quality (Bhander, Hauschild, and McAloone 2003; Boks and Stevels 2007; Bovea and Pérez-Belis 2012; Choi et al. 2008; Park, Lee, and Wimmer 2005; Poole et al. 1999; Ramani et al.

2010; Spangenberg, Fuad-Luke, and Blincoe 2010). As such, DfE and ED may be seen to seek the achievement of environmental sustainability in design (Ramani et al. 2010; Rosen and Kishawy 2012), i.e. to preserve the Earth system's resource base and waste processing capacity by ameliorating the environmental impacts of design on the system (Bhamra and Lofthouse 2007; Spangenberg, Fuad-Luke, and Blincoe 2010). To achieve this aim, DfE and ED prescribe that environmental considerations should be integrated into design (Ramani et al. 2010; Rosen and Kishawy 2012).

- Whilst not explicitly equated by authors sample under study, DfS and SD were found to share essentially the same aim and perspectives as shown in section 4.1.2. As such, they may be viewed as representing the same design philosophy, and aim to improve (i.e. either minimise negative (Bhamra and Lofthouse 2007; Chapman 2011), or create positive (McDonough and Braungart 2002; Spangenberg, Fuad-Luke, and Blincoe 2010)) the environmental, economic, and social impacts of a design throughout its life cycle. As such, DfS and SD may be seen to seek the achievement of environmental, economic, and social sustainability in design (Gagnon, Leduc, and Savard 2012; Spangenberg, Fuad-Luke, and Blincoe 2010), i.e. to (i) preserve the Earth system's resource base and waste processing capacity by ameliorating the environmental impacts of design on the system, and (ii) ensure that design is economically viable, and socially acceptable and desirable, by ameliorating the economic and social impacts of design on the system (Bhamra and Lofthouse 2007; Bhamra, Lilley, and Tang 2011; Chiu and Chu 2012; Hossain, Kahn, and Hawboldt 2010; Spangenberg, Fuad-Luke, and Blincoe 2010). To achieve this aim, DfS and SD prescribe that environmental, economic, and social considerations should be integrated into design (Bhamra and Lofthouse 2007; Gagnon, Leduc, and Savard 2012; Spangenberg, Fuad-Luke, and Blincoe 2010; Waage 2007).
- Finally, it was found that whilst WSD may not necessarily be conducive to the achievement of sustainability in every case (Blizzard and Klotz 2012), it is positioned by authors as effective in tackling sustainability challenges (Blizzard and Klotz 2012; Charnley, Lemon, and Evans 2011; Coley and Lemon 2009; Gagnon, Leduc, and Savard 2012; Stasinopoulos et al. 2009) as shown in section 4.1.3. In this context, the aim of WSD may be viewed as similar to that of DfS/SD (Stasinopoulos et al. 2009). However, WSD is founded in a systems view of the world (Coley and Lemon 2009). Thus, the aim of WSD may be stated as: to improve (i.e. minimise negative or create positive) the environmental, economic, and social impacts of a system throughout its life cycle (Blizzard and Klotz 2012; Charnley, Lemon, and Evans 2011; Stasinopoulos et al. 2009). As such, WSD may result in the achievement of environmental, economic, and social sustainability at the level of whole systems (Blizzard and Klotz 2012; Stasinopoulos et al. 2009). To achieve this aim, WSD prescribes that designers should adopt a systems view and rely more heavily upon ingenuity and intuition, as opposed to checklists and guidelines (Blizzard and Klotz 2012; Coley and Lemon 2009).

As discussed in section 5, one hundred and seventy three distinct methods and tools were identified. In turn, each of these methods and tools was classified as focusing on a particular kind of design activity:

- creativity = eighteen methods and tools (discussed in section 5.1.1), i.e. 10% of all methods and tools identified as shown in Figure 2 below;
- decision making = forty one methods and tools (discussed in section 5.1.2), i.e. 24% of all methods and tools identified as shown in Figure 2;
- evaluating and analysing = ninety methods and tools (discussed in section 5.1.3), i.e. 52% of all methods and tools identified as shown in Figure 2;
- modelling and simulating = twelve methods and tools (discussed in section 5.1.4), i.e. 7% of all methods and tools identified as shown in section 5.1.4 and in Figure 2; and
- optimising = twelve methods and tools (discussed in section 5.1.4), i.e. 7% of all methods and tools identified as shown in Figure 2 below.

Figure 2. Percentages of identified methods and tools focusing on different types of design activity (see Figure 4-6, Section 4.2.3, Chapter 4 of thesis)

Methods and tools were found to be discussed by authors in the context of different S-philosophies, as shown in Tables 4 to 7 in section 5. In a number of cases, methods and tools discussed in the literature on a particular S-philosophy were seen to clearly reflect certain perspectives expounded by the philosophy (discussed in section 5.1). On this basis, we may create a matrix of the methods and tools identified. In the resulting Design Sustainability Matrix (DSM), shown in Figure 3, methods and tools are positioned: (i) horizontally, according the S-philosophies that they were seen to be associated with; and (ii) vertically, according to the kinds of design activities that they are intended to support designers in.

The DSM is intended to serve three major purposes:

(i) it visually positions research on sustainability-oriented design;
(ii) it identifies shortcomings in current knowledge on sustainability-oriented design; and
(iii) it can guide designers with respect to the methods and tools that may be most appropriate given their sustainability aims and perspectives.

Figure 3. The Design Sustainability Matrix (see Figure 4-8, Section 4.2.3, Chapter 4 of thesis)

Given the necessary limitations on the extent of the literature sample studied during the investigation (eighty three sources), it is difficult to draw absolute conclusions regarding knowledge on sustainability-oriented design. However, on the basis of the investigation findings and the DSM presented above, a number of observations may be made regarding the state of the art and challenges in the field, as discussed in section 6.2.

6.2 State of the art and challenges in sustainability-oriented design

As shown in the DSM in Figure 3, DfE and ED may be viewed as conducive to the achievement of environmental sustainability in design (Ramani et al. 2010; Rosen and Kishawy 2012), via the integration of environmental considerations into design (Ramani et al. 2010; Rosen and Kishawy 2012). However, as touched upon in section 3, it is generally accepted in wider sustainability literature that from an anthropocentric perspective, it is not sufficient to achieve sustainability in the environmental dimension alone. Human activities should also be economically and socially sustainable (Kajikawa 2008; Spangenberg, Fuad-Luke, and Blincoe 2010), i.e. economically viable, and socially acceptable and desirable (Brown et al. 1987; Goerner, Lietaer, and Ulanowicz 2009; Vucetich and Nelson 2010). As shown in the DSM (Figure 3), a considerable number of methods and tools are discussed in the context of DfE and ED. Further, just under forty per cent of the papers on DfE and ED (Table 1) were published between 2007 and 2012. This suggests that DfE and ED continue to be developed and applied in practice, in spite of their seeming misalignment with wider sustainability goals for human activity.

Comments from design authors suggest that the continued application of DfE and ED may also be misaligned with current knowledge on sustainability in design. For instance, Bhamra and Lofthouse (2007, 39) position ED as a step in an evolution of "environmental philosophies" culminating in DfS, suggesting that DfS supersedes ED. Similarly, in an article on DfS, Spangenberg, Fuad-Luke, and Blincoe (2010, 1486) argue that "it is necessary to expand the scope of design education and practice beyond […] environmental concerns (Ecodesign) to include social and institutional issues." Stasinopoulos et al. (2009, 2) remark that a "DfE approach to reducing environmental impacts is one of the best approaches business and government can take to find win-win opportunities to both reduce costs and help the environment." However, the authors go on to argue that "if a Whole System Design approach is taken, then the cost savings and environmental improvements can be in the order of Factor 4-10 (75-90 per cent)," suggesting that WSD supersedes DfE. In the context of SD, Gagnon, Leduc, and Savard (2012, 61) argue that "incremental innovation is unlikely to provide the level of performance expected from sustainable solutions." However, upon examination, DfE and ED were found to display something of a tendency towards redesign activities, i.e. incremental innovation. In contrast, DfS, SD, and WSD were all found to focus on radical innovation in addition to redesign. Overall, therefore, it is somewhat unclear why DfE and ED have not been overtaken by DfS, SD, and WSD to a greater extent in theory and practice. Certain authors posit that it is simply easier to implement DfE/ED than the broader concepts of DfS, SD, and WSD (Chapman 2011; Spangenberg, Fuad-Luke, and Blincoe 2010). For instance, Chen et al. (2012, 352) suggest that "while reducing the overall life-cycle environmental impacts should be the ultimate goal of sustainable design, the DfE approach with incremental improvements on one or a few environmental performances is usually more executable for most businesses today." As such, a potential challenge for research is the provision of more effective support for the implementation of DfS, SD, and WSD in practice.

Again considering wider sustainability literature, it may be seen that there is a need to achieve sustainability at the level of whole systems, as opposed to isolated entities (Bodini 2012; Voinov 2007). To meet this challenge, a high degree of complexity may require to be overcome with respect to system relationships and competing dimensions of sustainability (e.g. environmental, economic, and social) within the system of interest (Baños et al. 2011; Bazmi and Zahedi 2011; Bouvy et al. 2010; Holling 2001). In turn, authors cite multidisciplinary working (Kemp and Martens 2007; Quental, Lourenco, and da Silva 2010; Sneddon, Howarth, and Norgaard 2006) and the adoption of a systems perspective (Kemp and Martens 2007; Kim and Oki 2011) as necessary for overcoming this complexity. As discussed in section 4.3, WSD was found to: acknowledge the complexity and multiple scales of the Earth system and in turn, design problems (Charnley, Lemon, and Evans 2011; Coley and Lemon 2009; Stasinopoulos et al. 2009); prescribe that designers adopt a systems view throughout the design process (Blizzard and Klotz 2012; Coley and Lemon 2009); and prescribe that cross-disciplinary collaboration should occur during design (Blizzard and Klotz 2012; Charnley, Lemon, and Evans 2011; Coley and Lemon 2009; Stasinopoulos et al. 2009). Thus, it seems that WSD can provide effective guidance for tackling the challenge of system sustainability in the context of design. Additionally, authors suggest that that optimisation methods, combined with modelling and simulation methods, can provide a means to overcome the complexity associated with attempts to achieve sustainability at the system level in a design context (Bazmi and Zahedi 2011; Halim and Srinivasan 2011; Sedki and Ouazar 2011; Singh and Lou 2006; Stasinopoulos et al. 2009).

In spite of its potential merits in relation to key sustainability challenges, WSD was found to be discussed in the lowest number of sources– just five i.e. 6% of the sample (Blizzard and Klotz 2012; Charnley, Lemon, and Evans 2011; Coley and Lemon 2009; Gagnon, Leduc, and Savard 2012; Stasinopoulos et al. 2009), in comparison to twenty four for the most frequently discussed S-philosophy, SD (i.e. 29% of the sample). Additionally, as shown in the DSM, few methods and tools were identified in the context of WSD. Further, as shown in Table 8 in section 5.2, only a single effort to integrate sustainability with the design process was uncovered (Stasinopoulos et al. 2009). Authors provide further commentary on the underdeveloped nature of WSD. For instance, Blizzard and Klotz (2012, 457) write that, "Whole systems design is one approach to sustainable design offering great potential, however the processes, principles, and methods guiding the whole systems approach are not clearly defined or understood by practicing designers or design educators." Similarly, Coley and Lemon (2009, 550) highlight that "it is thought that research into WSD would benefit from the identification of methods through which to approach […] problems." Charnley, Lemon, and Evans (2011, 156) remark that "there is limited research concerning the integrative process that actors are required to follow" in order to deliver sustainable solutions. As such, further development of the WSD philosophy, including the provision of clearer guidance on the methods and tools that should be employed and how they may be combined during the design process, represents a second challenge for research on sustainability-oriented design. Additionally, although methods for modelling, simulating, and optimising may be effective in tackling key sustainability challenges as discussed above, it may be seen from the DSM presented in Figure 3 that relatively few methods and tools of this nature were identified. As shown in Figure 2 in section 6.1, methods and tools for modelling, simulating and optimising represented just 14% of all methods and tools identified. In particular, although optimisation is delineated as a key activity under WSD (Stasinopoulos et al. 2009), no formal optimisation methods were found to be discussed by authors in the context of the philosophy. Therefore, the development and application of modelling, simulation, and optimisation methods to support the achievement of sustainability at the system level in design should be addressed by future research.

As discussed in section 6.1, ninety methods and tools for evaluating and analysing were identified, representing just over half of all methods and tools identified (one hundred and seventy three). Of these ninety methods and tools, sixty (67%) may be seen to focus upon the evaluation of environmental, economic, and/or social performance as shown in Figure 4.

Figure 4. Percentages of different types of evaluation and analysis methods and tools (see Figure 4-7, Section 4.2.3, Chapter 4 of thesis)

Additionally, as shown in section 5.2, the majority of design processes and methodologies identified (with the exception of one process (Gamage and Hyde 2012) and one methodology (Alfaris et al. 2010)) included at least one stage or step involving the evaluation of environmental, economic, and/or social performance. Taken together, these observations suggest that evaluating these aspects of performance is a key activity with respect to achieving sustainability in design. It may be seen in Table 6 in section 5.1.3 that the majority of the identified methods and tools for evaluating performance focus upon environmental aspects alone (73%), as shown in Figure 5 below.

Figure 5. Percentages of different types of performance evaluation methods (see Figure 4-10, Section 4.2.3, Chapter 4 of thesis)

However, as shown in the DSM in Figure 3, DfS, SD, and WSD were all found to seek the achievement of environmental, economic, and social sustainability (Gagnon, Leduc, and Savard 2012; Spangenberg, Fuad-Luke, and Blincoe 2010; Stasinopoulos et al. 2009), which requires designers to improve the impacts of design in all three of these dimensions (Bhamra and Lofthouse 2007; Bhamra, Lilley, and Tang 2011; Gagnon, Leduc, and Savard 2012; Mayyas et al. 2012a; Spangenberg, Fuad-Luke, and Blincoe 2010; Stasinopoulos et al. 2009). In turn, the results highlighted above suggest that there is a lack of support with respect to measuring the full spectrum of relevant impacts in the context of DfS, SD, and WSD (section 5.1.3). As such, the development of more extensive support in this respect may be viewed as a key challenge for research on sustainability-oriented design, given the apparent significance of performance assessment in the field.

Finally, as discussed in section 6.1, one hundred and seventy three distinct methods and tools were identified. In comparison, relatively few efforts to integrate sustainability into the design process as a whole were uncovered, as shown in Table 8 in section 5.2. Four authors were observed to examine existing design processes, and discuss the major sustainability issues that should be considered at each stage (Byggeth et al. 2007a; Gagnon, Leduc, and Savard 2012; Stasinopoulos et al. 2009; Waage 2007). Of these, two were observed to make rather fleeting suggestions for methods and tools that may be effective at different stages (Byggeth et al. 2007a; Stasinopoulos et al. 2009). Two authors were found to define new sustainability-oriented processes to be followed by designers during design, and discuss the major sustainability issues that should be considered at each stage (Gamage and Hyde 2012; Park, Lee, and Wimmer 2005). Of these, only one provided any indication of methods and tools that may be useful at different stages (Park, Lee, and Wimmer 2005). Further, the stages involved in each process were seen to differ considerably. Additionally, three authors were found to outline methodologies (Alfaris et al. 2010; Bovea and Vidal 2004; Hossain, Kahn, and Hawboldt 2010), considered here to constitute integrated sets of methods and/or tools to be applied during the design process. However, without exception, these were found to be applied at a particular stage in the design process or to tackle a particular kind of design problem, as opposed to spanning the whole design process.

Overall, the above findings suggest that in spite of the plethora of methods and tools available to support designing with sustainability in mind, it remains rather unclear how they should actually be used and integrated into the design process. For instance, in the context of DfE, Lindahl et al.

(2007, 138) argue that often, the "methods and work with DfE are executed separately from the rest of the product development [process.]" They posit that this "may be a result of the isolation that many methods and tools have been developed in." Byggeth et al. (2007a, 1) highlight the work of Baumann et al. (2002), who claim that "there is too much tool development and too few studies and evaluations of existing tools." Indeed, the findings of the investigation documented herein suggest that there is a need to shift research focus away from the rapid development of methods and tools for tackling sustainability issues, towards evaluation of existing methods and tools of this nature to determine: (i) their effectiveness in the context of the design process, rather than in an isolated context; and (ii) how they may be integrated with this process, to yield holistic methodologies.

As touched upon above, the stages involved in design processes discussed by authors were seen to differ considerably. Therefore, on a more fundamental level, it may be seen that the basic sequence of actions that should be undertaken to achieve sustainability during design remains somewhat unclear. For instance, during the investigation, Waage (2007) was found to outline an explicit process with four stages: 1. Establish sustainability context; 2. Define sustainability issues; 3. Assess; and 4. Act and receive feedback. In contrast, Stasinopoulos et al. (2009) were seen to suggest that sustainability may be achieved by executing the stages of the traditional systems engineering process, with the addition of certain sustainability considerations at each stage: 1. Need definition; 2. Conceptual design; 3. Preliminary design; and 4. Detail design. Again, authors may be seen to draw similar conclusions. For instance, in the context of WSD, Charnley, Lemon, and Evans (2011, 156) remark that "there is limited research concerning the integrative process that actors are required to follow" in order to deliver sustainable solutions. In an article exploring "the design and perceived benefit of sustainable solutions," Coley and Lemon (2009, 544) remark that, "Over the last decade, multiple approaches to design have focused on the development of products, services and systems for both improved social and environmental sustainability." However, the authors argue that "consensus is lacking" with respect to "the process that the consortium of stakeholders are required to follow." As such, there is a need for further research to clarify the basic mechanisms through which sustainability is achieved in design. Knowledge in this respect may serve to build bridges among designers in different domains, and go some way towards building consensus on the nature of sustainability-oriented design.

7. Conclusion

Authors suggest that there is a lack of clarity regarding the means and mindsets that may be adopted to effectively tackle sustainability issues in design. According to Coley and Lemon (2009, 544), there is "confusion surrounding the multiple approaches to the design of more sustainable solutions due to the numerous definitions and interpretations currently being used within the relevant literature." Similarly, Waage (2007, 638) remarks that there is "confusion about pathways forward for companies" owing to the proliferation of methods and tools, and that it is "unclear how existing approaches are complementary or distinct." In response, this paper has presented the results of a critical literature investigation on sustainability in design, aiming to clarify the range of philosophies, methods, and tools developed to guide and support designing with sustainability in mind. To this end, a sample of the literature on sustainability-oriented design, consisting of eighty three sources spanning multiple design domains, was examined. On the basis of the major findings of the investigation, a taxonomy of sustainability-oriented design philosophies, methods, and tools, known as the Design Sustainability Matrix, was constructed.

A total of sixteen sustainability-oriented design philosophies (S-philosophies) were identified. However, five were identified as major S-philosophies, on the basis that they were found to be discussed considerably more frequently by authors than the others:

- sustainable design (SD), discussed in twenty four sources (e.g. Bhamra, Lilley, and Tang 2011; Keitsch 2012), i.e. 29% of the sample;
- ecodesign (ED), discussed in nineteen sources (e.g. Bovea and Pérez-Belis 2012; Park, Lee, and Wimmer 2005), i.e. 23% of the sample;

- design for environment (DfE), discussed in sixteen sources (e.g. Boks and Stevels 2007; Lindahl 1999), i.e. 19% of the sample;
- design for sustainability (DfS), discussed in ten sources (e.g. Bhamra and Lofthouse 2007; Mayyas et al. 2012a), i.e. 12% of the sample; and
- whole system design (WSD), discussed in five sources (e.g. Blizzard and Klotz 2012; Stasinopoulos et al. 2009), i.e. 6% of the sample.

DfE and ED were found to represent the same design philosophy (Boks and Stevels 2007; Collado-Ruiz and Ostad-Ahmad-Ghorabi 2010; Ostad-Ahmad-Ghorabi and Collado-Ruiz 2011), and seek the achievement of environmental sustainability in design by reducing the negative environmental impacts of designed artefacts throughout their life cycles (Bhander, Hauschild, and McAloone 2003; Boks and Stevels 2007; Bovea and Pérez-Belis 2012; Choi et al. 2008; Poole et al. 1999; Spangenberg, Fuad-Luke, and Blincoe 2010). Similarly, DfS and SD were found to share essentially the same aim and perspectives and thus, may be considered to represent the same design philosophy. Both were seen to seek the achievement of environmental, economic, and social sustainability in design (Gagnon, Leduc, and Savard 2012; Spangenberg, Fuad-Luke, and Blincoe 2010), by either minimising negative (Bhamra and Lofthouse 2007; Chapman 2011) or creating positive (McDonough and Braungart 2002; Spangenberg, Fuad-Luke, and Blincoe 2010) environmental, economic, and social impacts throughout the life cycles of designed artefacts. Finally, it was found that whilst WSD may not necessarily be conducive to the achievement of sustainability in every case (Blizzard and Klotz 2012), it is positioned by authors as effective in tackling sustainability challenges (Blizzard and Klotz 2012; Charnley, Lemon, and Evans 2011; Coley and Lemon 2009; Gagnon, Leduc, and Savard 2012; Stasinopoulos et al. 2009). In turn, WSD was observed to seek the achievement of environmental, economic, and social sustainability at the level of whole systems as opposed to isolated entities (Stasinopoulos et al. 2009), by either minimising negative or creating positive environmental, economic, and social impacts throughout the life cycle of a system (Blizzard and Klotz 2012; Charnley, Lemon, and Evans 2011; Stasinopoulos et al. 2009).

One hundred and seventy three distinct methods and tools were identified. In turn, each of these methods and tools was classified as focusing on a particular kind of design activity:

- creativity (e.g. the generation and development of design concepts (Collado-Ruiz and Ostad-Ahmad-Ghorabi 2010)) = eighteen methods and tools, i.e. 10% of the total identified;
- decision making (e.g. key decisions to be made with respect to the life cycle of a design (Mayyas et al. 2012a)) = forty one methods and tools, i.e. 24% of the total identified;
- evaluating and analysing (e.g. evaluating the sustainability performance of designs (Chen et al. 2012), and analysing user requirements (M.D. Bovea and Pérez-Belis 2012)) = ninety methods and tools, i.e. 52% of the total identified;
- modelling and simulating (.g. developing a parametric model of a design (Ostad-Ahmad-Ghorabi and Collado-Ruiz 2011), or testing a process design by simulating its behaviour (Hossain, Khan, and Hawboldt 2010)) = fourteen methods and tools, i.e. 7% of the total identified; and
- optimising (e.g. finding the best configuration for a designed system given a set of competing objectives (Papandreou and Shang 2008)) = twelve methods and tools, i.e. 7% of the total identified.

In each of the above categories, a mixture of the following were identified:

- new methods and tools, i.e. those newly developed with the explicit purpose of tackling sustainability issues (e.g. the Templates for Sustainable Development tool developed by Ny et al. (2008));
- modified methods and tools, i.e. those developed by modifying conventional methods and tools to be more effective in tackling sustainability issues (e.g. the Environmental Effect Analysis method developed by Lindahl (2001)); and
- conventional methods and tools, i.e. those that may be applied in design conventionally, but are presented as effective in tackling sustainability issues in their original, unmodified

form (e.g. the brainstorming method presented by Gagnon, Leduc, and Savard (2012) and Stasinopoulos et al. (2009)).

Methods and tools were found to be discussed by authors in the context of different S-philosophies, and in a number of cases, methods and tools discussed in the literature on a particular S-philosophy were seen to clearly reflect certain perspectives expounded by the philosophy.

In comparison to the number of individual methods and tools identified, relatively few efforts to integrate sustainability into the design process as a whole were observed. Four authors were observed to examine existing design processes, and discuss the major sustainability issues that should be considered at each stage (Byggeth et al. 2007a; Gagnon, Leduc, and Savard 2012; Stasinopoulos et al. 2009; Waage 2007). Of these, two were observed to make rather fleeting suggestions for methods and tools that may be effective at different stages (Byggeth et al. 2007a; Stasinopoulos et al. 2009). Two authors were found to define new sustainability-oriented processes to be followed by designers during design, and discuss the major sustainability issues that should be considered at each stage (Gamage and Hyde 2012; Park, Lee, and Wimmer 2005). Of these, only one provided any indication of methods and tools that may be useful at different stages (Park, Lee, and Wimmer 2005). Further, the stages involved in each process were seen to differ considerably. Additionally, three authors were found to outline methodologies (Alfaris et al. 2010; Bovea and Vidal 2004; Hossain, Kahn, and Hawboldt 2010), considered here to constitute integrated sets of methods and/or tools to be applied during the design process (Evbuomwan, Sivaloganathan, and Jebb 1996; Hernandez 2010; OED 2013). Without exception, these were found to be applied at a particular stage in the design process (Bovea and Vidal 2004; Hossain, Kahn, and Hawboldt 2010) or to tackle a particular kind of design problem (Alfaris et al. 2010), as opposed to spanning the whole design process.

On the basis of the major findings of the investigation, the Design Sustainability Matrix (DSS) was constructed. Within the matrix, the methods and tools identified are positioned: (i) horizontally, according the S-philosophies that they were seen to be associated with; and (ii) vertically, according to the kinds of design activities that they are intended to support designers in. The DSM serves three major purposes: (i) it visually positions research on sustainability-oriented design; (ii) it identifies shortcomings in current knowledge on sustainability-oriented design; and (iii) it can guide designers with respect to the methods and tools that may be most appropriate given their sustainability aims and perspectives. On the basis of the DSM and the investigation findings overall, a number of observations may be made regarding the state of the art and challenges in the field:

1. The continued application of DfE and ED, with their focus on environmental sustainability, appears to be misaligned with wider sustainability goals for human activity (that focus on environmental, economic, and social sustainability (Kajikawa 2008)) and current knowledge on sustainability in design (authors suggest that DfS, SD, and WSD supersede DfE and ED (Bhamra and Lofthouse 2007; Gagnon, Leduc, and Savard 2012; Spangenberg, Fuad-Luke, and Blincoe 2010; Stasinopoulos et al. 2009)). A potential explanation for this trend is that DfE and ED are easier to implement in practice than DfS, SD, and WSD (Chapman 2011; Chen et al. 2012; Spangenberg, Fuad-Luke, and Blincoe 2010). Thus, the provision of more effective support for the implementation of DfS, SD, and WSD in practice represents a challenge for future research.
2. A need to achieve sustainability at the level of whole systems, as opposed to isolated entities, is discussed in wider sustainability literature (Bodini 2012; Voinov 2007). Given its key perspectives, the WSD philosophy (Blizzard and Klotz 2012; Charnley, Lemon, and Evans 2011; Coley and Lemon 2009; Stasinopoulos et al. 2009), and the combined use of optimisation, modelling, and simulation methods (Bazmi and Zahedi 2011; Halim and Srinivasan 2011; Sedki and Ouazar 2011; Singh and Lou 2006; Stasinopoulos et al. 2009), may provide a means to overcome the complexity associated with this challenge (Baños et al. 2011; Bazmi and Zahedi 2011; Bouvy et al. 2010; Holling 2001) in the context of design. However, WSD was found to be discussed in just 6% of the sources (compared with e.g. 29% for sustainable design) and was associated with few methods and tools by authors. Additionally, methods and tools for modelling, simulating and optimising represented just

14% of all methods and tools identified. Therefore, further development and application of (i) the WSD philosophy, and (ii) modelling, simulation, and optimisation methods to support the achievement of sustainability at the system level in design represents a challenge for future research.

3. Over 50% of all methods and tools identified were found to focus on evaluation and analysis. Of these, 67% were seen to focus on the evaluation of environmental, economic, and/or social performance. Further, the majority of design processes and methodologies identified included at least one stage or step involving the evaluation of environmental, economic, and/or social performance. This suggests that evaluating these aspects of performance is a key activity in sustainability-oriented design. DfS, SD, and WSD were all observed to seek the achievement of environmental, economic, and social sustainability (Blizzard and Klotz 2012; Gagnon, Leduc, and Savard 2012; Spangenberg, Fuad-Luke, and Blincoe 2010; Stasinopoulos et al. 2009), which requires designers to improve the impacts of design in all three of these dimensions (Bhamra and Lofthouse 2007; Bhamra, Lilley, and Tang 2011; Gagnon, Leduc, and Savard 2012; Mayyas et al. 2012a; Spangenberg, Fuad-Luke, and Blincoe 2010; Stasinopoulos et al. 2009). However, 70% of the aforementioned performance evaluation methods were found to focus on environmental aspects alone, suggesting that support is lacking with respect to measuring the full spectrum of relevant impacts in the context of DfS, SD, and WSD. Thus, the development of more extensive support in this respect represents another challenge for research on sustainability-oriented design.
4. In comparison to the number of individual methods and tools identified (one hundred and seventy three), relatively few efforts to integrate sustainability into the design process as a whole were uncovered (four authors examined existing design processes (Byggeth et al. 2007a; Gagnon, Leduc, and Savard, 2012; Stasinopoulos et al. 2009; Waage 2007), two suggested new sustainability-oriented processes (Gamage and Hyde 2012; Park, Lee, and Wimmer 2005), and three suggested methodologies to be applied at different stages of the design process or to solve a particular kind of problem (Alfaris et al. 2010; Bovea and Vidal 2004; Hossain, Kahn, and Hawboldt 2010)). This suggests that in spite of the plethora of methods and tools available, it remains rather unclear how they should actually be used and integrated into the design process. Thus, there is a need to shift research focus away from the rapid development of methods and tools for tackling sustainability issues, towards evaluation of existing methods and tools of this nature to determine: (i) their effectiveness in the context of the design process, rather than in an isolated context; and (ii) how they may be integrated with this process, to yield holistic methodologies.
5. Finally, considerable differences were observed among all of the design processes examined or suggested by authors, which suggests a lack of clarity regarding the basic sequence of actions that should be undertaken to achieve sustainability in design (Charnley, Lemon, and Evans 2011; Coley and Lemon 2009). Thus, there is a need for further research to clarify the basic mechanisms through which sustainability is achieved in this context. Knowledge in this respect may serve to build bridges among designers in different domains, and go some way towards building consensus on the nature of sustainability-oriented design.

8. Nomenclature

Common methods and tools:

FMEA = Failure mode and effects analysis
LCA = Life cycle assessment
LCC = Life cycle costing
MCDA = Multi criteria decision analysis
QFD = Quality function deployment
TRIZ = Theory of Inventive Problem Solving

Design contexts:

ABD = Architecture and building design
EED = Electrical and electronic design
EngD = Engineering design

ID = Industrial design
M = Manufacturing
PDD = Product design and development
PrcD = Process design
SD = Service design
SysD = Systems design

Method and tool categories:
C = Methods and tools for creativity
DM = Methods and tools for decision making
EA = Methods and tools for evaluating and analysing
MS = Methods and tools for modelling and simulating
O = Methods and tools for optimising

Sustainability-oriented design philosophies:
DfE = Design for environment
DfS = Design for sustainability
ED = Ecodesign
SD = Sustainable design
WSD = Whole system design

9. References

Alfaris, A., Siddiqi, A., Rizk, C., de Weck, O., and Svetinovic, D. 2010. Hierarchical Decomposition and Multidomain Formulation for the Design of Complex Sustainable Systems. *Journal of Mechanical Design* 132 (9): 091003–1 – 091003–13.

Andreasen, M.M., Wognum, N., and McAloone, T. 2002. Design Typology and Design Organisation. In *DESIGN 2002 - 7th International Design Conference*, 1–6.

Aschehoug, S.H., Boks, C., and Støren, S. 2012. Environmental Information from Stakeholders Supporting Product Development. *Journal of Cleaner Production* 31 (August): 1–13.

Azkarate, A., Ricondo, I., Pérez, A., and Martínez, P. 2011. An Assessment Method and Design Support System for Designing Sustainable Machine Tools. *Journal of Engineering Design* 22 (3): 165–179.

Baharudin, B.T., Tuah, H., Sulaiman, S., Ariffin, M.K.A., Fatchurrohman, N., and Sapuan, S.M. 2012. A New Concurrent Engineering – Multi Criteria Decision Making Technique for Conceptual Design Selection. *Applied Mechanics and Materials* 225 (30): 293–298.

Baños, R., Manzano-Agugliaro, F., Montoya, F.G., Gil, C., Alcayde, A., and Gómez, J. 2011. Optimization Methods Applied to Renewable and Sustainable Energy: A Review. *Renewable and Sustainable Energy Reviews* 15 (4): 1753–1766.

Barron, F.H., and Barrett, B.E. 1996. The Efficacy of SMARTER — Simple Multi-Attribute Rating Technique Extended to Ranking. *Acta Psychologica* 93 (1-3): 23–36.

Bazmi, A.A., and Zahedi, G. 2011. Sustainable Energy Systems: Role of Optimization Modeling Techniques in Power Generation and supply—A Review. *Renewable and Sustainable Energy Reviews* 15 (8): 3480–3500.

Belaziz, M., Bouras, A., and Brun, J.M. 2000. Morphological Analysis for Product Design. *Computer-Aided Design* 32 (5-6): 377–388.

De Benedetto, L., and Klemeš, J. 2009. The Environmental Performance Strategy Map: An Integrated LCA Approach to Support the Strategic Decision-making Process. *Journal of Cleaner Production* 17 (10): 900–906.

Bhamra, T.A., Evans, S., McAloone, T.C., Simon, M., Poole, S., and Sweatman, A. 1999. Integrating Environmental Decisions into the Product Development Process. I. The Early Stages. In *Proceedings First International Symposium on Environmentally Conscious Design and Inverse Manufacturing*, 329–333. IEEE.

Bhamra, T., Lilley, D., and Tang, T. 2011. Design for Sustainable Behaviour: Using Products to Change Consumer Behaviour. *The Design Journal* 14 (4): 19.

Bhamra, T., and Lofthouse, V. 2007. *Design for Sustainability: A Practical Approach*. Aldershot: Gower Publishing, Ltd.

Bhander, G.S., Hauschild, M., and McAloone, T. 2003. Implementing Life Cycle Assessment in Product Development. *Environmental Progress* 22 (4): 255–267.

Blizzard, J.L., and Klotz, L.E. 2012. A Framework for Sustainable Whole Systems Design. *Design Studies* 33 (5): 456–479.

Bodini, A. 2012. Building a Systemic Environmental Monitoring and Indicators for Sustainability: What Has the Ecological Network Approach to Offer? *Ecological Indicators* 15 (1): 140–148.

Boggia, A., and Cortina, C. 2010. Measuring Sustainable Development Using a Multi-criteria Model: a Case Study. *Journal of Environmental Management* 91 (11): 2301–6.

Boks, C., and Stevels, A. 2007. Essential Perspectives for Design for Environment. Experiences from the Electronics Industry. *International Journal of Production Research* 45 (18-19): 4021–4039.

Boks, C., and Diehl, J.C. 2005. EcoBenchmarking for All. In *2005 4th International Symposium on Environmentally Conscious Design and Inverse Manufacturing*, 792–798. IEEE.

Boks, C., and Stevels, A. 2003. Theory and Practice of Environmental Benchmarking in a Major Consumer Electronics Company. *Benchmarking: An International Journal* 10 (2): 120–135.

Bonanni, L., Hockenberry, M., Zwarg, D., Csikszentmihalyi, C., and Ishii, H. 2010. Small Business Applications of Sourcemap: A Web Tool for Sustainable Design and Supply Chain Transparency. In *CHI 2010: Sense and Sustainability, April 10-15, Atlanta*, 937–946.

Bouvy, C., Kausch, C., Preuss, M., and Henrich, F. 2010. On the Potential of Multi-objective Optimization in the Design of Sustainable Energy Systems. In *Multiple Criteria Decision Making for Sustainable Energy and Transportation Systems - Lecture Notes in Economics and Mathematical Systems*, eds. Ehrgott, M., Naujoks, B., Stewart, T.J, and Wallenius, J. 634:3–12. Berlin, Heidelberg: Springer Berlin Heidelberg.

Bovea, M.D., and Wang, B. 2007. Redesign Methodology for Developing Environmentally Conscious Products. *International Journal of Production Research* 45 (18-19): 4057–4072.

Bovea, M.D, and Vidal, R. 2004. Increasing Product Value by Integrating Environmental Impact, Costs and Customer Valuation. *Resources, Conservation and Recycling* 41 (2): 133–145.

Bovea, M.D., and Pérez-Belis, V. 2012. A Taxonomy of Ecodesign Tools for Integrating Environmental Requirements into the Product Design Process. *Journal of Cleaner Production* 20 (1): 61–71.

Boyle, I.M., Duffy, A.H.B., Whitfield, R.I., and Liu, S. 2009. Towards an Understanding of the Impact of Resources on the Design Process. In *17th International Conference on Engineering Design (ICED `09)*. Stanford: The Design Society.

Boyle, I.M., Duffy, A.H.B., Whitfield, R.I. and Liu, S. 2012. The Impact of Resources on Decision Making. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing* 26 (4): 407–423.

Brown, B.J., Hanson, M.E., Liverman, D.M., and Merideth, R.W. 1987. Global Sustainability: Toward Definition. *Environmental Management* 11 (6): 713–719.

Byggeth, S., Broman, G., and Robèrt, K.-H. 2007a. A Method for Sustainable Product Development Based on a Modular System of Guiding Questions. *Journal of Cleaner Production* 15 (1): 1–11.

Byggeth, S.H., Ny, H., Wall, J., Broman, G., and Robèrt, K.-H. 2007b. Introductory Procedure for Sustainability-driven Design Optimization. In *International Conference on Engineering Design, ICED "07, 28-31 August, Cite Des Sciences Et De L"Industrie, Paris, France*, 99–100.

Chapman, J. 2011. *Emotionally Durable Design*. 3rd ed. London, Washington DC: Earthscan.

Charnley, F., Lemon, M. and Evans, S. 2011. Exploring the Process of Whole System Design. *Design Studies* 32 (2): 156–179.

Chen, C., Zhu, J., Yu, J.-Y., and Noori, H. 2012. A New Methodology for Evaluating Sustainable Product Design Performance with Two-stage Network Data Envelopment Analysis. *European Journal of Operational Research* 221 (2): 348–359.

Chiu, M.-C., and Chu, C.-H. 2012. Review of Sustainable Product Design from Life Cycle Perspectives. *International Journal of Precision Engineering and Manufacturing* 13 (7): 1259–1272.

Choi, J.K., Nies, L.F. and Ramani, K. 2008. A Framework for the Integration of Environmental and Business Aspects Toward Sustainable Product Development. *Journal of Engineering Design* 19 (5): 431–446.

Clark, G., Kosoris, J., Hong, L.N., and Crul, M. 2009. Design for Sustainability: Current Trends in Sustainable Product Design and Development. *Sustainability* 1: 409–424.

Coley, F.J.S., and Lemon, M. 2009. Exploring the Design and Perceived Benefit of Sustainable Solutions: a Review" *Journal of Engineering Design* 20 (6): 543–554.
Collado-Ruiz, D., and Ostad-Ahmad-Ghorabi, H. 2010. Influence of Environmental Information on Creativity. *Design Studies* 31 (5): 479–498.
Cross, N. 2008. *Engineering Design Methods*. 4th ed. Chichester: John Willey & Sons Ltd.
Dempsey, N., Bramley, G., Power, S., and Brown, C. 2011. The Social Dimension of Sustainable Development: Defining Urban Social Sustainability. *Sustainable Development* 19 (5): 289–300.
Diwekar, U. 2008. *Introduction to Applied Optimization*. Vol. 22. Boston, MA: Springer US.
Dreher, J., Lawler, M., Stewart, J., Strasorier, G., and Thorne, M. 2009. *General Motors Metrics for Sustainable Manufacturing*.
Duffy, A. 2005. Design Process and Performance. In *Engineering Design - Theory and Practice, A Symposium in Honour of Ken Wallace*, ed. John Clarkson and Mari Huhtala, 76–85. Engineering Design Centre, University Of Cambridge.
Edeholt, H. 2012. Innovative Foresights in Sustainable Design and Architecture - How to Promote Seemingly Impossible, but Still Crucial, Radical Changes. *Sustainable Development* 20 (3): 155–165.
Ernzer, M., and Bey, N. 2003. The Link Between Life Cycle Design and Innovation. In *Proceedings of EcoDesign 2003: Third International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokyo, Japan, December 8-11, 2003*, 559–566. Tokyo.
Ernzer, M., and Wimmer, W. 2002. From Environmental Assessment Results to Design for Environment Product Changes: An Evaluation of Quantitative and Qualitative Methods. *Journal of Engineering Design* 13 (3): 233–242.
Eschenauer, H. A., Koski, J., and Osyczka, A. 1990. Multicriteria Optimization - Fundamentals and Motivation. In *Multicriteria Design Optimization*, eds. Eschenauer, H., Koski, J., and Osyczka, A. 1–34. Berlin, Heidelberg, New York: Springer-Verlag.
European Environment Agency. Indicators and Fact Sheets About Europe's Environment. Available at: http://www.eea.europa.eu/data-and-maps/indicators#c5=&c7=all&c0=10&b_start=0.
Evbuomwan, N.F.O., Sivaloganathan, S., and Jebb, A. 1996. A Survey of Design Philosophies, Models, Methods and Systems. *ARCHIVE: Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 1989-1996 (vols 203-210)*: 301–320.
Fargnoli, M., and Kimura, F. 2006. Screening Life Cycle Modelling for Sustainable Product Design. In *Innovation in Life Cycle Engineering and Sustainable Development*, ed. Daniel Brissaud, Serge Tichkiewitch, and Peggy Zwolinski, 281–292. Dordrecht: Springer Netherlands.
Fiksel, J. 2003. Designing Resilient, Sustainable Systems. *Environmental Science & Technology* 37 (23): 5330–5339.
Ford. "Product Sustainability Index." Available at: ttp://corporate.ford.com/microsites/sustainability-report-2011-12/environment-lifecycle-index.
Gagnon, B., Leduc, R., and Savard, L. 2012. From a Conventional to a Sustainable Engineering Design Process: Different Shades of Sustainability. *Journal of Engineering Design* 23 (1): 49–74.
Gamage, A., and Hyde, R. 2012. A Model Based on Biomimicry to Enhance Ecologically Sustainable Design" *Architectural Science Review* 55 (3): 224–235.
Goerner, S.J., Lietaer, B., and Ulanowicz, R.E. 2009. Quantifying Economic Sustainability: Implications for Free-enterprise Theory, Policy and Practice. *Ecological Economics* 69 (1): 76–81.
Gong, R., Li, Q., Liu, X., and Wang, Q. 2004. Modelling for Business Process Design: a Methodology Based on Causal Loop Diagram. In *2004 IEEE International Conference on Systems, Man and Cybernetics*, 6149–6154. IEEE.

Gould, D. 2011. 13 Inspirational Designers And Their Design Philosophies. Available at: http://www.psfk.com/2011/05/13-inspirational-designers-and-their-design-philosophies.html.
Gu, Y., and Frazer, J. 2009. Complex Modelling of Open System Design for Sustainable Architecture. In *Complex Sciences - Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering*, ed. Zhou, J. 5:1898–1906. Berlin, Heidelberg: Springer Berlin Heidelberg.

Halim, I., and Srinivasan, R. 2011. A Knowledge-based Simulation-optimization Framework and System for Sustainable Process Operations. *Computers & Chemical Engineering* 35 (1): 92–105.

Han, J.-H., Ahn, Y.-C., and Lee, I.-B. 2012. A Multi-objective Optimization Model for Sustainable Electricity Generation and CO2 Mitigation (EGCM) Infrastructure Design Considering Economic Profit and Financial Risk. *Applied Energy* 95 (July): 186–195.

Harun, K., and Cheng, K. 2011. Life Cycle Simulation (LCS) Approach to the Manufacturing Process Design for Sustainable Manufacturing. In *2011 IEEE International Symposium on Assembly and Manufacturing (ISAM)*, 1–8. IEEE. d

Heijungs, R., Huppes, G., and Guinée, J.B. 2010. Life Cycle Assessment and Sustainability Analysis of Products, Materials and Technologies. Toward a Scientific Framework for Sustainability Life Cycle Analysis. *Polymer Degradation and Stability* 95 (3): 422–428.

Hernandez, J. 2010. An Introduction to Design Methods. Lecture slides. Glasgow: Department of Design, Manufacture and Engineering Management, University of Strathclyde.

Holling, C.S. 2001. Understanding the Complexity of Economic, Ecological, and Social Systems. *Ecosystems* 4 (5): 390–405.

Holt, R., and Barnes, C. 2009. Towards an Integrated Approach to 'Design for X': An Agenda for Decision-based DFX Research. *Research in Engineering Design* 21 (2): 123–136.

Hong, T., Ji, C., and Park, H. 2012. Integrated Model for Assessing the Cost and CO2 Emission (IMACC) for Sustainable Structural Design in Ready-mix Concrete. *Journal of Environmental Management* 103 (July): 1–8.

Horváth, I, and Duhovnik, J. 2005. Towards a Better Understanding of the Methodological Characteristics of Engineering Design Research. In *Proceedings of IDETC/CIE 2005 ASME 2005 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference September 24-28, 2005*. Long Beach, California.

Horvath, I. 2004. A Treatise on Order in Engineering Design Research. *Research in Engineering Design* 15 (3): 155–181.

Hossain, K., Khan, A.F., and Hawboldt, K. 2010. SusDesign – An Approach for a Sustainable Process System Design and Its Application to a Thermal Power Plant. *Applied Thermal Engineering* 30 (14-15): 1896–1913.

Hubka, V. 1982. *Principles of Engineering Design*. Butterworth & Co (Publishers) Ltd.

Huisman, J., Boks, C.B., and Stevels, A.L.N. 2003. Quotes for Environmentally Weighted Recyclability (QWERTY): Concept of Describing Product Recyclability in Terms of Environmental Value. *International Journal of Production Research* 41 (16): 3649–3665.

Huisman, J., Boks, C., and Stevels, A. 2000. Environmentally Weighted Recycling Quotes-better Justifiable and Environmentally More Correct. In *Proceedings of the 2000 IEEE International Symposium on Electronics and the Environment (Cat. No.00CH37082)*, 105–111. IEEE.

IChemE. *The Sustainability Metrics - Sustainable Development Progress Metrics Recommended for Use in the Process Industries*. Rugby. Available at: http://nbis.org/nbisresources/metrics/triple_bottom_line_indicators_process_industries.pdf.

Jones, J.C. 1991. *Designing Designing*. London: Architecture Design and Technology Press.

Jones, J.C. 1992. *Design Methods*. 2nd ed. New York: John Wiley & Sons Inc.

Kajikawa, Y. 2008. Research Core and Framework of Sustainability Science. *Sustainability Science* 3 (2): 215–239.

Karlsson, R., and Luttropp, C. 2006. EcoDesign: What's Happening? An Overview of the Subject Area of EcoDesign and of the Papers in This Special Issue. *Journal of Cleaner Production* 14 (15-16): 1291–1298.

Keitsch, M. 2012. Sustainable Design: A Brief Appraisal of Its Main Concepts. *Sustainable Development* 20 (3): 180–188.

Kemp, R., and Martens, P. 2007. Sustainable Development: How to Manage Something That Is Subjective and Never Can Be Achieved? *Sustainability: Science, Practice, & Policy* 3 (2): 5–14.

Kemp, R., and Parto, S. 2005. Governance for Sustainable Development: Moving from Theory to Practice. *International Journal of Sustainable Developent* 8 (1/2): 12–30.

Kim, J., and Oki, T. 2011. Visioneering: An Essential Framework in Sustainability Science. *Sustainability Science* 6 (March): 247–251.

Kimita, K., Tateyama, T., and Shimomura, Y. 2012. Process Simulation Method for Product-Service Systems Design. *Procedia CIRP* 3 (January): 489–494. d
Laitala, K., Boks, C., and Klepp, I.G. 2011. Potential for Environmental Improvements in Laundering. *International Journal of Consumer Studies* 35 (2): 254–264.
Larkin, P. A. 1977. An Epitaph for the Concept of Maximum Sustained Yield. *Transactions of the American Fisheries Society* 106 (1): 1–11.
Laszlo, A., Laszlo, K.C., and Dunsky, H. 2009. Redefining Success: Designing Systemic Sustainable Strategies. *Systems Research and Behavioral Science* 27: 3–21.
Latham, J.R. 2009. Complex System Design: Creating Sustainable Change in the Mortgage-Finance System. *The Quality Management Journal* 16 (3): 19–25.
Lele, S., and Norgaard, R.B. 1996. Sustainability and the Scientist's Burden. *Conservation Biology* 10 (2): 354–365.
Lenau, T, and Bey, N. 2001. Design of Environmentally Friendly Products Using Indicators. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* 215 (5): 637–645.
Levine, L., and Mohr, B.J. 1998. Whole System Design (WSD): The Shifting Focus of Attention and the Threshold Challenge. *The Journal of Applied Behavioral Science* 34 (3): 305–326.
Lindahl, M. 1999. E-FMEA-a New Promising Tool for Efficient Design for Environment. In *Proceedings First International Symposium on Environmentally Conscious Design and Inverse Manufacturing*, 734–739. IEEE.
Lindahl, M. 2001. Environmental Effect Analysis - How Does the Method Stand in Relation to Lessons Learned from the Use of Other Design for Environment Methods. In *Proceedings Second International Symposium on Environmentally Conscious Design and Inverse Manufacturing*, 864–869. IEEE Comput. Soc.
Lindahl, M., Hjelm, O., Sundin, E., and Thuresson, L. 2005. What Could Be Learned from the Utilization of Design for Environment Within Manufacturing Companies? In *2005 4th International Symposium on Environmentally Conscious Design and Inverse Manufacturing*, 232–237. IEEE.
Lindahl, M. 2006. Engineering Designers' Experience of Design for Environment Methods and Tools – Requirement Definitions from an Interview Study. *Journal of Cleaner Production* 14 (5): 487–496.
Lindahl, M., Sundin, E., Sakao, T., and Shimomura, Y. 2007. Integrated Product and Service Engineering Versus Design for Environment - A Comparison and Evaluation of Advanatges and Disadvantages. In *Advances in Life Cycle Engineering for Sustainable Manufacturing Businesses*, 137–142.
Lopes, A.M., Fam, D., and Williams, J. 2012. Designing Sustainable Sanitation: Involving Design in Innovative, Transdisciplinary Research. *Design Studies* 33 (3): 298–317.
Lu, B., Zhang, J., Xue, D., and Gu, P. 2011. Systematic Lifecycle Design for Sustainable Product Development. *Concurrent Engineering* 19 (4): 307–324.
Luchs, M.G., Brower, J., and Chitturi, R. 2012. Product Choice and the Importance of Aesthetic Design Given the Emotion-laden Trade-off Between Sustainability and Functional Performance. *Journal of Product Innovation Management* 29 (6): 903–916.
Luttropp, C., and Lagerstedt, J. 2006. EcoDesign and The Ten Golden Rules: Generic Advice for Merging Environmental Aspects into Product Development. *Journal of Cleaner Production* 14 (15-16): 1396–1408.
M'Pherson, P.K. 1980. Systems Engineering: An Approach to Whole-system Design. *Radio and Electronic Engineer* 50 (11-12).
Manesh, S.V., and Tadi, M. 2011. Sustainable Urban Morphology Emergence Via Complex Adaptive System Analysis: Sustainable Design in Existing Context. *Procedia Engineering* 21 (January): 89–97.
Marcuse, P. 1998. Sustainability Is Not Enough. *Environment and Urbanization* 10 (2): 103–112.
Marler, R.T., and Arora, J.S. 2004. Survey of Multi-objective Optimization Methods for Engineering. *Structural and Multidisciplinary Optimization* 26 (6): 369–395.
Mayall, W. H. 1979. *Principles in Design*. London: Design Council.

Mayyas, A., Qattawi, A., Omar, M., and Shan, D. 2012. Design for Sustainability in Automotive Industry: A Comprehensive Review. *Renewable and Sustainable Energy Reviews* 16 (4): 1845–1862.

Mayyas, A.T., Qattawi, A., Mayyas, A.R., and Omar, M.A. 2012. Life Cycle Assessment-based Selection for a Sustainable Lightweight Body-in-white Design. *Energy* 39 (1): 412–425.

McAloone, T. 2001. Confronting Product Life Thinking with Product Life Cycle Analysis. In *Proceedings Second International Symposium on Environmentally Conscious Design and Inverse Manufacturing*, 60–64. IEEE Comput. Soc.

McAloone, T.C., and Andreasen, M.M. 2004. Design for Utility, Sustainability and Societal Virtues: Developing Product Service Systems. In *International Design Conference - Design 2004, Dubrovnik, May 18-21, 2004*, 1–8. Dubrovnik.

McDonough, W., and Braungart, M. 2002. Design for the Triple Top Line: New Tools for Sustainable Commerce. *Corporate Environmental Strategy* 9 (3): 251–258.

Ness, B., Urbel-Piirsalu, E., Anderberg, S., and Olsson, L. 2007. Categorising Tools for Sustainability Assessment. *Ecological Economics* 60 (3): 498–508.

Neumayer, E. 2003. *Weak Versus Strong Sustainability : Exploring the Limits of Two Opposing Paradigms*. 2nd ed. Cheltenham, UK; Northampton, MA: Edward Elgar.

Niinimäki, K., and Koskinen, I. 2011. I Love This Dress, It Makes Me Feel Beautiful! Empathic Knowledge in Sustainable Design. *The Design Journal* 14 (2): 22.

Ny, H., Hallstedt, S., Robèrt, K.-H., and Broman, G. 2008. Introducing Templates for Sustainable Product Development. *Journal of Industrial Ecology* 12 (4): 600–623.

Ny, H., Haraldsson, H.V., Sverdrup, H.U., and Robèrt, K.-H. 2005. System Dynamic Modelling Within Sustainability Constraints. In *Industrial Ecology for a Sustainable Future, 3rd International Conference of the International Society for Industrial Ecology (ISIE)*, 99–100. Stockholm: The International Society for Industrial Ecology (ISIE).

Ny, H., MacDonald, J.P., Broman, G., Yamamoto, R., and Robért, K.-H. 2008. Sustainability Constraints as System Boundaries: An Approach to Making Life-Cycle Management Strategic. *Journal of Industrial Ecology* 10 (1-2): 61–77.

O'Donnell, F. J., and Duffy, A.H.B. 2005. *Design Performance*. London: Springer-Verlag.

OECD Environment Directorate. 2008. *OECD Key Environmental Indicators*. Paris. Available at: http://www.oecd.org/env/environmentalindicatorsmodellingandoutlooks/oecdenvironmentaldataandindicators.htm#OECD_Key_Environmental_Indicators.

Oram, D. 2010. Designing for Sustainability: Negotiating Ethical Implications. *IEEE Technology and Society Magazine* 29 (3): 31–36.

Ostad-Ahmad-Ghorabi, H., and Collado-Ruiz, D. 2011. Tool for the Environmental Assessment of Cranes Based on Parameterization. *The International Journal of Life Cycle Assessment* 16 (5): 392–400.

Oxford English Dictionary. 2013. Oxford English Dictionary. Oxford: Oxford University Press. Available at: http://www.oed.com/.

Papandreou, V., and Shang, Z. 2008. A Multi-criteria Optimisation Approach for the Design of Sustainable Utility Systems. *Computers & Chemical Engineering* 32 (7): 1589–1602.

Papanek, V. 1972. *Design for the Real World*. London: Thames and Hudson Ltd.

Park, P.-J., Lee, K.-M., and Wimmer, W. 2005. Development of an Environmental Assessment Method for Consumer Electronics by Combining Top-down and Bottom-up Approaches. *The International Journal of Life Cycle Assessment* 11 (4): 254–264.

Pérez-Fortes, M., Laínez-Aguirre J.-M., Arranz-Piera, P., Velo, E., and Puigjaner, L. 2012. Design of Regional and Sustainable Bio-based Networks for Electricity Generation Using a Multi-objective MILP Approach. *Energy* 44 (1): 79–95.

Poole, S., Simon, M., Sweatman, A., Bhamra, T.A., Evans, S., and McAloone, T.C. 1999. Integrating Environmental Decisions into the Product Development Process. II. The Later Stages. In *Proceedings First International Symposium on Environmentally Conscious Design and Inverse Manufacturing*, 334–337. IEEE.

Quental, N., Lourenço, J.M., and da Silva, F.N. 2010. Sustainability: Characteristics and Scientific Roots. *Environment, Development and Sustainability* 13 (2): 257–276.

Ramani, K., Ramanujan, D., Bernstein, W.Z., Zhao, F., Sutherland, J., Handwerker, C., and Choi, J.-K. 2010. Integrated Sustainable Life Cycle Design: A Review. *Journal of Mechanical Design* 132.

Rodriguez, E., and Boks, C. 2005. How Design of Products Affects User Behaviour and Vice Versa: The Environmental Implications." In *2005 4th International Symposium on Environmentally Conscious Design and Inverse Manufacturing*, 54–61. IEEE.
Rosen, M.A., and Kishawy, H.A. 2012. Sustainable Manufacturing and Design: Concepts, Practices and Needs. *Sustainability* 4: 154–174.
Sakao, T. 2009. Quality Engineering for Early Stage of Environmentally Conscious Design. *The TQM Journal* 21 (2): 182–193.
Santana, F.S., Barberato, C., and Saraiva, A.M. 2010. A Reference Process to Design Information Systems for Sustainable Design Based on LCA, PSS, Social and Economic Aspects. In *What Kind of Information Society? Governance, Virtuality, Surveillance, Sustainability, Resilience*, eds. Berleur, J., Hercheui, M.D., and Hilty, L.M. 328:269–280. Berlin, Heidelberg: Springer Berlin Heidelberg.
Sedki, A., and Ouazar, D. 2011. Simulation-Optimization Modeling for Sustainable Groundwater Development: A Moroccan Coastal Aquifer Case Study. *Water Resources Management* 25 (11): 2855–2875.
Shearman, R. 1990. The Meaning and Ethics of Sustainability. *Environmental Management* 14 (1): 1–8.
Shedroff, N. 2009. *Design Is the Problem - The Future of Design Must Be Sustainable*. New York: Rosenfield Media.
Singh, A. and Lou, H.H. Hierarchical Pareto Optimization for the Sustainable Development of Industrial Ecosystems. *Industrial & Engineering Chemistry Research* 45 (9): 3265–3279.
Skjerven, A. 2012. Cultural Traditions for the Sake of Innovation: The Concept of Scandinavian Design as a Potential Tool in the Development of a Sustainable China. *Sustainable Development* 20 (3): 230–238.
Sneddon, C., Howarth, R., and Norgaard, R. 2006. Sustainable Development in a post-Brundtland World. *Ecological Economics* 57 (2): 253–268.
Spangenberg, J.H., Fuad-Luke, A., and Blincoe, K. 2010. Design for Sustainability (DfS): The Interface of Sustainable Production and Consumption. *Journal of Cleaner Production* 18 (15): 1485–1493.
Stasinopoulos, P., Smith, M.H., Hargroves, K., and Desha, C. 2009. *Whole System Design. An Integrated Approach to Sustainable Engineering*. London: Earthscan.
Strasser, C., and Wimmer, W. 2003. Supporting Customer Driven Eco-solutions - Implementing Ecodesign in the Daily Work of Product Developers. In *Proceedings of EcoDesign 2003: Third International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokyo, Japan, December 8-11, 2003*. Tokyo.
Taras, S., and Woinaroschy, A. 2012. An Interactive Multi-objective Optimization Framework for Sustainable Design of Bioprocesses. *Computers & Chemical Engineering* 43 (August): 10–22.
Tharp, B.M., and Tharp, S.M. *Discursive Design: Beyond Purely Commerical Notions of Industrial and Product Design*. Available at: http://www.idsa.org/discursive-design.
Trotta, M.G. 2010. Product Lifecycle Management: Sustainability and Knowledge Management as Keys in a Complex System of Product Development. *Journal of Industrial Engineering and Management* 3 (2): 309–322.
Ulgiati, S., Ascione, M., Bargigli, S., Cherubini, F., Franzese, P.P., Raugei, M., Viglia, S., and Zucaro, A. 2011. Material, Energy and Environmental Performance of Technological and Social Systems Under a Life Cycle Assessment Perspective. *Ecological Modelling* 222 (1): 176–189.
Ulrich, K.T., and Eppinger, S.D. 2008. *Product Design and Development*. 4th ed. New York: McGraw-Hill/Irwin.
Unger, N., Schneider, F., and Salhofer, S. 2008. A Review of Ecodesign and Environmental Assessment Tools and Their Appropriateness for Electrical and Electronic Equipment." *Progress in Industrial Ecology* 5 (1/2): 13–29.
United Nations. 2007. *Indicators of Sustainable Development: Guidelines and Methodologies*. New York: United Nations. Available at: www.un.org/esa/sustdev/natlinfo/indicators/guidelines.pdf.
United Nations Environment Programme. 2012. *GEO5 - Environment for the Future We Want*. Valletta, Malta: United Nations Environment Programme. Available at: http://www.unep.org/geo/geo5.asp.

Urban, R.A., Bakshi, B.R., Grubb, G.F., Baral, A., and Mitsch, W.J. 2010. Towards Sustainability of Engineered Processes: Designing Self-reliant Networks of Technological–ecological Systems. *Computers & Chemical Engineering* 34 (9): 1413–1420.
Urken, A.B., Nimz, A., and Schuck, T.M. 2012. Designing Evolvable Systems in a Framework of Robust, Resilient and Sustainable Engineering Analysis. *Advanced Engineering Informatics* 26 (3): 553–562.
Vinodh, S., and Rathod, G. 2010. Integration of ECQFD and LCA for Sustainable Product Design. *Journal of Cleaner Production* 18 (8): 833–842.
Voinov, A. 2007. Understanding and Communicating Sustainability: Global Versus Regional Perspectives. *Environment, Development and Sustainability* 10 (4): 487–501.
Vos, R.O. 2007. Defining Sustainability: a Conceptual Orientation. *Journal of Chemical Technology & Biotechnology* 82 (4): 334–339.
Vucetich, J.A., and Nelson, M.P. 2010. Sustainability: Virtuous or Vulgar? *BioScience* 60 (7): 539–544.
Waage, S.A. 2007. Re-considering Product Design: a Practical 'road-map' for Integration of Sustainability Issues. *Journal of Cleaner Production* 15 (7): 638–649.
Wahl, D.C. 2012. Scale-linking Design for Systemic Health: Sustainable Communities and Cities in Context. In *Ecodynamics - The Prigogine Legacy*, 233–248. Southampton, Billerica: WIT Press.
Wahl, D.C., and Baxter, S. 2008. The Designer's Role in Facilitating Sustainable Solutions. *Design Issues* 24 (2): 72–83.
Wang, G., and Côté, R. 2011. Integrating Eco-efficiency and Eco-effectiveness into the Design of Sustainable Industrial Systems in China. *International Journal of Sustainable Development & World Ecology* 18 (1): 65–77.
Wever, R., Boks, C., van Es, H., and Stevels, A. 2005. Multiple Environmental Benchmarking Data Analysis and Its Implications for Design: a Case Study on Packaging. In *2005 4th International Symposium on Environmentally Conscious Design and Inverse Manufacturing*, 799–806. IEEE.
Whitfield, R.I., Duffy, A.H.B., Gatchell, S., Marzi, J., and Wang, W. 2012. A Collaborative Platform for Integrating and Optimising Computational Fluid Dynamics Analysis Requests. *Computer-Aided Design* 44 (3): 224–240.
Wigum, K.S., Zachrisson, J., and Boks, C. 2011. The Role of Product and System Interfaces in Designing Zero Emission Buildings. In *Proceedings of the 2011 IEEE International Symposium on Sustainable Systems and Technology*, 1–6. IEEE.
Wimmer, W., and Judmaier, P. 2003. Learning and Understanding ECODESIGN - Preparing the Complex Environmental Relations of Products for Straightforward Application in Companies. In *Proceedings of EcoDesign 2003: Third International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokyo, Japan, December 8-11, 2003*, 404 – 408. Tokyo.
Yeo, D.H., and Gabbai, R.D. 2011. Sustainable Design of Reinforced Concrete Structures Through Embodied Energy Optimization. *Energy and Buildings* 43 (8): 2028–2033.
Yoshikawa, H. 1989. Design Philosophy: The State of the Art. *CIRP Annals - Manufacturing Technology* 38 (2): 579–586.
Zachrisson, J., and Boks, C. 2011. A Framework for Selecting Sustainable Behavior Design Strategies. In *Proceedings of the 2011 IEEE International Symposium on Sustainable Systems and Technology*, 1–1. IEEE.

Appendix 2: Paper B

This appendix contains Paper B, which presents the findings of the analytical study of performance indicators conducted as part of the evaluation of the S-Cycle model (Section 7.3, Chapter 7 and Section 8.2.3.2, Chapter 8). The paper has been submitted to the Journal of Environmental Management. It is currently under revision for submission to an engineering journal, where it is felt the work may be more relevant and appropriate given the technical systems focus. As such, as with Paper A, the ideas and concepts discussed are in a state of evolution. With respect to references and styles, the paper is presented here largely as it is formatted for the journal.

Sections 4.1 and 4.3 of Chapter 4, as well as parts of Chapters 7 and 8 as noted above, present a summary of key points and findings from this paper. Note that owing to space limitations, certain tables and figures presented elsewhere in the thesis have been removed from the following paper. Where this is the case, readers are referred to the appropriate section of the thesis.

The S-Cycle Performance Matrix: A rational basis for selecting comprehensive sustainability performance indicators for technical systems

Abstract

There is a general consensus that technical systems may have a considerable impact on the environment throughout their life cycle, leading to increased scrutiny of their sustainability performance. However, a lack of consistency with respect to the performance indicators applied in this context raises a fundamental question: what type and range of sustainability performance indicators (SPIs) constitutes a comprehensive set for a technical system? We present a review and analysis of the literature on sustainability performance evaluation of technical systems, aiming to develop a generic classification of SPIs to guide the selection of a comprehensive set in this context. The major contribution is a matrix of generic sustainability goals, SPI archetypes, and associated metrics for technical systems, known as the S-Cycle Performance Matrix.

Literature on both the fundamental characteristics of performance, and sustainability performance evaluation of technical systems is reviewed. From this corpus, three criteria for comprehensive SPI sets emerge: (i) inclusion of both efficiency and effectiveness indicators; (ii) coverage of all sustainability goals governing the system; and (iii) inclusion of indicators measuring performance at all relevant spatio-temporal scales, given the purposes of the evaluation. In spite of the identified need to link SPIs with goals, authors evaluating the sustainability performance of technical systems are rarely seen to state any, suggesting a lack of clarity surrounding their nature. In response, the S-Cycle model is applied to define a generic set of sustainability goals for technical systems.

The S-Cycle Performance Matrix may support the development of a comprehensive set of SPIs for a technical system by highlighting: (i) the different types of efficiency and effectiveness indicator at the disposal of evaluators; (ii) the range of sustainability goals that should be covered by the SPIs; and (iii) the different spatio-temporal scales that each of the SPIs may be evaluated at. The matrix was evaluated through analysis of 324 indicators reported in a sample of the literature on sustainability performance evaluation of technical systems. Future work is required to clarify certain aspects and test the practical applications. However, following several refinements, 94.1% of the indicators in the sample were found to be classifiable with respect to the matrix. Furthermore, all proposed SPI archetypes and metrics (apart from three metrics) are seen to be supported. As such, we believe that the current matrix represents a solid step towards more consistent guidance on what constitutes a comprehensive set of SPIs for a technical system.

Keywords: sustainability assessment; sustainability indicators; sustainability performance; system sustainability; technical systems

1. Introduction

Technical systems may be viewed as "the "technical means" by which the human achieves his [or her] "ends"" (Hubka and Eder, 1988, p.7). That is, artificial systems designed and built by humans to satisfy the needs of society. Developed through the processes of engineering design (Eder, 2003; Hubka, 1982) and systems engineering (Blanchard and Fabrycky, 1981; Stasinopoulos et al., 2009), they are both ubiquitous outputs of economic production and key enablers of human activity generally. The label encompasses all technical products and processes, from simple consumer products up to large scale, complex systems such as ships and aircraft (Hubka and Eder, 1988).

In the 1980s, Hubka and Eder (1988, p.32) highlighted that the "equilibrium of [...] ecosystems should be respected and considered" during the development of technical systems. Today, there is a general consensus that these systems may have a considerable impact on the environment and the resource base throughout their life cycle (Stasinopoulos et al., 2009; Ulgiati et al., 2006). Accordingly, the sustainability performance of technical products, machinery, and plant is increasingly under scrutiny. For instance, organisations in the business of designing and manufacturing technical systems typically need to evaluate and report the performance of their technical products as part of a comprehensive sustainability report (Global Reporting Initiative, 2013a; International Standards Organization, 1999). Additionally, whilst sustainability reporting is typically a voluntary activity (Lozano and Huisingh, 2011), organisations are also coming under increasing regulatory pressure to improve the sustainability performance of their technical systems (Brynolf et al., 2014; Holan Fenwick Willan, 2013; Park et al., 2005). Thus, it may be seen that there is a growing need for information on the sustainability performance of technical systems to support decision making at various levels, from design (Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010; Park et al., 2005) up to organisational management and even consumer purchasing (Global Reporting Initiative, 2013a; Marimon et al., 2012).

It is broadly accepted that in order to make effective decisions, comprehensive information on the issue at hand is required (Boyle et al., 2012; (Dalal-Clayton and Bass, 2002; Wahl and Baxter, 2008). To obtain comprehensive information on the sustainability performance of any system, be it technical in nature or otherwise, a suitably comprehensive set of sustainability performance indicators (SPIs) is required (Dalal-Clayton and Bass, 2002; Ulgiati et al., 2011). The SPIs employed by a considerable number of authors evaluating the sustainability performance of technical systems appear to be drawn from formal evaluation methods including life cycle assessment (Adams and McManus, 2014; Russell-Smith et al., 2014), material flow analysis (Buonocore et al., 2012; Ulgiati et al., 2011), energy analysis (Caliskan et al., 2012; Waheed et al., 2014), exergy analysis (Aydin et al., 2013; Balta et al., 2010), and emergy analysis (Moss et al., 2014; Raugei et al., 2005). All of these methods entail the evaluation of performance indicators focusing on material and energetic flows associated with the production, operation, and disposal of technical systems (Ness et al., 2007; Ulgiati et al., 2011). However, the specific performance aspects measured by the indicators vary across methods, and the indicators are evaluated through different procedures. Additionally, authors may be seen to define SPIs in an *ad hoc* manner, seeming to draw upon their knowledge of the system and sustainability generally rather than any formal method (e.g. Asif and Muneer, 2014; Denholm et al., 2005; Rotella et al., 2012). The fact that all of these different indicators are applied does not, of course, necessarily mean that any of them are wrong or irrelevant. However, the lack of consistency among different methods and different authors does raise a rather fundamental question: what type and range of SPIs constitutes a comprehensive set for a technical system?

In an organisational context, the Global Reporting Initiative (GRI) has developed a set of guidelines for organisational sustainability reporting (SR), intended to foster greater consistency in the SR efforts of organisations worldwide (Dalal-Clayton and Bass, 2002; Global Reporting Initiative, 2013a; Hussey et al., 2001). The guidelines provide clear guidance on the type and range of SPIs that should be included in a comprehensive assessment of an organisation's sustainability performance (Hussey et al., 2001; Morhardt et al., 2002). They do not prescribe the use of any particular evaluation methods, leaving the choice up to the assessor with the caveat that they report any "standards, methodologies, and assumptions used" (Global Reporting Initiative, 2013b, p.91). In contrast, there is a lack of any overarching guidance of this nature in a technical systems context. Each of the formal methods briefly outlined above of course has particular indicators associated with it, which are typically defined and evaluated through specific procedures. However, whilst all of these methods may be presented as potentially useful in attempts to evaluate the sustainability performance of technical systems, none of them claim to be comprehensive sustainability evaluation methods *per se* (Ness et al., 2007; Ulgiati et al., 2011). Thus, although they may be useful in sustainability performance evaluation, applying formal methods may not necessarily result in a comprehensive set of SPIs for a technical system. To address these shortcomings, this paper presents the results of a review and analysis of the literature on sustainability performance evaluation of technical systems, aiming to develop a generic classification of SPIs to guide the selection of a comprehensive set for a technical system. The major contribution is a matrix of generic sustainability goals, SPI archetypes, and associated metrics for technical systems, known as the S-Cycle Performance Matrix.

To develop an understanding of what constitutes a comprehensive set of SPIs for a technical system, we consulted two major bodies of literature: (i) business/ organisational performance measurement, where the basic concepts and characteristics of performance have been defined (e.g. Neely et al., 1995; Neely et al., 2002a; Kaplan and Norton, 1996); and (ii) sustainability performance evaluation in a technical systems context (e.g. Adams and McManus, 2014; Aydin et al., 2013; Ulgiati et al., 2011). We also considered two fundamental models: (i) a generic performance model known as E^2, described by O'Donnell and Duffy (2002; 2005); and (ii) a generic model of system sustainability known as the S-Cycle, described by Hay et al. (2014). Additionally, we examined a set of performance axioms derived from the E^2 model. That is, a set of basic principles relating to performance "that commends itself to general acceptance" (Oxford English Dictionary, 2014). As will be shown in Sections 2, and 3, three criteria for comprehensive SPI sets for technical systems may be seen to emerge from this theoretical base:

- *Inclusion of both efficiency and effectiveness indicators.* As discussed in Section 2, a performance indicator may be generally defined as a parameter used to quantify the efficiency or effectiveness of a system's activity in relation to its goals (Neely et al., 2002; O'Donnell and Duffy, 2002). In turn, to provide a holistic picture on the performance of a system, any set of indicators, including SPIs, should include both efficiency and effectiveness indicators. A one-eyed focus on a single aspect may lead to the achievement of gains in efficiency (e.g. resource productivity) at the expense of effectiveness (e.g. resource consumption), and vice versa. O'Donnell and Duffy (2002, p.1219) remark that all performance indicators "can be typified to efficiency or effectiveness indicators" regardless of the specific aspects being measured. This idea forms the basis for the SPI archetypes included in the S-Cycle Performance Matrix.
- *Coverage of all sustainability goals governing the system.* In Section 2, it is also shown that performance indicators, including SPIs, should be closely related to performance goals. Performance goals define the system behaviour required to achieve certain performance, whilst indicators provide information on whether system behaviour is shifting towards or away from the goals. Sustainability performance goals focus on the aspects of behaviour that contribute to a technical system's sustainability performance. Thus, it is clear that if we wish to obtain a comprehensive view on a system's sustainability performance, we need to define SPIs relating to all of the sustainability performance goals defined for the system. In Section 4, we use a fundamental sustainability model, known as the S-Cycle, to illustrate the basic material and energetic aspects of behaviour contributing to the sustainability performance of technical systems. These aspects form the basis of the generic sustainability goals included in the performance matrix.
- *Inclusion of indicators measuring performance at different spatio-temporal scales.* In Section 3, it is shown that sustainability performance evaluation may be carried out at different spatio-temporal scales: *local*, focusing on the operation phase of the system life cycle; *regional*, additionally focusing on the manufacturing phase of the life cycle (and potentially also recycling and disposal); and *global*, additionally focusing on the extraction and processing phase. As the scale increases, the technical system's material and energetic performance must be evaluated over a broader portion of the life cycle, up to the full life

cycle at the global scale. In this respect, Ulgiati et al. (2011, p.177) highlight that the "value of a given indicator is only 'true' at the scale at which it is calculated." As such, a set of SPIs for a technical system should include SPIs measuring performance at all relevant spatio-temporal scales, given the purposes of the evaluation.

To construct the S-Cycle Performance Matrix, a set of generic sustainability goals for technical systems was first defined using the S-Cycle, a novel and fundamental model of system sustainability described by Hay et al. (2014). These goals focus on the production of output, the use of resources, and the production of waste. Next, SPI archetypes (i.e. generic efficiency and effectiveness indicators) and associated metrics were defined for each of the sustainability goals. These archetypes and metrics were based on the definitions of efficiency and effectiveness provided in the performance literature, and the behavioural aspects described in the S-Cycle model. The validity of the resulting matrix was then tested through analysis of a sample of 42 sources evaluating the sustainability performance of technical systems or elements thereof. A total of 324 indicators were considered. Initially, 88.6% of the indicators in the sample were found to be fully classifiable with respect to the proposed matrix. Of the remaining 11.4%, just under half were found to suggest additional metrics for the proposed SPI archetypes. The other half (19 indicators) were deemed to not be classifiable with respect to the matrix in its current form, for reasons discussed in Section 5. An additional SPI archetype was also identified during the analysis, and certain indicators in the sample were seen to suggest an additional sustainability goal that is not apparent in the S-Cycle model. After incorporating the additional goal, SPI archetype, and metrics into the matrix, a total of 94.1% of the indicators in the sample were found to be fully classifiable. Furthermore, all of the proposed SPI archetypes and associated metrics were observed to be supported in the sample, with the exception of four metrics (two of which are discussed below). On the basis of observations made during the testing of the matrix, three key areas for future research were identified as outlined below.

Firstly, the SPI archetypes initially proposed in relation to a goal to minimise resource use all focused on what are termed passive resources in the S-Cycle model. Simply speaking, these are the material and energetic inputs transformed by a technical system to produce output. However, the additional SPI archetype identified during the analysis focuses on the consumption of what are termed active resources, i.e. the components of the technical system *per se*. This consumption appears to occur through wear and tear during system operation. Although measured at the local scale, this aspect appears to influence material and energetic performance at the regional and global scales owing to the need to manufacture replacement components, i.e. spares (discussed in Section 5.3). Further research is needed to properly understand the nature of these relationships and the SPI *per se*, as well as appropriate metrics to evaluate it.

Secondly, as discussed above, the generic sustainability goals defined using the S-Cycle model focus on the production of output, the use of resources, and the production of waste by a technical system. However, the additional goal that appears to be suggested by certain indicators in the analysis sample focuses on an aspect that is not apparent in the S-Cycle: the potential for system outputs to act as contaminants in other systems and activities, a concept that goes beyond the notion of waste. This potentially highlights a shortcoming in the S-Cycle model. As such, future research is required to explore if and how this aspect should be accommodated in the model. Modelling in this respect may also provide insight into what constitute appropriate SPI archetypes and metrics to measure the contaminating potential of outputs.

Finally, SPI archetypes focusing on the production of resources by a technical system for its own consumption are included in the performance matrix, in relation to a goal focused on maximising the self-sufficiency of the system. Out of three metrics defined to evaluate these SPIs, only one was found to be supported in the analysis sample. The reasons for this are unclear. For instance, it could be that this aspect of behaviour is rarely observed in technical systems and consequently, rarely measured. Alternatively, it is possible that the S-Cycle model incorrectly describes this aspect of behaviour. Further research is needed to clarify these issues, examining both the S-Cycle model and the wider literature on sustainability performance in technical systems.

The S-Cycle Performance Matrix is intended to support the development of a comprehensive set of SPIs for a technical system by highlighting: (i) the different types of efficiency and effectiveness indicator at the disposal of evaluators (i.e. SPI archetypes and associated metrics for technical systems); (ii) the range of sustainability goals that should be covered by the SPIs (i.e. generic sustainability goals for technical systems); and (iii) the different spatio-temporal scales that each of the SPIs may be evaluated at. Furthermore, the matrix is generic and thus may be used in conjunction with any combination of formal evaluation methods, which as shown in Section 3.2, are applicable at different spatio-temporal scales. As discussed above, future work is required to clarify certain aspects of the matrix, and further research is clearly needed to explore its applications in practice. However, the fact that 94.1% of the indicators in the analysis sample were found to be classifiable with respect to the matrix in its present form suggests that the goals, SPI archetypes, and associated metrics are strongly supported in the literature. Thus, we believe that the matrix represents a solid step towards more consistent guidance on what constitutes a comprehensive set of SPIs for a technical system.

The remainder of the paper is organised as follows. In Section 2, the basic concepts and characteristics of performance are outlined. Literature on performance measurement in a business/organisational context is first consulted, before the E^2 model and its associated performance axioms are introduced to provide a more generic view. This discussion reveals the first two criteria for comprehensiveness presented above. In Section 3, the literature on sustainability performance evaluation of technical systems is reviewed. The technical system life cycle is first highlighted as a central concept. In turn, the different spatio-temporal scales at which evaluation may be carried out are delineated, leading to the identification of the third criterion for comprehensiveness presented above. The range of methods and indicators currently used to evaluate sustainability performance in this context are also explored, highlighting differences between methods in terms of their scale of application and material/energetic focus. In Section 4, it is shown that in spite of the need to relate SPIs to goals as identified in Section 2, authors evaluating the sustainability performance of technical systems rarely explicitly state any sustainability goals. This suggests a lack of clarity surrounding their nature and relationship with SPIs. To address this, we apply the S-Cycle model to explain the basic aspects of behaviour that contribute to the sustainability performance of a technical system. We then define a set of generic sustainability goals for technical systems based on these aspects. Section 5 discusses the development and testing of the S-Cycle Performance Matrix. The initial and evolved versions of the matrix are presented, and a discussion is provided on key observations made during the evaluation of the matrix. Areas for future research are also highlighted. The paper concludes with a summary of the work in Section 6.

2. The characteristics of performance

As stated in Section 1, our aim is to develop a *generic* classification of SPIs to guide the selection of a *comprehensive* set for a technical system. To achieve this, we need to understand two key elements: (i) the basic characteristics of performance, i.e. those that are common to different evaluation methods and their associated indicators; and (ii) the criteria that a set of SPIs should meet in order to be considered comprehensive. As highlighted in Section 1 and illustrated in Section 3, a plethora of SPIs are applied to measure the sustainability performance of technical systems, evaluated through different formal and *ad hoc* approaches and focusing on different aspects of performance. Before we consider these, it is necessary to grasp (i) and (ii) – in the words of Neely et al. (2002, p.xii), to "strip away the superfluous terminology and focus on the fundamental concepts."

To this end, in Section 2.1, we explore and define the basic concepts of performance and performance measurement. In doing so, we draw from several authors in the business/organisational management literature. Although this work was conducted in a business context, it has at its base generic definitions of key terms and concepts that may be directly translated to other contexts. Note that the intention here is not to provide a comprehensive review of approaches to performance measurement. Rather, the aim is to present an overview of performance measurement as a general activity and to outline the basic concepts involved. For broad reviews of business performance approaches, readers are referred to Neely et al. (1995) and O'Donnell and Duffy (2005). In Section 2.2, we briefly consider a set of performance axioms described in the literature. That is, a set of basic principles relating to performance "that commends itself to general acceptance" (Oxford English Dictionary, 2014). These axioms, derived from a generic performance model (E^2) and the wider performance literature (O'Donnell and Duffy, 2002), provide insight into the nature of performance indicators and indicator sets. This reveals two criteria for comprehensive SPI sets: (i) inclusion of indicators measuring both efficiency and effectiveness; and (ii) coverage of all sustainability goals governing the technical system being evaluated.

2.1 What is performance measurement?

Much of the underpinnings of performance and performance measurement have been defined in a business/organisational context by the likes of Neely (e.g. Neely et al., 1995; Neely et al., 2002a; and Neely et al., 2002b) and Kaplan and Norton (1992; 1996). As stated above, generic definitions of key terms and concepts may be found at the base of this body of work. Thus, it provides an appropriate reference point for understanding the fundamental concepts of performance and performance measurement. Firstly, Neely et al. (2002a, p.xii) suggest that *performance measurement* "can be defined as the process of quantifying the efficiency and effectiveness of past action," where measurement "is the process of quantification," and efficiency and effectiveness are "the two fundamental dimensions of performance." However, as we show in Section 3.2, it is both possible and at times necessary to evaluate sustainability performance *prospectively*, i.e. to forecast or estimate the performance of *future* actions. Neely et al. (2002b, p.12) provide a slightly different definition of performance measurement, which better accommodates this perspective owing to the absence of any temporal dimension: "Performance measurement is the process of quantifying purposeful action."

Neely et al. (2002a, p.xiii) highlight that with respect to performance measurement, "[the] terms efficiency and effectiveness are used precisely." They define *effectiveness* as referring to "the extent to which stakeholder requirements are met," whilst *efficiency* is "a measure of how economically the firm's resources are utilized when providing a given level of stakeholder satisfaction." Whilst these concepts are defined by Neely et al. (2002a) in business terms, O'Donnell and Duffy (2002; 2005) may be seen to provide a more general view by way of a generic performance model known as E^2 (Figure 1). They suggest that efficiency may be viewed as the relationship between what has been materially gained from an activity and the level of resource used. Effectiveness, on the other hand, refers to the degree to which the result or output from an activity meets the activity's goal. The authors also argue that whilst effectiveness "cannot be measured without specific knowledge of the activity goals," efficiency is inherent in a particular activity. That is, it exists whether it is evaluated or not. Thus, it is possible to measure efficiency without knowing the goals of the activity. However, the goals may affect "the behaviour of resources used in the activity and consequently the level of efficiency resulting from their use" (O'Donnell and Duffy, 2005, p.77).

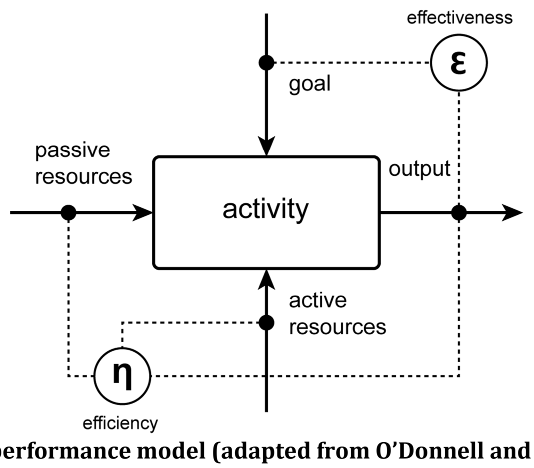


Figure 1. The E2 performance model (adapted from O'Donnell and Duffy 2005, p.79)

With respect to practically measuring performance, Neely et al. (2002b, p.12) define a *performance measure* as "an indicator used to quantify the efficiency and/or effectiveness of a purposeful action." Additionally, Neely et al. (2002a, p.xiii) provide a definition of a *performance metric*: "the definition of the scope, content, and component parts of a broadly-based performance measure." However, the latter acknowledge the breadth of terminology in this respect, remarking that authors may use alternative terms such as "performance indicators" or "performance metrics" to refer to the same concept. For example, Duffy (2005, p.79) appears to use the terms "metric" and "measure" in different senses to those put forth by Neely et al. (2002a, b). He writes that to improve performance, it is necessary to "define appropriate metrics" and "determine their corresponding measures (the actual data used to populate the metrics)." This suggests that a metric is a broad area to be measured, whilst a measure is a specific component of a metric. As will become evident in Section 3.2, the term "performance indicator" appears to be widely used to refer to parameters used to quantify sustainability performance. As such, we will adopt the following terminology throughout the paper, noting instances where other authors may be describing the same concept using different terms. A *performance indicator* is taken to be a parameter used to quantify the efficiency or effectiveness of an action, i.e. equivalent to the concept of a performance measure outlined by Neely et al. (2002a). In line with Neely et al. (2002a), a *performance metric* is defined here as a specification for a broadly based performance indicator, i.e. a definition of the formula and data required to compute a value for the indicator. Finally, drawing from Duffy (2005), we consider a *measure* to refer to an item of data required to compute a value for an indicator as specified in the metric.

In summary, the basic concepts of performance and performance measurement outlined in Section 2.1 may described as follows:

- *performance* refers to the efficiency and effectiveness of an activity/action (Neely et al., 2002a; O'Donnell and Duffy, 2005);
- *efficiency* is the ratio of what has been materially gained to what has been used, whilst *effectiveness* is the degree to which a goal has been met (O'Donnell and Duffy, 2005);
- *performance measurement* is the process of quantifying the efficiency and effectiveness of an activity (Neely et al., 2002a, b);
- a *performance indicator* is taken to be a parameter used to quantify the efficiency or effectiveness of an activity (Neely et al., 2002b);
- a *performance metric* is defined here as a specification for a broadly based performance indicator (Neely et al., 2002a); and
- a *measure* is considered to be an item of data required to compute a value for an indicator (Duffy, 2005).

In addition to the definitions outlined above, three performance axioms may be identified in the literature (O'Donnell and Duffy, 2002). These axioms may be viewed as a set of basic principles relating to performance "that commends itself to general acceptance" (Oxford English Dictionary, 2014). As shown in Section 2.2 below, they provide insight into the nature of performance indicators and indicator sets. In turn, owing to the general nature of the axioms, these insights may be considered to be generally applicable to performance measurement in any context. Their examination reveals two basic criteria that should be met by any set of performance indicators, including SPIs for technical systems.

2.2 Performance axioms

The performance axioms referenced above were derived by O'Donnell and Duffy (2002) from the E^2 model (Figure 1) and the wider performance literature. Briefly, they state that: "activities are the fundamental means that create performance, activities and their management are inextricably linked, and [...] all metrics [i.e. indicators] can be typified to efficiency or effectiveness indicators" (O'Donnell and Duffy, 2002). These are discussed in greater detail below, leading to the identification of two criteria for comprehensive SPI sets for technical systems.

2.2.1 Efficiency and effectiveness

The first axiom of interest states that: "All performance can be measured by efficiency and/or effectiveness. That is, no matter the metric(s) or aspect(s) under consideration, all indicators of performance, no matter how general or specific, will indicate either an efficiency or effectiveness measure" (O'Donnell and Duffy, 2002, p.1218). In turn, O'Donnell and Duffy (2005, p.79) argue that performance "is completely described within the elements of efficiency and effectiveness," and therefore both elements must be measured to obtain "a fully informed view of activity performance." This is supported by others. For instance, Kennerley and Neely (2002, p.149) state that a set of performance measures should include both efficiency and effectiveness measures in order to be "balanced." Neely et al. (1995, p.81) define a performance measurement system as "the set of metrics used to quantify *both* the efficiency and effectiveness of actions [emphasis ours]."

A one-eyed focus on efficiency may mean that gains are achieved at the expense of effectiveness, and vice versa. To illustrate this, consider the performance of a manufacturing system as an example. We may represent the activity carried out by this system using the formalism adopted by O'Donnell and Duffy (2005) in the E^2 model (Figure 1). The manufacturing system (a collection of resources) carries out an activity whereby materials and energy (inputs) are transformed into some kind of product (output), with the goal of maximising the annual output of products, as shown in Figure 2.

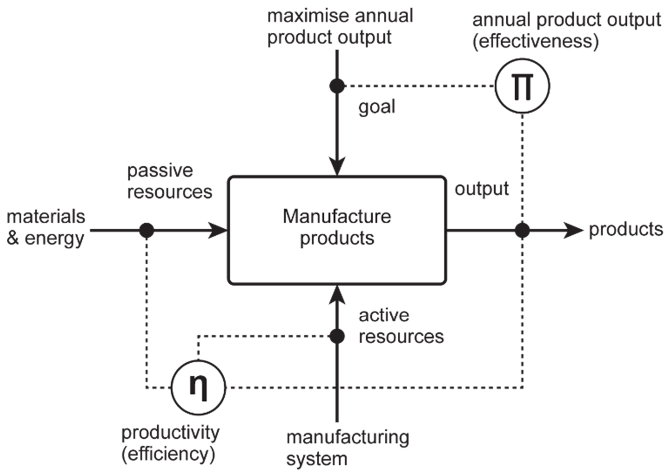


Figure 2. Activity carried out by a manufacturing system

The efficiency of the activity may be measured by an indicator such as productivity, i.e. the number of products produced per unit of materials and/or energy consumed. Given the activity goal, effectiveness may be measured by the number of products produced in a year. In isolation, we may set a target level for the effectiveness measure that appears to be appropriate given our knowledge of the system, the wider business, the customer, and so on. However, without considering the potential productivity inherent in the activity – that is, the potential level of productivity that could be obtained given the attributes of the activity – this level of effectiveness may be produced by a grossly inefficient activity. In contrast, we may evaluate the productivity of the activity, without any knowledge of the target level for the effectiveness measure, and find that the activity is highly efficient in producing products from materials/energy. However, beyond our knowledge, the activity may be producing an output of products either far below or exceeding the target level considered adequate by decision makers. In both cases, it may be seen that measuring one performance component in isolation can yield a misleading view on the overall performance of the activity.

Given that high effectiveness cannot necessarily be inferred from high efficiency and vice versa, it is necessary to measure both elements to fully understand a system's performance (O'Donnell and Duffy, 2005). As we will show in Section 5, the majority of SPIs currently applied to technical systems may indeed be typified to efficiency or effectiveness indicators, although the sets of SPIs currently applied may not always cover both elements. On this basis, we define an initial criterion for comprehensive SPI sets for technical systems:

- *Criterion 1.* A comprehensive set of SPIs for a technical system should include indicators measuring both efficiency and effectiveness.

In Section 2.2.2, we identify a second criterion to complement this by considering the remaining two axioms postulated by O'Donnell and Duffy (2002).

2.2.2 The relationship between indicators and goals

The next two axioms we will consider are stated thus:

i. "Activities are the fundamental means that create performance. […] Other aspects influence the type, definition and behaviour of an activity but it is the activity itself that realises performance"; and
ii. "Activities and their management are inextricably linked. Carrying out an activity will always involve an element of management. Thus, every activity, even at an individual cognitive level, will involve its management" (O'Donnell and Duffy, 2002, pp.1217-1218).

In short: it is fundamentally activities that produce performance (Bourne and Bourne, 2007; Lebas and Euske, 2002; Neely et al., 2002a), and these activities are managed by some decision maker (be it a human or an artificial intelligence system). A key element of managing an activity is setting performance goals (Neely et al., 2002b; O'Donnell and Duffy, 2005). Performance goals essentially define the system behaviour required to deliver a desired level of performance (Hay et al., 2014; Hubka and Eder, 1988; O'Donnell and Duffy, 2005). For example, the production of waste is a key sustainability consideration for technical systems, as shown in Section 4. The ideal performance to be achieved in this area is a waste output level of zero (we make no claims about whether or not this is actually achievable). Thus, a goal such as "minimise waste production" may be defined for the system. We may then take action by, for instance, making changes to the system or its support environment to ensure that it produces less waste in the future (Hay et al., 2014). Note that performance goals can be applied to existing and conceptual systems. For instance, a designer may set the above goal for a conceptual system design and then make changes to the design to minimise its potential waste output (O'Donnell and Duffy, 2005; Russell-Smith et al., 2014).

Of course, setting goals and taking action alone tells us nothing about the effectiveness of our management efforts, and what we need to do if they have not been effective. In this respect, we need information on two aspects: (i) the performance of the system in relation to its goals, to determine whether the goals are being fulfilled as a result of the actions taken; and (ii) the performance of the actions taken to improve system performance, to determine whether they had the effects they were intended to (Dalal-Clayton and Bass, 2002; International Standards Organization, 1999; O'Donnell and Duffy, 2005). As discussed in Section 2.1, a performance indicator may be defined as a parameter used to quantify the performance (i.e. efficiency and effectiveness) of an activity (Neely et al., 2002 a,b). Thus, this information can be obtained through the definition and evaluation of performance indicators – that is, indicators for the system, and indicators for the management actions. The focus of this paper is the former, i.e. SPIs for technical systems. However, the latter is discussed in certain areas of the sustainability performance literature, particularly at the national (Dalal-Clayton and Bass, 2002) and organisational (International Standards Organization, 1999) level. For instance, Dalal-Clayton and Bass (2002, p.309) discuss the need to measure both "sustainability" and the "implementation of the strategy" to achieve it at national level. Nonetheless, exploration of this type of indicator is beyond the scope of this paper and wherever we make reference to "indicator," we are referring to the former type.

The above discussion highlights a key consideration with respect to performance indicators – namely that they should be related to performance goals. That is, those performance goals that are relevant with respect to the focus of the evaluation. A relationship between goals and indicators is supported in the wider literature on performance. For example, as discussed in Section 2.1, O'Donnell and Duffy (2005, p.77) argue that effectiveness "cannot be measured without specific knowledge of the activity goals." This suggests that effectiveness indicators are inextricably tied to goals. The authors also state that efficiency may be viewed as "an inherent property of [an] activity," i.e. it exists "irrespective of whether it is measured or not." However, they also remark that the "selection and application of metrics to determine efficiency allow particular views of efficiency to be created, e.g. cost based efficiency" (O'Donnell and Duffy, 2005, p.73). It seems reasonable to suggest that the desired "views" of efficiency are likely to reflect certain goals of the activity being evaluated. For instance, it is unlikely that one would define an indicator to measure the cost-based efficiency of an activity if the activity has no cost-focused goals. Further support may be identified in the wider literature on organisational performance measurement. For example:

- Bourne and Bourne (2007, p.45) argue that companies "should design measures to support the achievement of the top-level objectives."
- Bourne et al. (2000, pp.757-758) suggest that "the two requirements of the design phase [for performance indicators] are identifying the key objectives to be measured and designing the measures." They highlight that there is "now a strong consensus amongst authors that measures should be derived from strategy."
- Kaplan and Norton (1992, p.73) state that in order to apply their balanced scorecard framework, "companies should articulate goals for time, quality, and performance and service and then translate these goals into specific measures."
- Neely et al. (1995, p.97) argue that, "Performance criteria must be chosen from the company's objectives."
- Neely et al. (2002b, p.69) outline a process for designing and implementing an organisational performance measurement system. One of the aims of Part 3 of this process is to "develop a performance measure for each business objective."

In summary, then: goals define the system behaviour required to achieve certain performance, whilst indicators provide information on whether system behaviour is shifting in the required direction in response to management actions (Hay et al. 2014; O'Donnell and Duffy 2005). In Section 4, we will explore the nature of sustainability performance goals for technical systems. That is, goals focusing on the aspects of behaviour that contribute to a technical system's sustainability performance. However, for now, it is clear that if we want to obtain a fully informed view on the performance of a system from a particular perspective, be it sustainability or something else, we need to define indicators relating to *all* of the relevant performance goals defined for the system. Thus, we may define a second criterion for comprehensive SPI sets for technical systems:

- *Criterion 2.* A comprehensive set of SPIs for a technical system should cover all of the sustainability performance goals defined for the system.

In Section 3, we review the methods currently applied under the umbrella of sustainability performance evaluation in a technical systems context, highlighting their associated indicators. This yields a final criterion for comprehensive SPI sets: inclusion of indicators measuring performance at all relevant spatio-temporal scales, given the purposes of the evaluation.

3. Sustainability performance evaluation of technical systems

In Section 2, we outlined the fundamental concepts and characteristics of performance and performance measurement. That is, those underpinnings that hold true in any context. However, clearly there are particular nuances that will colour performance measurement in specific contexts. In this section, we explore the characteristics of sustainability performance in a technical systems context, highlighting the kind of behaviour typically measured along with the methods and indicators applied.

As highlighted in Hubka and Eder (1988, p.7), technical systems may be viewed as "the "technical means" by which the human achieves his [or her] "ends"." That is, artificial systems designed and built by humans to satisfy the needs of society. In Section 3.1, we illustrate the life cycle of a technical system. In turn, we show that sustainability performance evaluation in this context typically seeks to measure the material and energetic flows associated with a technical system during its life cycle. These flows may be evaluated at local, regional, and/or global scales, each focusing on different life cycle phases. From this discussion, we derive a final criterion for comprehensive SPI sets for technical systems to supplement Criteria 1 and 2 defined in Section 2.

In Section 3.2, we review the range of methods and indicators currently applied to evaluate the sustainability performance of technical systems throughout their life cycle. This reveals that evaluation efforts may be split into two broad categories: (i) those adopting *ad hoc* approaches, relying primarily upon their knowledge of the system and sustainability generally rather than any defined method; and (ii) those applying formal methods, such as life cycle assessment, material flow analysis, and energy analysis. The findings of this review provide an overview of the state of the art, but also provide a basis for developing and testing a generic classification of SPIs for technical systems in Section 5.

3.1 Sustainability performance and the technical system life cycle

As touched upon above, technical systems are developed in response to human needs (Blanchard and Fabrycky, 1981; Hubka and Eder, 1988). Typically, this development is carried out via the processes of engineering design (Eder, 2003; Hubka, 1982) and, particularly in the case of large-scale, complex technical systems, systems engineering (Blanchard and Fabrycky, 1981; Sage, 1992; Stasinopoulos et al., 2009). As noted by Hubka and Eder (1988, p.58), the technical systems developed to meet the needs of society are "practically unlimited in numbers, quantity, and variety." They may be viewed as both outputs of economic production, and key enablers of human activity generally. An overview of some key technical systems employed in major branches of the economy is provided in Table 1, representing a fraction of the total range of technical systems in existence.

Following design and development, a technical system is brought into being through production and manufacturing processes, and enters into its operational life where it will "serve industry and mankind" (Hubka and Eder, 1988, p.27) until it is decommissioned and recycled or disposed of (Stasinopoulos et al., 2009). Collectively, these stages – manufacturing, operation, and recycling and disposal – may be termed the "life cycle" of a technical system, illustrated in Figure 2 (Blanchard and Fabrycky, 1981; Stasinopoulos et al., 2009). Additionally, extraction and processing of the raw materials required to manufacture the system may also be included as a stage preceding manufacture in the life cycle (Adams and McManus, 2014; Ulgiati et al., 2011). Sustainability performance evaluation in this context seeks to measure the material and energetic flows associated with a technical system throughout its life cycle. The nature of these flows is discussed in greater detail in Section 4.1.

Table 1. Examples of technical systems for different economic sectors, adapted from Hubka and Eder 1988, p.94 (see Table 4-1, Section 4.1, Chapter 4 of thesis)

Figure 3. The technical system life cycle (see Figure 4-1, Section 4.1, Chapter 4 of thesis)

Sustainability performance evaluation may be carried out across different portions of the technical system life cycle. For instance, certain authors focus upon performance during the operation phase only (e.g. Aydin et al., 2013; Caliskan et al., 2012; Rotella et al., 2012), whilst others apply methods such as life cycle assessment (discussed in Section 3.2) to evaluate performance across the full life cycle (e.g. Adams and McManus, 2014; Ofori-Boateng and Lee, 2014; Ulgiati et al., 2011). Furthermore, different temporal orientations may be adopted. For instance, the performance of an existing technical system may be evaluated either: (i) retrospectively, i.e. considering past performance during the life cycle (Moss et al., 2014); or (ii) prospectively, i.e. estimating or predicting potential future performance during the life cycle (Russell-Smith et al., 2014). For instance, conceptual systems may be evaluated prospectively during the design process. This allows designers to make changes to improve the performance of the system before it is manufactured, after which it is often difficult to implement further improvements (Park et al., 2005).

In a technical systems context, Ulgiati et al. (2011, p.177) highlight that the life cycle stages outlined above are closely tied to the spatial scale at which material and energetic flows are evaluated. They state that evaluation may be carried out at local, regional, or global scales, with each scale "characterized by well-specified processes" occurring at different life cycle stages:

- the *local* scale involves "final resource use," i.e. the operation of the technical system – here, only the direct material and energetic inputs to and outputs from the system need to be considered;
- the *regional* scale involves "manufacturing and transport of components" – here, the indirect material and energetic inputs/outputs associated with manufacturing and transporting system components must be considered in addition to the direct inputs/outputs above; and
- the *global* scale involves "resource extraction and refining" – here, the indirect inputs/outputs resulting from the extraction and processing of the raw materials consumed to manufacture the components must additionally be considered.

As discussed above, there is a final stage in the technical system life cycle that does not appear to be covered by Ulgiati et al. (2011) – that is, recycling and disposal. In essence, recycling and disposal mirror the manufacturing phase, only they focus on deconstructing the system as opposed to constructing it. Like manufacturing processes, recycling and disposal processes may be considered to occur at the regional scale. However, for a number of technical systems, data on the material and energetic flows associated with recycling and disposal are rather limited. Thus, in certain cases this phase may be excluded from a regional or global scale evaluation of a technical system's sustainability performance (Gurzenich and Wagner, 2004; Hondo, 2005; Raugei et al., 2005).

We may illustrate the different spatio-temporal scales delineated above by considering the notion that all of the processes involved in the technical system life cycle, including the operation of the system *per se*, occur within a wider system of interest (SOI) that provides inputs and receives the outputs produced (Hay et al., 2014; Hubka and Eder, 1988). Essentially, increasing the spatial scale over which sustainability performance is to be evaluated means that: (i) more of the Earth system is included in the SOI; and (ii) the technical system's interactions with this SOI must be considered across a broader portion of the system life cycle, as shown in Figure 4.

Figure 4. The spatio-temporal scales of sustainability performance evaluation (see Figure 4-11, Section 4.3.1, Chapter 4)

Ulgiati et al. (2011, p.177) highlight that the "value of a given indicator is only 'true' at the scale at which it is calculated." In other words, from the perspective of a decision maker, system performance that seems to be sustainable at one spatio-temporal scale may in fact appear to be unsustainable at others. To illustrate, consider the use of non-renewable resources by a solar panel. A solar panel may be viewed as a relatively simple technical system that converts solar energy into electrical energy. At the local scale, we may evaluate the solar panel's use of non-renewable resources and find that it uses none – the only energetic input to the system during its operation is renewable solar energy. For sustainability, the use of non-renewable resources by a technical system should be minimised (Hay et al., 2014), ideally to zero if at all possible (Daly, 1990) (discussed further in Section 4). Thus, at the local scale, the panel's use of non-renewable resources appears to be sustainable. However, if we evaluated the same aspect of performance at the regional scale, we would likely obtain a rather different picture. The manufacture of solar panels involves non-renewable and scarce metals (Silicon Valley Toxics Coalition, 2009) and is likely to be driven by fossil fuels, which are also non-renewable. Furthermore, solar panels require rather intensive processing in order to be recycled and/or disposed of at the end of their life cycle (PV Cycle UK, 2013). Again, this is likely to be driven by fossil fuels. Thus, whilst the panel's use of non-renewable resources appears to be sustainable at the local scale, it seems far less so at the regional scale.

It can be seen from the above that the sustainability performance of a technical system may be interpreted differently depending on the spatio-temporal scale of the evaluation. Ulgiati et al. (2011, p.187) suggest that "a selection of many indicators is needed in order to have a comprehensive evaluation across space and time scales." Of course, evaluations of a technical system's sustainability performance may be carried out for different reasons. For example, the intention may be to identify areas where technical changes could potentially be made to the system to improve aspects such as energy efficiency and consumption during its life in service (Aydin et al., 2013). In this case, evaluation at the local scale is likely sufficient. In other cases, it may be desired to understand what phase in a system's life cycle is associated with the worst sustainability performance (Park et al., 2005). This is likely to entail evaluation at the regional and possibly also global scales. As such, it may not always be necessary to consider indicators at *every* scale outlined above. However, it *is* necessary to consider indicators that are sufficiently comprehensive in this respect given the purposes of the evaluation. On this basis, we may define a final criterion for comprehensive SPI sets for technical systems:

- *Criterion 3.* A comprehensive set of SPIs for a technical system should include indicators measuring performance at all relevant spatio-temporal scales, given the purposes of the evaluation.

Ulgiati et al. (2011, p.177) suggest that different "[evaluation] method[s] may supply a piece of information about system performance at an appropriate scale, to which the others do not apply." Thus, it may be seen that one way to achieve comprehensiveness with respect to Criterion 3 is to combine the indicators associated with different evaluation methods applicable at different scales. For example, Ulgiati et al. (2006, 2011) present an integrated evaluation approach known as SUMMA (Sustainability Multi-method Multi-scale Assessment), in which several evaluation methods applicable at different scales are applied complementary to each other. Decision makers may select appropriate indicators from each method to obtain a view on the system's performance, according to the purposes of their assessment. In Section 3.2 below, the range of evaluation methods and indicators currently applied to technical systems is briefly reviewed, highlighting differences among them in terms of their scale of application.

3.1 Major evaluation methods and associated indicators

As discussed in Section 3.1, the major aim of sustainability performance evaluation in a technical systems context is to evaluate the material and energetic flows associated with a technical system during its life cycle. In practice, authors carrying out this kind of performance evaluation may be broadly split into two categories: (i) those applying *ad hoc* approaches; and (ii) those applying formal evaluation methods. Each category is briefly discussed below, before an overview of the major formal methods and their associated indicators is provided in Sections 3.2.1 – 3.2.6.

Category (i) refers to authors who appear to define and evaluate SPIs for technical systems based on their knowledge of the system rather than any predefined method. A selection of several authors applying this kind of approach is presented in Table 2. Although the specific material and energetic aspects measured are different in a number of cases, similarities may be detected with respect to the broad areas being measured: emissions and waste products, energy efficiency, and material/energy consumption. For those systems evaluated at the local scale, these include only direct inputs and outputs. For those systems evaluated at regional and global scales, they include both direct and indirect inputs and outputs, as discussed in Section 3.1. In a couple of cases, the useful output of the system also seems to be measured. For instance, Chandrasekaran and Guha (2012) measure the net thrust produced by a turbofan engine, and Bianchi et al. (2014) consider the "electric power size" of a combined heat and power plant – that is, the electrical output capacity of the plant.

Table 2. A selection of authors applying ad hoc approaches to evaluating the sustainability performance of technical systems (see Table 4-5, Section 4.3.1, Chapter 4 of thesis)

With respect to category (ii) above, Ness et al. (2007) provide a review of tools and methods for assessing sustainability. Under the umbrella of product-related assessment, they highlight several methods that, as shown in Table 3 below, are commonly applied to technical systems, namely: life cycle assessment; material flow analysis; energy analysis; exergy analysis; and emergy accounting. None of these methods are claimed to be comprehensive with respect to sustainability performance. However, they all focus on the material and/or energetic flows associated with a technical system at varying spatio-temporal scales. Thus, they are frequently presented as useful for assessing the sustainability performance of technical systems. As shown in Table 3, the nature of the indicators associated with each method depends primarily upon its particular material and/or energetic perspective. These perspectives, and the basic procedures involved in each method, are briefly summarised in Sections 3.2.1 – 3.2.6 below.

3.1.1 Life cycle assessment

According to Russell-Smith et al. (2014, p.1), the purpose of life cycle assessment (LCA) is "to quantify the energy and material flows associated with each life cycle stage from raw material extraction through material processing, manufacture, distribution, use and maintenance, and end-of-life for a given product or service." LCA has been standardised by the International Standards Organisation in ISO 14040 and 14044 (Ulgiati et al., 2011), and involves four procedural steps: (i) goal and scope definition; (ii) life cycle inventory analysis; (iii) life cycle impact assessment; and (iv) interpretation of results (Ofori-Boateng and Lee, 2014). Impact indicators are typically associated with LCA, although authors may be seen to evaluate other types of indicator under a life cycle perspective, i.e. considering performance throughout the full life cycle (e.g. Ulgiati et al., 2011). Impact indicators are appended with '[I]' in Table 3. These indicators focus on various environmental aspects (e.g. climate change, acidification, eutrophication, ozone depletion, and so on), and are evaluated by assigning material/energetic flows to impact categories and converting them to equivalent units so that they may be compared and consolidated (SAIC, 2006). Impact indicators are typically evaluated at either:

Table 3. Formal sustainability performance evaluation methods applied to technical systems, and associated indicators (see Table 4-6, Section 4.3.2, Chapter 4 of thesis)

3.1.2 Material flow analysis

According to Raugei et al. (2005, p.124), the purpose of material flow analysis (MFA) is "to evaluate the environmental disturbance associated with the withdrawal or diversion of resources from their natural ecosystemic pathways." Material intensity (MI) indicators are typically associated with MFA (Raugei et al., 2005; Ulgiati et al., 2011), and may be viewed as global scale indicators (Ulgiati et al., 2006). To evaluate MI indicators, data is first gathered to quantify the material flows into a system. Each flow is then multiplied by predefined material intensity factors to account for "the total amount of abiotic matter, water, air and biotic matter that is directly or indirectly required in order to provide that […] input to the system" (Raugei et al., 2005, p.124). Finally, for each material category the material intensity values calculated for the input flows are summed to yield total values for the categories (i.e. abiotic material, biotic material, air, and water). These indicators are intended to provide a "quantitative measure of [the system's] cumulative environmental burden" with respect to each category (Ulgiati et al., 2006, p.435). Additional indicators may also be defined and evaluated by authors applying MFA, e.g. global to local ratios of material intensities, and material intensities per unit of output (Ulgiati et al., 2011) as shown in Table 3.

3.1.3 Energy analysis

Two types of energy analysis approach may be identified in the literature on sustainability performance evaluation. The first, simply termed "energy analysis" (EnA) in Table 3, is typically carried out at the local scale, focusing on the energy consumed directly by a system during its operation (Balta et al., 2010). EnA typically involves writing thermodynamic energy balances or developing quantitative models of the system (Balta et al., 2010; Caliskan et al., 2012; Waheed et al., 2014), and evaluating indicators focusing on aspects such as energy efficiency (Söğüt et al., 2012), energy input (Caliskan et al., 2011b), and energy losses (Waheed et al., 2014) as shown in Table 3. Indicators focusing on emissions, particularly CO2, may also be evaluated as part of EnA (Caliskan et al., 2012). In certain cases, indicators focusing on system-specific aspects may also be defined, e.g. wet bulb effectiveness for cooling systems (Caliskan et al., 2012), as shown in Table 3. EnA is commonly combined with exergy analysis (e.g. (Balta et al., 2010; Caliskan et al., 2012), another local scale method, which is discussed below.

3.1.4 Embodied energy analysis

The second type of energy analysis approach identifiable in the literature is known as embodied energy analysis (EEA). According to Ulgiati et al. (2006, p.435), EEA "deals with the gross (direct and indirect) energy requirement of the analysed system." Unlike EnA, EEA is carried out at the global scale, considering the full life cycle (Ulgiati et al., 2006). The indicators typically associated with EEA include oil equivalents for the material and energy inputs to the system, total oil equivalent applied, and the Gross Energy Requirement (GER) (Buonocore et al., 2012) as shown in Table 3. To calculate oil equivalents, data is first gathered on the material and energetic inputs to the system. Each input is then multiplied by an oil equivalent factor to determine its equivalent magnitude in terms of grams of oil per unit of input. The cumulative oil equivalent is then the sum of the oil equivalents for individual inputs (Buonocore et al., 2012; Ulgiati et al., 2006). According to Ulgiati et al. (2006, p.435), the GER expresses "the total commercial energy requirement of one unit of output in terms of equivalent Joules of petroleum." Buonocore et al. (2012, p.74) suggest that only non-renewable inputs should be included in the evaluation of GER, as it is "concerned with the depletion of fossil energy." Energy efficiency indicators may also be associated with EEA, as shown in Table 3. In this respect, Ulgiati et al. (2006, p.435) suggest that the method "offers useful insight on the first-law energy efficiency of the analysed system on the global scale." This may be contrasted with EnA above, which evaluates energy efficiency at the local scale.

3.1.5 Exergy analysis

Gasparatos et al. (2009, p.957) define exergy, or "available energy," as "the maximum work that can be extracted from a system when this system moves towards thermodynamic equilibrium with a reference state." In short, exergy accounts for the "usefulness or quality or potential to cause change" inherent in a particular energy form. According to Balta et al. (2010, p.1320), exergy analysis (ExA) therefore enables "the locations, types, and true magnitudes of wastes and losses [in a system] to be determined," leading to "more efficient energy-resource use." ExA typically involves writing exergy balances or developing quantitative models of the system being evaluated (Caliskan et al., 2011b; Waheed et al., 2014), in a similar vein to EnA discussed in Section 3.2.3. A key indicator associated with ExA is exergy efficiency (Balta et al., 2010; Rosen and Dincer, 2001), also known as second law efficiency (Hepbasli, 2008; Raugei et al., 2005). Certain authors suggest a direct relationship between exergy efficiency and environmental impact (e.g. Gasparatos et al., 2009; Rosen and Dincer, 2001), with increased exergy efficiency corresponding to reduced impact (although others are more cautious in this respect, e.g. Ulgiati et al. (2006)). As shown in Table 3, a range of other indicators may be evaluated through ExA, focusing on similar aspects to the energy indicators discussed above e.g. exergy input and exergy losses (Caliskan et al., 2012; Waheed et al., 2014). As noted above, ExA may be applied in conjunction with EnA (e.g. (Caliskan et al., 2012; Waheed et al., 2014), to obtain views on both the first and second law efficiencies of a system. Like energy analysis, ExA is typically viewed as a local scale method, focusing primarily on performance during the operation phase (Ulgiati et al., 2006). However, certain authors may be observed to carry out exergy analysis from a life cycle perspective, i.e. considering all life cycle stages (Ofori-Boateng and Lee, 2014).

3.1.6 Emergy accounting

The final method commonly applied to evaluate the sustainability performance of technical systems is emergy accounting (EmA), sometimes called emergy analysis (Moss et al., 2014). Like EnA, EEA, and ExA above, EmA is an energy-based method (Ness et al., 2007). According to Ulgiati et al.

(2006, p.435), EmA "looks at the environmental performance of the system on the global scale." However, in comparison to the other major global scale energy-based method, i.e. EEA, EmA is broader in scope, "taking into account all the free environmental inputs such as sunlight, wind, rain, as well as the indirect environmental support embodied in human labour and services." Moss et al. (2014, p.392) state that EmA employs various environmental indices to quantify and compare "the contribution of renewable and non-renewable components of labor, materials, and feedstocks" to a system, in order to "determine the ability of a system or process to efficiently and sustainably produce products over time." Key indicators associated with EmA include a range of indices relating the renewable and non-renewable aspects touched upon above, including the Environmental Loading Ratio and the Emergy Yield Ratio (Buonocore et al., 2012; Moss et al., 2014). Also associated with EmA is the Emergy Sustainability Index, which essentially relates the emergy yielded by a system to the system's environmental burden (Moss et al., 2014). To evaluate emergy indices, all flows of material and energy into a system must first be accounted for "in terms of their solar emergy, defined as the total amount of solar available energy (exergy) that was directly or indirectly required to make a given product or to support a given flow, and measured in solar equivalent Joules (seJ)." Measuring the total emergy requirement of the system provides "an indication of the total appropriation of environmental services" by the system (Ulgiati et al., 2006, pp.435-436).

4. Sustainability performance goals for technical systems

In Sections 2 and 3, we considered the basic characteristics of performance, and some of the nuances of sustainability performance evaluation in a technical systems context. On the basis of this investigation, we defined three criteria that SPI sets for technical systems should meet in order to be considered comprehensive. To recap, these are:

- *Criterion 1.* A comprehensive set of SPIs for a technical system should include indicators measuring both efficiency and effectiveness.
- *Criterion 2.* A comprehensive set of SPIs for a technical system should cover all of the sustainability performance goals defined for the system.
- *Criterion 3.* A comprehensive set of SPIs for a technical system should include indicators measuring performance at all relevant spatio-temporal scales, given the purposes of the evaluation.

In Section 3.2, we also reviewed the range of methods and indicators commonly applied to evaluate the sustainability performance of technical systems. These include both *ad hoc* approaches relying primarily upon system knowledge, and formal methods with defined procedures and/or indicators i.e.: life cycle assessment; material flow analysis; energy analysis; embodied energy analysis; exergy analysis; and emergy accounting. A salient point that was not highlighted in Section 3 is that authors evaluating the sustainability performance of technical systems rarely explicitly state any sustainability performance goals. For example, in Section 5.2 we will outline a sample of 42 sources evaluating the sustainability performance of technical systems (or at least elements thereof). Of these, only three sources were observed to state goals: Chandrasekaran and Guha (2012); Coelho et al. (2012); and Russell-Smith et al. (2014). Of course, we cannot determine if goals were implicitly acknowledged by authors during their evaluation efforts. Nonetheless, the absence of stated goals at least suggests a lack of clarity with respect to the nature of sustainability performance goals for technical systems and their relationship with SPIs. In turn, it is rather difficult to build a classification of SPIs to help decision makers fulfil Criterion 2 above without any appreciation of the general nature of sustainability goals in this context. As such, we will address this point in the following sections.

It is clear that in human efforts towards sustainability in any context, the ultimate goal is "sustainability" *per se*. The achievement of this goal then hinges upon the achievement of a number of sub-goals. It is the nature of these sub-goals that form the major focus of this section; however, before we can understand what they are, we need to understand what we are trying to achieve overall. Thus, in Section 4.1, we explore the meaning of sustainability in a technical systems context, identifying the central target to be sustained on the basis of human needs and values. As discussed in Section 2.2.2, performance goals define the system behaviour required to deliver a desired level of performance. On this basis, sustainability goals may be viewed as goals defining the system behaviour required to achieve a desired level of sustainability performance. In Section 4.2 we introduce a generic sustainability model described in the literature, known as the S-Cycle. We apply this model to illustrate the broad aspects of material and energetic behaviour that fundamentally contribute to the sustainability performance of a technical system throughout its life cycle. In turn, we outline a set of generic sustainability performance goals for technical systems based on these aspects in Section 4.3.

4.1 Defining technical system sustainability

As discussed in Section 3, technical systems are ubiquitous throughout society and the economy (Hubka and Eder, 1988). The concept of sustainability is similarly pervasive, with roots in a number of disciplines including ecology, economics (Kidd, 1992; Quental et al., 2010), and forestry (Wiersum, 1995). In recent years, its application has spread to diverse areas such as agriculture (Darnhofer et al., 2010), business (Hannon and Callaghan, 2011), design (Chapman, 2011), fishery (Standal and Utne, 2011), manufacturing (Schönsleben et al., 2010), socio-economic development (UNDP, 2011; WCED, 1987), and urban planning (Pierce et al., 2011), among others. In general terms, sustainability simply means the ability to sustain (Kajikawa, 2008), maintain (Lele and Norgaard, 1996), or continue something over time (Shearman, 1990). More precise definitions may be formulated by specifying a target to be sustained in a particular context, a decision that ultimately hinges upon what people value (Hay et al., 2014; Lele and Norgaard, 1996). Thus, to understand the specific meaning of sustainability in a technical systems context, we must first examine what facets of these systems humans consider to be fundamentally valuable, and therefore wish to sustain.

As discussed in Section 3, technical systems are developed in response to human needs. These needs are actively met during the operation phase of the life cycle, where the system carries out the *function(s)* it was designed for. Function refers to 'what the technical system is for' (Gero and Kannengiesser, 2004). A technical system fulfils its function by exhibiting a certain kind of purposeful behaviour (Hubka and Eder, 1988; Wang et al., 2008). Hubka and Eder (1988) demonstrate that on a basic level, this purposeful behaviour may be described as the conversion of inputs to outputs, both of which may be material, energetic, or informational in nature (Blanchard and Fabrycky, 1981). As discussed in Section 3, the focus is primarily upon materials and energy in a sustainability context.

The inputs to and outputs from a technical system may "contain both desired and unwanted elements" (Hubka and Eder, 1988, p.26). These will be outlined in more detail in Section 4.2. However, among the desired outputs is the particular output that the system produces in order to fulfil its function. This may be termed the system's "intended output" (Hay et al., 2014; Hubka and Eder, 1988). Hubka and Eder (1988, p.27) suggest that the function of a technical system may be described as "what it should and can do when it is made to work." Along these lines, we may view the system's intended output as 'what it can and should *produce* when it is made to work.' To illustrate this concept, consider an air conditioning system. The function of this system may be described as 'produce and distribute cool air.' To fulfil this function, the system converts material and energetic inputs including warm air, electricity, and a cooling medium into an output consisting of a flow of cool air and certain unwanted byproducts. The system's intended output in this case is a flow of cool air; if this output is not produced, then the system is not fulfilling its function. Note that a complex technical system may have both multiple functions and multiple intended outputs (Hubka and Eder, 1988).

In summary, technical systems satisfy human needs by fulfilling desired functions through certain purposeful behaviour. This behaviour can be more precisely described as the *production of intended output*. We argue that it is this facet of technical systems that is most fundamentally valuable to humans: if the production of intended output ceases, the system will no longer be fulfilling its function and therefore, human needs will not be satisfied. On this basis, technical system sustainability is defined here as *the ability of a technical system to continue producing its intended output over time*. A list of technical systems commonly discussed in the sustainability performance literature, alongside their inferred functions and intended outputs, is presented in Table 4.

Table 4. Inferred functions and intended outputs for technical systems discussed in the sustainability performance literature

Technical system	Inferred function	Inferred intended output	Source
Buildings and structural systems:			
Educational building	Provide shelter for people and other entities	Inhabitable structure	Russell-Smith et al. (2014)
Residential building	Provide shelter for people and other entities	Inhabitable structure	Thiers and Peuportier (2012)
Ceiling structure	Maintain barrier between internal space and external surroundings	Weathertight barrier	Antony et al. (2014)
Windows	Maintain barrier between internal space and external surroundings	Weathertight barrier	Asif and Muneer (2014)
Energy conversion systems:			
Waste-to-energy plant	Transform waste to electrical and heat energy	Electrical and heat energy	Coelho et al. (2012)
Wind farm	Transform kinetic energy to electrical energy	Electrical energy (to national grid)	Denholm et al. (2005)
Wind turbine	Transform kinetic energy to electrical energy	Electrical energy (to wind farm storage)	Uddin and Kumar (2014)
Various types of combined heat & power plant	Transform materials and energy to electrical and heat energy	Electrical and heat energy	Adams and McManus (2014); Bianchi et al. (2014); Buonocore et al. (2012); Chicco and Mancarella (2008); Rosato et al. (2013); Rosato et al. (2014 a,b); Ulgiati et al. (2011)
Ground source heat pump	Transfer heat from a source to a sink	Heat energy (to sink)	Balta et al. (2010); Caliskan et al. (2011b)
Various types of solar PV system	Transform solar energy to electrical energy	Electrical energy	Evans et al. (2009); Kim et al. (2014); Pacca et al. (2007)
Molten carbonate fuel cell	Transform chemical energy to electrical energy	Electrical energy	Raugei et al. (2005)
Fuel production systems:			
Biorefinery	Transform biomass to bioethanol	Bioethanol	Ofori-Boateng and Lee (2014)
Anaerobic digestion system	Transform organic matter to biogas and water	Biogas	Moss et al. (2014)
Heating and cooling systems:			
Air conditioning system	Produce and distribute cool air	Flow of cool air	Abdel-Salam and Simonson (2014); Caliskan et al. (2011a); Caliskan et al. (2012); Shah et al. (2008)
Residential heating system	Produce and distribute heat energy	Heat energy carried by a fluid flow (e.g. water)	Shah et al. (2008)
Solar collector	Transform solar energy to	Heat energy	Balta et al. (2010)

	heat energy		
Various types of boiler	Heat a particular fluid (e.g. water)	Heated fluid (e.g. steam)	Balta et al. (2010)
Machining and industrial processing systems:			
Hard machining system	Transform workpieces to useful components	Useful materials and components	Rotella et al. (2012)
Coal preparation unit	Grind coal for use in production processes	Grinded coal	Söğüt et al. (2012)
Propulsive and transportation systems:			
Car	Move people and other entities from one position to another	Velocity and displacement	Agarski et al. (2012)
Turboprop engine	Produce thrust	A certain level of thrust	Aydin et al. (2013)
Turbofan engine	Produce thrust	A certain level of thrust	Chandrasekaran and Guha (2012)
Compression ignition engine	Produce torque	A certain level of torque	Rahman et al. (2014)
Refining and distillation systems:			
Reverse osmosis desalination plant	Transform saltwater to fresh water	Fresh water	Shahabi et al. (2014)
Crude oil distillation unit	Transform crude oil to useful oil- and gas-based products (e.g. diesel and naphtha)	Useful oil- and gas-based products	Waheed et al. (2014)
Azeotropic distillation column	Dehydrate alcohol	Ethanol and water	Li et al. (2012)

4.2 Aspects of behaviour contributing to the sustainability performance of technical systems

As discussed previously, sustainability goals may be viewed as goals defining the system behaviour required to achieve a desired level of sustainability performance. The S-Cycle (Figure 5) is a novel and fundamental model describing the behaviour of a system operating within a wider SOI, from a sustainability perspective. That is, highlighting the basic material and energetic aspects of behaviour that affect system sustainability and should therefore form the focus of sustainability goals. The model was developed from literature spanning multiple sectors (Hay et al., 2014), and has been validated through application to a complex technical system in the marine sector (Hay, 2014). Thus, we may apply it here to briefly outline the behaviour contributing to the sustainability performance of a technical system throughout its life cycle. Readers are referred to Hay et al. (2014) for a detailed explanation of the model and its development.

Figure 5. The S-Cycle model (see Figure 6-5, Section 6.5.1, Chapter 6 of thesis)

In Section 2.2.2, it was shown that *activities* fundamentally generate performance. Appropriately, the S-Cycle model adopts an activity formalism to represent system behaviour. An activity is a goal-directed physical or cognitive action (as stated in Section 2.2.2), where active resources use passive resources to produce an output that satisfies the goal(s) of the activity (Boyle et al., 2009). Active resources carry out the processing, whilst passive resources are the inputs being processed. According to the S-Cycle model, there are three key material/energetic aspects of a technical system's behaviour that affect its sustainability within a wider SOI. Each of these aspects focuses on a different kind of input or output, as shown below (note that the following discussion is drawn from Hay et al. (2014)).

Perhaps the most obvious aspect affecting sustainability is the production of intended output, given the definition of technical system sustainability provided in Section 4.1. The continued production of intended output by a technical system during the operation phase of its life cycle, i.e. at the local scale, depends fundamentally upon the availability of the passive resources (PR) it directly consumes in order to carry out its activity (with the system representing the active resource).

However, as discussed in Section 3.1, sustainability performance evaluation may also be carried out at regional and global scales. At these scales, the PR indirectly consumed to manufacture and extract the materials for the system in the first place must also be taken into account, in addition to direct inputs (Ulgiati et al., 2011). Both direct and indirect PR inputs originate from stocks within the wider SOI that, as shown in Figure 5, may be renewable (RR, i.e. regenerate over time) or non-renewable (NRR, i.e. do not regenerate significantly over time) in nature. Direct PR inputs may also be produced by the technical system's activity *per se*, i.e. intended resources as shown in Figure 5. The availability of a particular type of RR or NRR at a given time depends on the ratio between the consumption and regeneration rates of the stock. Given that multiple systems may be consuming and contributing to the same stock simultaneously, these rates may not always be straightforward or even possible to measure (although the rate at which an individual system consumes a resource can of course be measured).

In addition to the desirable system outputs discussed above, waste may also be produced as shown in Figure 5. In the same vein as direct resource inputs, a technical system may produce direct waste outputs during the operation phase of its life cycle, i.e. at the local scale. However again, at the regional and global scales, the indirect waste outputs produced during manufacturing and extraction/processing of materials for the system must additionally be accounted for. Both direct and indirect waste outputs must be processed within the wider SOI, to avoid accumulations that can potentially disrupt the functioning and in turn, sustainability of systems operating within the SOI. The magnitude of a certain waste accumulation at a given time depends on the ratio between the production and processing rates for that type of waste. Again, given that multiple systems and processes are likely to be involved, these rates may be difficult to measure.

4.3 A set of generic sustainability performance goals for technical systems

In Section 4.2, it was shown that the following aspects of behaviour contribute to the sustainability performance of a technical system: (i) the production of intended output; (ii) the use of renewable and non-renewable resources; (iii) the production and use of intended resources; and (iv) the production of waste. On the basis of these, we may now outline a set of generic sustainability goals for technical systems. That is, goals that may be viewed as generally applicable to all technical systems.

Firstly, in Section 4.1, technical system sustainability was defined as a system's ability to continue producing its intended output over time. As shown in Section 4.2, this ability is realised during the operation phase of the life cycle, i.e. at the local scale, where the technical system operates. As briefly discussed in Section 3.2, certain authors may indeed be seen to measure the production of intended output when evaluating the sustainability performance of technical systems. Thus, we may define the following high-level sustainability goal:

- *Produce intended output*, since this is the valuable target to be sustained for a technical system. A failure to continue producing intended output over time indicates a loss of sustainability.

In turn, the continued production of intended output hinges upon the availability of passive resources and the prevention of excessive waste. Accordingly, Hay et al. (2014) outline three general sustainability goals focusing on these aspects (based on the work of Daly (1990, 1992)), which may be directly translated to technical systems:

- *Minimise use of non-renewable resources*, since their continued availability cannot be guaranteed owing to the fact that they do not regenerate significantly over time.
- *Minimise use of renewable resources*, since their availability may be compromised if consumed faster than stocks can regenerate.
- *Minimise waste produced*, since harmful accumulations may develop in the wider SOI if waste is produced faster than it can be processed.

Unlike the intended output goal above, these goals may focus on behaviour at the regional and global scales as well as the local scale, depending on the purposes of the evaluation. That is, considering resource inputs and waste outputs consumed and produced indirectly during other life cycle phases in addition to those consumed and produced directly during the operation phase (as discussed in depth in Section 3.1).

It is wise to manage the use of renewable and non-renewable resources separately owing to the differing regeneration rates of the respective stocks. Since non-renewable stocks do not regenerate significantly over time, non-renewable resources should not be consumed at all wherever possible. However, because renewable stocks do regenerate, the consumption of renewable resources is permissible providing the stock's regeneration rate is respected (Daly, 1990; Hay et al., 2014). In short: the goal to minimise non-renewable resource use is more restrictive than its sister goal pertaining to renewable resources. Nonetheless, given that both goals seek to minimise the use of resources, they may be combined to form a parent goal:

- *Minimise overall resource use*, i.e. the use of both renewable and non-renewable resources.

Like its sub-goals, this goal may focus on behaviour at local, regional, and global scales.

Additionally, the S-Cycle model suggests a further goal that is not highlighted in Hay et al. (2014). As discussed in Section 4.2, a technical system may also produce its own passive resources, i.e. intended resources. As shown in Figure 5, the production and use of intended resources may reduce the system's reliance upon external resource stocks (Zhang et al., 2011). In other words, its self-sufficiency may be increased. Self-sufficiency is desirable from a sustainability perspective, because it affords a technical system a degree of protection from external shocks and disturbances to resource supplies that could potentially disrupt the production of intended output (Darnhofer et al., 2010; Urban et al., 2010). On this basis, the following goal may be defined:

- *Maximise self-sufficiency*, to minimise the impact of external shocks and disturbances on intended output production.

Given that by nature, intended resources are those produced by a technical system for its own use, it may be seen that this goal focuses solely on performance at the local scale, i.e. during the operation phase (like the intended output goal defined above).

As discussed throughout this paper, our aim is to develop a generic classification of SPIs to guide the selection of a comprehensive set for a technical system. On the basis of the literature covered in Sections 2 and 3, we defined three criteria for comprehensive SPI sets in a technical systems context: (i) inclusion of both efficiency and effectiveness indicators; (ii) coverage of all sustainability goals governing the system; and (iii) inclusion of indicators measuring performance at different spatio-temporal scales. According to O'Donnell and Duffy (2002, p.1219), all performance indicators "can be typified to efficiency or effectiveness indicators," regardless of the specific aspects they measure. In turn, highlighting basic *types* of SPI that may be defined in relation to each of the generic goals outlined above could foster the development of comprehensive SPI sets, by making explicit: (i) the range of sustainability goals that should be covered for a technical system; and (ii) the range of efficiency and effectiveness indicators at the disposal of evaluators. Furthermore, a generic matrix of this nature could be used in conjunction with any combination of evaluation methods. Given that different methods are applicable at different scales as discussed in Section 3.2, this would facilitate the construction of SPI sets covering performance at different spatio-temporal scales if necessary. These ideas form the basis of the S-Cycle Performance Matrix, which is presented and discussed in Section 5.

5. The S-Cycle Performance Matrix

As discussed in Section 1 and elaborated upon in Section 3, a plethora of SPIs are applied to measure the sustainability performance of technical systems, evaluated through different formal and *ad hoc* approaches and focusing on different aspects of performance. The fact that all of these different indicators are applied does not, of course, necessarily mean that any of them are wrong or irrelevant. However, the lack of consistency among different methods and different authors does raise a rather fundamental question: what type and range of SPIs constitute a comprehensive set for a technical system? The need for answers to this question is further strengthened by the observation that none of the formal evaluation methods outlined in Section 3 claim to be comprehensive with respect to sustainability performance. Thus, applying these predefined methods may not necessarily result in a comprehensive set of SPIs. In a corporate context, the GRI guidelines provide consistent guidance on comprehensive SPIs for organisations whilst leaving the choice of evaluation method up to the assessors. However, there is a lack of any overarching guidance of this nature in a technical systems context.

To address this shortcoming, we sought to develop a *generic* classification of SPIs to guide the selection of a *comprehensive* set for a technical system. From the literature covered in Sections 2 (fundamental characteristics of performance), 3 (sustainability performance evaluation of technical systems), and 4 (sustainability goals for technical systems), we now have the underpinnings of such a classification. That is:

- knowledge of the basic characteristics of performance and performance measurement, i.e. essentially: (i) the nature of performance as the efficiency and effectiveness of an activity (Neely et al., 2002; O'Donnell and Duffy, 2005), and (ii) the nature of performance indicators as parameters used to quantify the efficiency and effectiveness of activities (Neely et al., 2002 a,b) (Section 2.1);
- three criteria a set of SPIs should meet in order to be comprehensive, i.e.: (i) inclusion of indicators measuring both efficiency and effectiveness (Section 2.2.1), (ii) coverage of all sustainability goals governing the system (Section 2.2.2), and (iii) inclusion of indicators measuring performance at all relevant spatio-temporal scales, given the purposes of the evaluation (Section 3.1); and
- a set of generic sustainability performance goals for technical systems derived from a generic sustainability model (the S-Cycle), i.e. goals focusing on the fundamental aspects of behaviour contributing to a technical system's sustainability performance, that can be translated to different systems on the basis of their specific behaviour (Section 4.3).

In the following sections, we will discuss the development, testing, and applications of a generic SPI classification known as the S-Cycle Performance Matrix. Firstly, in Section 5.1, we discuss how the matrix was developed via a process of induction from the literature and the S-Cycle model (Figure 5, Section 4.2). Next, in Section 5.2, we outline how the matrix was evaluated through an analysis of 324 indicators discussed in the literature on sustainability performance evaluation of technical systems. Finally, in Section 5.3, we discuss the key observations from the evaluation and highlight future work required to clarify certain aspects.

5.1 Matrix development

In full, the three criteria for comprehensive SPI sets derived from the literature in Sections 2 and 3 may be stated as:

- *Criterion 1.* A comprehensive set of SPIs for a technical system should include indicators measuring both efficiency and effectiveness (Section 2.2.1).
- *Criterion 2.* A comprehensive set of SPIs for a technical system should cover all of the sustainability goals defined for the system (Section 2.2.2).
- *Criterion 3.* A comprehensive set of SPIs for a technical system should include indicators measuring performance at all relevant spatio-temporal scales, given the purposes of the evaluation (Section 3.1).

The S-Cycle Performance Matrix is a set of SPI archetypes and associated metrics for technical systems, covering each of the fundamental sustainability goals defined in Section 4.3. The matrix was developed via a process of induction from the literature covered in Sections 2 and 3, and the S-Cycle model introduced in Section 4.2 (Figure 5). The matrix is presented in Table 5 below.

As discussed in Section 2.1, *effectiveness* is the degree to which an activity goal has been met, whilst *efficiency* is the ratio between what has been materially gained from an activity and what has been used. Furthermore, efficiency is an inherent property of an activity. As such, O'Donnell and Duffy (2005, p.73) suggest that efficiency indicators should closely reflect "the actual types of efficiencies that are inherent in the activity." Thus, to define the SPI archetypes presented in Table 5, we considered the following:

i. Given the nature of a technical system's activity from a sustainability perspective (i.e. as represented in the S-Cycle model, Figure 5 in Section 4.2), what indicators would provide information on the achievement of the generic sustainability goals defined in Section 4.3?
ii. Given the inputs and outputs described in the S-Cycle model, what kinds of efficiency are inherent in a technical system's activity from a sustainability perspective?

Table 5. The S-Cycle Performance Matrix (please refer to Figure 7-10, Section 7.3, Chapter 7 of the thesis for the S-Cycle Performance Matrix)

With respect to (i), we derived the following effectiveness indicators from the S-Cycle model to provide information on the achievement of each of the sustainability goals. Note that different ways of calculating these indicators (i.e. metrics) are outlined later in this section:

- Information on the goal *produce intended output* may be obtained by measuring the intended output produced by a system over some time period. We termed this indicator *intended output production*. Given that the goal focuses solely on behaviour at the local scale (i.e. during the operation phase) as discussed in Section 4.3, the indicator may only be evaluated at this scale. The maximum time period it can be evaluated over is the full length of the operation phase.
- Information on the goal *minimise overall resource use* may be obtained by measuring the renewable and non-renewable passive resources consumed by the system over some time period. We termed this indicator *resource consumption*. Given that the goal may focus on behaviour at local, regional, and/or global scales (i.e. across several phases of the life cycle) as discussed in Section 4.3, the indicator may be evaluated at any of these scales. The maximum time period it can be evaluated over is the full length of the system life cycle.
- Information on the goals *minimise renewable resource use* and *minimise non-renewable resource use* may be obtained by measuring the renewable and non-renewable passive resources consumed by the system over some time period, respectively. We termed these indicators *renewable resource consumption* and *non-renewable resource consumption*. Given that the goals may focus on behaviour at local, regional, and/or global scales (i.e. across several phases of the life cycle) as discussed in Section 4.3, the indicators may be evaluated at any of these scales. The maximum time period they can be evaluated over is the full length of the system life cycle.
- Information on the goal *maximise self-sufficiency* can be obtained by measuring the intended resources produced and consumed by the system over some time period. We termed these indicators *intended resource consumption* and *intended resource production*, respectively. Given that the goal focuses solely on behaviour at the local scale (i.e. during the operation phase) as discussed in Section 4.3, the indicator may only be evaluated at this scale. The maximum time period it can be evaluated over is the full length of the operation phase.
- Finally, information on the goal *minimise waste produced* can be obtained by measuring the waste produced by the system over some time period. We termed this indicator *waste production*. Given that the goal may focus on behaviour at local, regional, and/or global scales (i.e. across several phases of the life cycle) as discussed in Section 4.3, it seems that the indicator may be evaluated at any of these scales. The maximum time period it can be evaluated over is the full length of the system life cycle.

With respect to (ii), we argue that there are four types of efficiency inherent in a technical system's activity when viewed from a sustainability perspective. These are:

1. The ratio of intended output produced (i.e. desirable gain) to passive resources consumed (including non-renewable and renewable), i.e. *resource efficiency*, which may be related to the goal *minimise overall resource use*. As discussed, intended output production can only be measured at the local scale over the operation phase, whilst (passive) resource consumption may be potentially be measured at all three scales and over the full length of the life cycle. However, the two aspects need not be measured at the same scale in order to

compute a value for resource efficiency. Rather, we may evaluate the efficiency with which a system uses its direct and/or indirect inputs (discussed in Section 3.1) to produce intended output. That is, resource efficiency at the local, regional, and/or global scales. This is supported by Ulgiati et al. (2006, p.435), who refer to the evaluation of energy efficiency on the global scale using the EEA method and an indicator defined as "the total commercial energy requirement [i.e. across the full life cycle] of one unit of output [i.e. intended output].

2. The ratio of intended output produced (i.e. desirable gain) to non-renewable resources consumed, i.e. *non-renewable resource efficiency*, which may be related to the goal *minimise non-renewable resource use*. The same points on spatio-temporal scale raised for the *resource efficiency* indicator above apply here.
3. The ratio of intended output produced (i.e. desirable gain) to renewable resources consumed, i.e. *renewable resource efficiency*, which may be related to the goal *minimise renewable resource use*. Again, the same points on spatio-temporal scale apply.
4. The ratio of waste produced (i.e. undesirable gain) to passive resources consumed, i.e. *resource inefficiency*, which may be related to the goal minimise waste produced. Both (passive) resource consumption and waste production may potentially be measured at all three scales, i.e. across the full life cycle. However, as shown below, the resource inefficiency indicator refers to the waste directly produced by the technical system, i.e. waste production at the local scale. Thus, it seems that resource inefficiency may be evaluated in the same way as resource efficiency discussed above. That is, we may evaluate how inefficiently a system uses its direct and/or indirect passive resource inputs, i.e. resource inefficiency at the local, regional, and/or global scales.

Conventionally, efficiency essentially indicates what fraction of a system's input resources were transformed to useful output rather than waste. In contrast, the *resource inefficiency* indicator defined above indicates what fraction of a system's input resources are being transformed to waste rather than useful output. In other words, how *inefficiently* the system is using its resources. It should be noted that the *resource efficiency* and *resource inefficiency* indicators are two sides of the same coin – summing their values should always yield a total of one or less (provided that they are measured at the same spatio-temporal scale, of course).

Next, we defined metrics for the SPI archetypes outlined above, considering how the SPIs may be expressed from two perspectives: (i) a data perspective, i.e. considering what measures are needed to compute a value for the indicator, how these measures relate, and whether they can be related in different ways; and (ii) a spatio-temporal perspective, i.e. considering whether the measures in each metric are evaluated at the local, regional, and/or global scales (as discussed above in relation to the SPI archetypes). With respect to (i), we consider a measure to be an item of data required to compute a value for an indicator according to its metric(s) as discussed in Section 2.1. Accordingly, the measures defined for each of the SPI archetypes in the initial matrix refer to the aspects of system behaviour that we require data on in order to calculate a value for the indicator. With respect to (ii), the scale(s) at which each measure may be evaluated is indicated in the matrix (Table 5) by a superscript letter appended to the measure: L = local, R = regional, and G = global. As we will show in Section 5.2, not all of the proposed metrics included in the matrix presented in Table 5 were found to be supported in the literature. Furthermore, the literature also suggests some additional metrics that we will discuss in Section 5.3.

5.2 Matrix evaluation

The performance matrix outlined in Section 5.1 is a product of induction from the literature covered in Sections 2 and 3, and the S-Cycle model introduced in Section 4.2. To test its validity, we carried out an analysis of 324 indicators discussed in the literature on sustainability performance evaluation of technical systems. In doing so, we sought to determine:

i. whether the indicators currently applied to evaluate the sustainability performance of technical systems could be classified with respect to the proposed SPI archetypes and metrics, thus providing support for the latter; and

ii. whether there are any indicators currently applied to technical systems that are *not* described in the performance matrix, which may be suggestive of additional SPI archetypes, metrics, and potentially even sustainability goals.

A sample of 42 sources evaluating the sustainability performance of technical systems (or elements thereof) was constructed. These sources are presented in Table 6, alongside the types of technical system forming the foci of the evaluations. It may be seen that the majority of authors included in the sample apply either *ad hoc* approaches, or one of the formal evaluation methods discussed in Section 3.2.

Table 6. Indicator analysis sample

Source	Technical system	Evaluation method/approach	Scale[1]
Buildings and structural systems:			
Antony et al. (2014)	Biomimetic ceiling structure	Life cycle assessment	G
Asif and Muneer (2014)	Window (panel & frame)	Ad hoc approach	L
Russell-Smith et al. (2014)	Mixed-use university campus building (design)	Life cycle assessment	G
Thiers and Peuportier (2012)	High energy performance building	Life cycle assessment	G
Energy conversion systems:			
Adams and McManus (2014)	Biomass gasification combined heat & power plant	Life cycle assessment	G
Balta et al. (2010)	Heat pump (ground-source)	• Energy analysis • Exergy analysis	L
Bianchi et al. (2014)	Three different types of combined heat and power plant	• Avoided Heat Generator • Pollution savings	L
Buonocore et al. (2012)	Combined heat & power plant	• Embodied energy analysis • Emergy accounting • Material flow analysis • Life cycle assessment	G
Caliskan et al. (2011b)	Solar ground-based heat pump with thermal energy storage	• Energy analysis • Exergy analysis	L
Cellura et al. (2013)	Two different types of biomass-fuelled energy production systems	• Embodied energy analysis • Life cycle assessment	G
Chicco and Mancarella (2008)	Poly-generation system	Primary Energy Saving	L
Coelho et al. (2012)	Ten different waste-to-energy plants	Ad hoc approach	L
Denholm et al. (2005)	Baseload wind energy system, including turbines & storage)	Ad hoc approach	R
Evans et al. (2009)	Photovoltaic, wind, hydro, & geothermal energy production systems	Ad hoc approach	L – G
Hondo (2005)	A range of different power production systems	Ad hoc approach	R
Kim et al. (2014)	PV systems composed of sc-Si/mc-Si modules with a 100 kWp power conditioning system	Life cycle assessment	G
Liu (2014)	Renewable energy systems generally	Ad hoc approach	L – G
Maxim (2014)	Energy generation systems generally	Multi criteria assessment	G
Onat and Bayar (2010)	Power production systems generally	Ad hoc approach	L
Pacca et al. (2007)	Roof mounted solar photovoltaic system	Life cycle assessment	G
Raugei et al. (2005)	Molten carbonate fuel cell, & three different types of gas turbine system	• Embodied energy analysis • Emergy accounting • Material flow analysis • Exergy analysis	G L
Rosato et al. (2013)	Three different types of combined heat and power plant	Ad hoc approach	L

Rosato et al. (2014a)	Building-integrated cogeneration system	Ad hoc approach	L
Rosato et al. (2014b)	Building-integrated cogeneration system	An emissions factor approach	L
Uddin and Kumar (2014)	Horizontal & vertical axis wind turbines	Life cycle assessment	G
Ulgiati et al. (2011)	Six different types of cogeneration system	• Embodied energy analysis • Emergy accounting • Life cycle assessment • Material flow analysis • Exergy analysis	G L
Fuel production systems:			
Moss et al. (2014)	Anaerobic digestion system	Emergy accounting	G
Ofori-Boateng and Lee (2014)	Biorefinery producing cellulosic ethanol & phytochemicals	• Exergetic life cycle assessment • Life cycle assessment	G
Heating and cooling systems:			
Abdel-Salam and Simonson (2014)	Membrane liquid desiccant air conditioning system	Ad hoc approach	L
Balta et al. (2010)	Condensing and conventional boilers, and a solar collector	• Energy analysis • Exergy analysis	L
Caliskan et al. (2011a)	Four different types of air cooling system for buildings	Exergy analysis	L
Caliskan et al. (2012)	Three different types of M-cycle air cooler	• Energy analysis • Exergy analysis • Emission factor approach	L G
Shah et al. (2008)	Three different residential heating and cooling systems	Life cycle assessment	G
Machining and industrial processing systems:			
Rotella et al. (2012)	Hard machining system	Ad hoc approach	L
Söğüt et al. (2012)	Coal preparation unit for cement production	• Energy analysis • Exergy analysis	L
Propulsive and transportation systems:			
Agarski et al. (2012)	Five different car models	Multi criteria assessment	L
Aydin et al. (2013)	Turboprop engine	Exergy analysis	L
Chandrasekaran and Guha (2012)	Turbofan engine	Ad hoc approach	L
Rahman et al. (2014)	Compression ignition engine	Ad hoc approach	L
Singh et al. (2014)	Biodiesel-fuelled HCCI engine	Ad hoc approach	L
Refining and distillation systems:			
Li et al. (2012)	Heterogeneous azeotropic distillation partitioned distillation column	• Energy analysis • Exergy analysis	L
Shahabi et al. (2014)	Seawater reverse osmosis desalination plant	Life cycle assessment	R
Waheed et al. (2014)	Crude oil distillation unit	• Energy analysis • Exergy analysis • IPCC CO2 emissions guidelines	L

[1] "Scale" refers to the spatio-temporal scale at which indicators are evaluated. L = local scale; R = regional scale; and G = global scale. Please refer to Section 3.1 for a discussion on the characteristics of each scale.

To gather these sources, we carried out a series of searches through Web of Science and two major engineering databases: Compendex, generally considered to be the most comprehensive engineering database; and the Technology Research Database, which encompasses a number of others including the Engineering Research Database, High Technology Research Database, and METADEX. In our search terms, we included both sustainability performance and environmental performance given that the latter is a major component of the former. We also applied terms relating to key concepts involved in performance measurement: assess*, eval*, indicator, measur*, and metric. Finally, although the phrase "technical system" encompasses a broad range of systems as discussed in Section 3, the use of the term in practice is primarily limited to the engineering design literature. Thus, we applied the terms product, system, and engineer* instead, using the characteristics of technical systems as described by Hubka and Eder (1988) to distinguish between technical and other kinds of system in the results.

To carry out the analysis, we built a spreadsheet containing the indicators used in each source, the units of the indicators, and their definitions. In total, 390 indicators were identified. However, 66 of these were immediately removed from the sample for the following reasons:

- not enough information was provided to classify the indicator, e.g. no formal definition or units;
- the indicator focused on purely technical aspects rather than those relevant from a sustainability perspective (this was to be expected given that a number of sources openly aim to evaluate both sustainability/environmental performance and technical performance);
- the indicator focused on a technical system's contribution to sustainable development (e.g. a focus on social and economic impacts) or socio-economic development generally (e.g. a focus on financial aspects) – a distinction can be made between technical system sustainability and sustainable development (as shown in Section 4.2), and the latter is not the focus of this paper; or
- the indicator focused on measuring something that may influence system performance, but is not performance *per se* e.g. the availability of an energy resource.

Using the spreadsheet, we attempted to classify the remaining 324 indicators with respect to the SPI archetypes and associated metrics proposed in the performance matrix presented in Section 5.1 (Table 5). In classifying the indicators, we considered: (i) which of the fundamental sustainability goals they may relate to, if any (given that just two authors in the sample explicitly stated goals as discussed in Section 4); (ii) what element of performance they measure, i.e. efficiency or effectiveness, given the definitions of each element identified in Section 2.1; and (iii) whether their metrics and measures align with those proposed in the matrix. Key observations resulting from the evaluation of the matrix, including future work required, are discussed in Section 5.3.

5.3 Key observations and future work

In total, 88.6% (287) of the indicators considered during the analysis (i.e. 324) were found to be immediately classifiable with respect to both the SPI archetypes and metrics proposed in the initial performance matrix. Of the remaining 11.4% (37), 48.6% (18 indicators) were found to be classifiable with respect to the SPI archetypes, but not the metrics. Thus, in total, 94.1% (305) of the indicators analysed were found to be classifiable with respect to the proposed SPI archetypes. Upon closer examination, the 18 indicators whose metrics did not align with any of those proposed in the performance matrix were seen to suggest additional metrics that had been overlooked. These are presented in Table 7, alongside the indicators from the sample that we based them on.

Table 7. Additional metrics suggested by indicators in the analysis sample (see Table 8-11, Section 8.2.3.2, Chapter 8)

On top of additional metrics for proposed SPI archetypes, one indicator identified in the sample was seen to suggest an additional SPI in relation to the goal *minimise overall resource use*. Rotella et al. (2012) evaluate the sustainability performance of a hard machining system. Among their indicators is one termed "wear rate," measuring the amount of material worn off of the cutting tool per minute during operation. With respect to the activity carried out by the machining system, the cutting tool is an active resource. That is, it transforms passive resources (e.g. a workpiece) into an output (e.g. a finished component). Thus, the wear rate indicator appears to measure the consumption of active resources during the operation phase of the life cycle (i.e. at the local scale).

This is suggestive of an additional SPI archetype, i.e. *active resource consumption* in relation to the goal *minimise overall resource use*. It seems that this SPI would only be measurable at the local scale, since it refers to the consumption of the physical components comprising the system. Nonetheless, it may be seen to relate to material and energy consumption at the regional scale. Clearly, the lower the active resource consumption rate for a particular system component, the longer the life of the component. In turn, the longer the life of the component, the less frequently it will need to be replaced, meaning that fewer replacements will be required over the operational life of the system. In turn, this means that fewer replacements need to be manufactured in the first place, potentially reducing the material and energy consumption associated with the manufacturing phase of the life cycle (i.e. performance at the regional scale). Potentially, we could even trace this all the way back to the extraction and processing phase. Additionally, active resource consumption may have an impact on material and/or energetic performance at the local scale during system operation. For example, the efficiency of a compressor may be reduced by wear on rotor tips. Thus, given the potential impact of active resource consumption on material and energetic performance at all scales, the additional SPI archetype proposed above seems to be pertinent. However, given that only one example was identified in the sample, further research is required to explore the above points and to identify appropriate metrics for the SPI.

Certain indicators were also seen to suggest that there may be an additional sustainability goal for technical systems, which is not apparent in the S-Cycle model. A number of the impact indicators (associated with LCA as discussed in Section 3.2) identified in the sample appear to focus on aspects that go beyond just waste, e.g. human toxicity, acidification, eutrophication, and so on. In essence, they seem to focus on the potential for a system's waste outputs to pollute other systems and activities within the Earth system. As touched upon in Section 4.2, accumulations of waste within an SOI may potentially disrupt the functioning and in turn, sustainability of systems operating within the SOI. The reason for this is that waste may contaminate a system's resource input, which may in turn lead to unexpected system behaviour and even damage to active resources (Hay et al., 2014). This may occur in artificial systems and processes, but also in natural systems and processes leading to issues such as acidification and eutrophication, the focus of a number of impact indicators in the sample. Furthermore, it may be seen that even certain types of intended output from systems may have the potential to contaminate in this way. For example, plastics produced as an intended output of a manufacturing system may be toxic to humans and therefore viewed as potential contaminants in certain human activities. On this basis, it seems that an additional sustainability goal may be defined for technical systems: *minimise the contaminating potential of outputs*. Given that this goal is not immediately apparent in the S-Cycle model, future research is required to explore if and how this aspect should be accommodated in the model. Modelling in this respect may also provide insight into what constitute appropriate SPI archetypes and metrics to measure the contaminating potential of outputs.

As discussed in Section 5.1, our proposed SPI archetype of *resource inefficiency* seems to be a somewhat unconventional application of the efficiency concept (i.e. the ratio of what has been materially gained to resource used). Rather than measuring how much of a system's input resources were converted to intended output, it measures how much of these resources were converted to waste *instead of* intended output via a metric termed "wastefulness," i.e. the ratio of waste produced to passive resources consumed. The SPI and associated metric were found to be supported in the analysis sample, as shown in Table 8. For instance, Aydin et al. (2013) report the indicator "waste exergy ratio," defined as the ratio of total waste exergy to total inlet exergy. However additionally, we observed that one author expressed the wastefulness metric the opposite way around, i.e. the ratio of passive resources used to waste produced (Ofori-Boateng and Lee, 2014). This additional formula is highlighted in Table 7 previously. As discussed in Section 5.1, it seems that it is possible to measure resource inefficiency at the local, regional, and/or global scales. That is, to evaluate how inefficiently a system uses its direct and/or indirect passive resource inputs. The two examples identified in the sample are evaluated at the local scale only, i.e. both the waste produced and passive resources consumed are measured locally. However, both authors apply the exergy analysis method, which is typically applied at the local scale as a matter of course. Thus, further research is needed to determine if resource inefficiency can be evaluated at different scales via other methods. We also highlighted in Section 5.1 that summing the values of the resource inefficiency and resource efficiency indicators should always yield a value of one or less. This is confirmed in the sample, by way of an additional formula that was identified for resource productivity (Ofori-Boateng and Lee, 2014):

$$Resource\ productivity = 1 - \left(\frac{W}{PR}\right)$$

The latter term in this formula is equal to the resource inefficiency of a system (i.e. the wastefulness metric originally proposed in Section 5.1).

Whilst all of the SPI archetypes proposed in the initial performance matrix were found to be supported in the analysis sample along with the majority of the proposed metrics, there are certain metrics that do not appear to be supported, as shown in Table 8 below. Namely, these are: (i) *non-renewable resource fraction*, defined for the SPI archetype *non-renewable resource consumption*; (ii) *renewable resource productivity*, defined for the SPI archetype *renewable resource consumption*; (iii) *absolute passive IR output*, defined for the SPI archetype *intended resource production*; and (iv) *intended resource production rate*, also defined for the SPI archetype *intended resource production*. A possible reason for the lack of support is of course simply that there did not happen to be any examples in our sample. With respect to (i), the metric *renewable resource fraction* defined for the sister indicator *renewable resource consumption* was found to be supported. Thus, there seems to be no particular reason why *non-renewable resource fraction* would not be measured. The same point may be made with respect to (ii). With respect to (iii) and (iv), it is of course possible that the S-Cycle model is incorrect in describing the production of intended resources as contributing to sustainability performance. However, the metric *passive intended resource fraction* defined for the SPI archetype *intended resource consumption* was found to be supported, suggesting that this area at least is measured. It may be the case that measuring the intended resources produced by a system is not possible, hence the focus on consumption. More fundamentally, it may be the case that technical systems are not typically designed to be self-sufficient – in such cases, there would be no intended resource production to measure. In any case, further research is required to clarify if and how the production and consumption of intended resources by a technical system should be measured.

Unfortunately, given the necessary space limitations of a journal article, it is not possible to report the full analysis results covering all indicators analysed. However, an overview is provided in Table 8 below. This table includes the full list of SPI archetypes and metrics defined during the investigation, including both those originally proposed in Section 5.1 and the additional ones identified in Table 7 above. Examples of supporting indicators from the analysis sample are provided, and those metrics that are unsupported are highlighted.

Table 8. Complete list of all SPI archetypes and metrics considered in the investigation (see Table 8-10, Section 8.2.3.2, Chapter 8)

Finally, it should be noted that the nature of certain indicators identified in the sample in relation to the performance matrix is unclear. As such, they were deemed not to be classifiable with respect to the performance matrix in its present form. Further research is required to understand these indicators and how they may be accommodated in the matrix, if appropriate. Broadly speaking, these indicators may be split into two categories, briefly discussed below:

- Firstly, there are indices that seem to relate output to resources in some way, but do not appear to be classifiable as efficiency indicators. For example, the Emergy Sustainability Index (Buonocore et al., 2012; Moss et al., 2014) is essentially the ratio of system yield to environmental burden; however, it relates two other emergy indices measuring resource efficiency and resource consumption and thus, from a performance perspective, it is unclear what the overall index is measuring. Furthermore, there are indicators such as the exergetic sustainability index (Aydin et al., 2013; Caliskan et al., 2011a; Caliskan et al., 2011b; Caliskan et al., 2012) that include efficiency as a term, but do not measure efficiency *per se*.

- Secondly, there are indicators that appear to benchmark the performance of one system against the performance of another, some theoretical level of performance, or performance at another scale. That is, they provide a means to compare aspects of system sustainability performance against a datum. For example, the Primary Energy Saving index (Chicco and Mancarella, 2008; Rosato et al., 2013; Rosato et al., 2014a) compares the primary energy consumption of a proposed energy generation system with a conventional system, to calculate how much primary energy resource may be saved by switching to the proposed system. A considerable body of research is dedicated to benchmarking in the performance literature, but it is not the focus of the work documented in this paper.

An evolved version of the S-Cycle Performance Matrix, taking into account the observations discussed above, is presented in Table 9. Additional goals, SPI archetypes, and metrics that were revealed during the evaluation exercise are highlighted in grey.

Table 9. Evolved version of the S-Cycle Performance Matrix (see Figure 8-9, Section 8.2.3.2, Chapter 8)

As discussed previously, three criteria should be met by a set of SPIs for a technical system in order for it to be considered comprehensive: (i) inclusion of both efficiency and effectiveness indicators; (ii) coverage of all sustainability goals governing the system; and (iii) inclusion of indicators measuring performance at all relevant spatio-temporal scales, given the purposes of the evaluation. In turn, the S-Cycle Performance Matrix is intended to support the definition of a comprehensive set of SPIs for a technical system by highlighting: (i) the different types of efficiency and effectiveness indicator at the disposal of evaluators (i.e. SPI archetypes and associated metrics for technical systems); (ii) the range of sustainability goals that should be covered (i.e. generic sustainability goals for technical systems); and (iii) the different spatio-temporal scales that each of the SPIs may be evaluated at (i.e. local, regional, and/or global). Furthermore, the matrix is generic and thus may be used in conjunction with any combination of formal evaluation methods, which as shown in Section 3.2, are applicable at different spatio-temporal scales. As discussed above, future work is required to clarify certain aspects of the matrix, and further research is clearly needed to explore its applications in practice. However, the fact that 94.1% of the indicators in the analysis sample were found to be classifiable with respect to the matrix in its present form suggests that the goals, SPI archetypes, and associated metrics are strongly supported in the literature. Thus, we believe that the matrix represents a solid step towards more consistent guidance on what constitutes a comprehensive set of SPIs for a technical system.

6. Conclusion

A plethora of indicators are applied to evaluate the sustainability performance of technical systems, focusing on different material and energetic aspects of behaviour and evaluated through different procedures. Whilst the application of different indicators does not necessarily mean that they are wrong or irrelevant, the lack of consistency among different methods and authors does raise a fundamental question: what type and range of sustainability performance indicators (SPIs) constitutes a comprehensive set for a technical system? In the corporate arena, the GRI guidelines provide clear and consistent guidance on comprehensive SPIs for organisations whilst leaving the choice of evaluation method up to the assessors (Global Reporting Initiative, 2013a). However, there is a lack of any overarching guidance of this nature in a technical systems context. The need for answers to the above question is further strengthened by the observation that none of the major formal evaluation methods currently applied to technical systems claim to be comprehensive with respect to sustainability performance. To address these shortcomings, this paper has presented the results of a review and analysis of the literature on sustainability performance evaluation of technical systems, aiming to develop a generic classification of SPIs to guide the selection of a comprehensive set for a technical system. The major contribution is a matrix of generic sustainability goals, SPI archetypes, and associated metrics for technical systems, known as the S-Cycle Performance Matrix.

The basic concepts and characteristics of performance were outlined in Section 2, firstly considering literature on performance measurement in a business/organisational context before introducing a generic performance model (E^2) to provide a more general view. This reveals efficiency and effectiveness as the basic components of performance and the fundamental focus of all performance indicators. The literature on sustainability performance evaluation of technical systems was then reviewed in Section 3. The technical system life cycle was outlined as a central concept, and the different spatio-temporal scales at which sustainability performance may be evaluated (i.e. local, regional, and global) were highlighted. Three criteria for comprehensive SPI sets for technical systems were seen to emerge from the literature covered in Sections 2 and 3: (i) inclusion of indicators measuring both efficiency and effectiveness; (ii) coverage of all sustainability performance goals governing the system; and (iii) inclusion of indicators measuring sustainability performance at all relevant spatio-temporal scales, given the purposes of the evaluation. In Section 4, it was shown that in spite of the need to relate SPIs to goals, authors evaluating the sustainability performance of technical systems rarely explicitly state any sustainability goals. To address this, the S-Cycle model was introduced and applied to illustrate the basic aspects of behaviour contributing to the sustainability performance of a technical system. In turn, a set of generic sustainability goals for technical systems was defined based on these aspects.

The development and testing of the S-Cycle Performance Matrix was discussed in Section 5. To construct the matrix, SPI archetypes (i.e. generic efficiency and effectiveness indicators) and associated metrics were defined for each of the generic sustainability goals defined in Section 4. The different spatio-temporal scales at which each SPI may be evaluated were also highlighted. Next, the approach adopted to evaluate the proposed matrix was outlined. A sample of sources from the literature on sustainability performance evaluation of technical systems was analysed, with the aim of trying to classify the reported indicators with respect to the SPI archetypes and metrics in the proposed performance matrix. In total, 324 indicators were analysed. Initially, 88.6% of the indicators in the sample were found to be fully classifiable with respect to the proposed matrix. Of the remaining 11.4%, just under half were found to suggest additional metrics for the proposed SPI archetypes. The other half (19 indicators) were deemed to not be classifiable with respect to the matrix in its current form. An additional SPI archetype was also identified during the analysis, and certain indicators in the sample were seen to suggest an additional sustainability goal that is not apparent in the S-Cycle model. After incorporating the additional goal, SPI archetype, and metrics into the matrix, a total of 94.1% of the indicators in the sample were found to be fully classifiable. Furthermore, all of the proposed SPI archetypes and associated metrics were observed to be supported in the sample, with the exception of four metrics.

On the basis of observations made during evaluation of the matrix, three key areas for future research were identified and discussed in Section 5:

- the nature of the SPI archetype *active resource consumption* (measuring the consumption of system components through e.g. wear during operation) identified during evaluation of the matrix, and its relationship to material and energetic performance at the regional and global scales;
- exploration of if and how the S-Cycle model should be evolved to accommodate the goal *minimise contaminating potential of system outputs* identified during evaluation of the matrix (if appropriate), and the nature of SPIs and metrics to measure this aspect; and
- exploration of SPIs and metrics defined in relation to the goal *maximise self-sufficiency*, which were found to be largely unsupported in the analysis sample. It may be the case that these aspects of behaviour are rarely observed and therefore measured in technical systems, or it may be the case that the S-Cycle model incorrectly describes these aspects. As such, any investigation in this area should consider both the S-Cycle model and the wider literature on sustainability performance in technical systems.

The S-Cycle Performance Matrix is intended to support the development of a comprehensive set of SPIs for a technical system by highlighting: (i) the different types of efficiency and effectiveness indicator at the disposal of evaluators (i.e. SPI archetypes and associated metrics for technical systems); (ii) the range of sustainability goals that should be covered by the SPIs (i.e. generic sustainability goals for technical systems); and (iii) the different spatio-temporal scales that each of the SPIs may be evaluated at. Furthermore, the matrix is generic and thus may be used in conjunction with any combination of formal evaluation methods, which as shown in Section 3.2, are applicable at different spatio-temporal scales. As discussed above, future work is required to clarify certain aspects of the matrix, and further research is clearly needed to explore its applications in practice. However, the fact that 94.1% of the indicators in the analysis sample were found to be classifiable with respect to the matrix in its present form suggests that the generic goals, SPI archetypes, and associated metrics are strongly supported in the literature. Thus, we believe that the matrix represents a solid step towards more consistent guidance on what constitutes a comprehensive set of SPIs for a technical system.

Acknowledgements

The authors gratefully acknowledge the University of Strathclyde for funding the research documented in this paper through a university research studentship.

References

Abdel-Salam, A.H., Simonson, C.J., 2014. Annual evaluation of energy, environmental and economic performances of a membrane liquid desiccant air conditioning system with/without ERV. Appl. Energy 116, 134–148. doi:10.1016/j.apenergy.2013.11.047

Adams, P.W.R., McManus, M.C., 2014. Small-scale biomass gasification CHP utilisation in industry: Energy and environmental evaluation. Sustain. Energy Technol. Assessments 6, 129–140. doi:10.1016/j.seta.2014.02.002

Agarski, B., Kljajin, M., Budak, I., Tadic, B., Vukelic, D., Bosak, M., Hodolic, J., 2012. Application of multi-criteria assessment in evaluation of motor vehicles' environmental performances. Tech. Gaz. 19, 221–221–226–226.

Antony, F., Grießhammer, R., Speck, T., Speck, O., 2014. Sustainability assessment of a lightweight biomimetic ceiling structure. Bioinspir. Biomim. 9, 016013. doi:10.1088/1748-3182/9/1/016013

Asif, M., Muneer, T., 2014. Briefing: Sustainability assessment of super-insulated timber windows. Proc. ICE - Constr. Mater. 167, 3–7. doi:10.1680/coma.12.00034

Aydin, H., Turan, Ö., Karakoç, T.H., Midilli, A., 2013. Exergo-sustainability indicators of a turboprop aircraft for the phases of a flight. Energy 58, 550–560. doi:10.1016/j.energy.2013.04.076

Balta, M.T., Dincer, I., Hepbasli, A., 2010. Performance and sustainability assessment of energy options for building HVAC applications. Energy Build. 42, 1320–1328. doi:10.1016/j.enbuild.2010.02.026

Bianchi, M., Branchini, L., De Pascale, A., Peretto, A., 2014. Application of environmental performance assessment of CHP systems with local and global approaches. Appl. Energy. doi:10.1016/j.apenergy.2014.04.017

Blanchard, B.S., Fabrycky, W.J., 1981. Systems Engineering and Analysis. Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Bourne, M., Bourne, P., 2007. Balanced Scorecard in a week, 2nd ed. Hodder & Stoughton, London.

Bourne, M., Mills, J., Wilcox, M., Neely, A., Platts, K., 2000. Designing, implementing and updating performance measurement systems. Int. J. Oper. Prod. Manag. 20, 754–771. doi:10.1108/01443570010330739

Boyle, I.M., Duffy, A.H.B., Whitfield, R.I., Liu, S., 2009. Towards an understanding of the impact of resources on the design process, in: 17th International Conference on Engineering Design (ICED `09). The Design Society, Stanford.

Boyle, I.M., Duffy, A.H.B., Whitfield, R.I., Liu, S., 2012. The impact of resources on decision making. Artif. Intell. Eng. Des. Anal. Manuf. 26, 407–423.

Brynolf, S., Fridell, E., Andersson, K., 2014. Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol. J. Clean. Prod. 74, 86–95. doi:10.1016/j.jclepro.2014.03.052

Buonocore, E., Franzese, P.P., Ulgiati, S., 2012. Assessing the environmental performance and sustainability of bioenergy production in Sweden: A life cycle assessment perspective. Energy 37, 69–78. doi:10.1016/j.energy.2011.07.032

Caliskan, H., Dincer, I., Hepbasli, A., 2011a. Exergetic and sustainability performance comparison of novel and conventional air cooling systems for building applications. Energy Build. 43, 1461–1472. doi:10.1016/j.enbuild.2011.02.006

Caliskan, H., Dincer, I., Hepbasli, A., 2012. A comparative study on energetic, exergetic and environmental performance assessments of novel M-Cycle based air coolers for buildings. Energy Convers. Manag. 56, 69–79. doi:10.1016/j.enconman.2011.11.007

Caliskan, H., Hepbasli, A., Dincer, I., 2011b. Exergy Analysis and Sustainability Assessment of a Solar-Ground Based Heat Pump With Thermal Energy Storage. J. Sol. Energy Eng. 133, 011005. doi:10.1115/1.4003040

Cellura, M., La Rocca, V., Longo, S., Mistretta, M., 2013. Energy and environmental impacts of energy related products (ErP): a case study of biomass-fuelled systems. J. Clean. Prod. doi:10.1016/j.jclepro.2013.12.059

Chandrasekaran, N., Guha, A., 2012. Development and optimization of a sustainable turbofan aeroengine for improved performance and emissions. Proc. Inst. Mech. Eng. Part G J. Aerosp. Eng. 227, 1701–1719. doi:10.1177/0954410012462183

Chapman, J., 2011. Emotionally Durable Design, 3rd ed. Earthscan, London, Washington DC.

Chicco, G., Mancarella, P., 2008. A unified model for energy and environmental performance assessment of natural gas-fueled poly-generation systems. Energy Convers. Manag. 49, 2069–2077. doi:10.1016/j.enconman.2008.02.015

Coelho, H.M.G., Lange, L.C., Coelho, L.M.G., 2012. Proposal of an environmental performance index to assess solid waste treatment technologies. Waste Manag. 32, 1473–81. doi:10.1016/j.wasman.2012.03.001

Collado-Ruiz, D., Ostad-Ahmad-Ghorabi, H., 2010. Influence of environmental information on creativity. Des. Stud. 31, 479–498. doi:10.1016/j.destud.2010.06.005

Dalal-Clayton, B., Bass, S., 2002. Sustainable Development Strategies - A Resource Book. Earthscan Publications Ltd., London.

Daly, H.E., 1990. Toward some operational principles of sustainable development. Ecol. Econ. 2, 1–6. doi:10.1016/0921-8009(90)90010-R

Daly, H.E., 1992. Steady-state economics, 2nd ed. Earthscan, London.

Darnhofer, I., Fairweather, J., Moller, H., 2010. Assessing a farm's sustainability: insights from resilience thinking. Int. J. Agric. Sustain. 8, 186–198.

Denholm, P., Kulcinski, G.L., Holloway, T., 2005. Emissions and Energy Efficiency Assessment of Baseload Wind Energy Systems. Environ. Sci. Technol. 39, 1903–1911. doi:10.1021/es049946p

Duffy, A., 2005. Design process and performance, in: Clarkson, J., Huhtala, M. (Eds.), Engineering Design - Theory and Practice, A Symposium in Honour of Ken Wallace. Engineering Design Centre, University Of Cambridge, pp. 76–85.

Eder, W.E., 2003. A TYPOLOGY OF DESIGNS AND DESIGNING, in: ICED03: 14th International Conference on Engineering Design.

Evans, A., Strezov, V., Evans, T.J., 2009. Assessment of sustainability indicators for renewable energy technologies. Renew. Sustain. Energy Rev. 13, 1082–1088. doi:10.1016/j.rser.2008.03.008

Gasparatos, A., El-Haram, M., Horner, M., 2009. Assessing the sustainability of the UK society using thermodynamic concepts: Part 1. Renew. Sustain. Energy Rev. 13, 1074–1081. doi:10.1016/j.rser.2008.03.004

Gero, J.S., Kannengiesser, U., 2004. The situated function–behaviour–structure framework. Des. Stud. 25, 373–391. doi:10.1016/j.destud.2003.10.010

Global Reporting Initiative, 2013a. G4 Sustainability Reporting Guidelines - Reporting Principles and Standard Disclosures. Amsterdam.

Global Reporting Initiative, 2013b. G4 Sustainability Reporting Guidelines - Implementation Manual. Amsterdam.

Gurzenich, D., Wagner, H.-J., 2004. Cumulative energy demand and cumulative emissions of photovoltaics production in Europe. Energy 29, 2297–2303. doi:10.1016/j.energy.2004.03.037

Hannon, A., Callaghan, E.G., 2011. Definitions and organizational practice of sustainability in the for-profit sector of Nova Scotia. J. Clean. Prod. 19, 877–884. doi:10.1016/j.jclepro.2010.11.003
Hay, L., 2014. A model of the chilled water system and its sustainability. Glasgow.
Hay, L., Duffy, A., Whitfield, R.I., 2014. The Sustainability Cycle and Loop: models for a more unified understanding of sustainability. J. Environ. Manage. 133, 232–57. doi:10.1016/j.jenvman.2013.11.048
Hepbasli, A., 2008. A key review on exergetic analysis and assessment of renewable energy resources for a sustainable future. Renew. Sustain. Energy Rev. 12, 593–661. doi:10.1016/j.rser.2006.10.001
Holan Fenwick Willan, 2013. Green Shipping Bulletin. London.
Hondo, H., 2005. Life cycle GHG emission analysis of power generation systems: Japanese case. Energy 30, 2042–2056. doi:10.1016/j.energy.2004.07.020
Hubka, V., 1982. Principles of Engineering Design. Butterworth & Co (Publishers) Ltd.
Hubka, V., Eder, W.E., 1988. Theory of Technical Systems, 2nd ed. Springer-Verlag, Berlin, Heidelberg, New York.
Hussey, D.M., Kirsop, P.L., Meissen, R.E., 2001. Global Reporting Initiative Guidelines: An Evaluation of Sustainable Development Metrics for Industry. Environ. Qual. Manag. 11, 1–20. doi:10.1002/tqem.1200
International Standards Organization, 1999. ISO 14031:1999 Environmental management - Environmental performance evaluation - Guidelines.
Kajikawa, Y., 2008. Research core and framework of sustainability science. Sustain. Sci. 3, 215–239. doi:10.1007/s11625-008-0053-1
Kaplan, R.S., Norton, D.P., 1992. The Balanced Scorecard - Measures that Drive Performance. Harv. Bus. Rev. January-Fe, 71–70.
Kaplan, R.S., Norton, D.P., 1996. The Balanced Scorecard. Harvard Business School Press, Boston, MA.
Kennerley, M., Neely, A., 2002. Performance measurement frameworks: A review, in: Neely, A. (Ed.), Business Performance Measurement. Cambridge University Press, Cambridge, pp. 145–155.
Kidd, C. V., 1992. The evolution of sustainability. J. Agric. Environ. Ethics 5, 1–26. doi:10.1007/BF01965413
Kim, B., Lee, J., Kim, K., Hur, T., 2014. Evaluation of the environmental performance of sc-Si and mc-Si PV systems in Korea. Sol. Energy 99, 100–114. doi:10.1016/j.solener.2013.10.038
Lebas, M., Euske, K., 2002. A conceptual and operational delineation of performance, in: Neely, A. (Ed.), Business Performance Measurement. Cambridge University Press, Cambridge, pp. 65–79.
Lele, S., Norgaard, R.B., 1996. Sustainability and the Scientist's Burden. Conserv. Biol. 10, 354–365. doi:10.1046/j.1523-1739.1996.10020354.x
Li, J., Wang, J., Ma, Z., Sun, L., 2012. Environmental Performance Assessment for Heterogeneous Azeotropic Distillation Partitioned Distillation Column. Adv. Mater. Res.
Liu, G., 2014. Development of a general sustainability indicator for renewable energy systems: A review. Renew. Sustain. Energy Rev. 31, 611–621. doi:10.1016/j.rser.2013.12.038
Lozano, R., Huisingh, D., 2011. Inter-linking issues and dimensions in sustainability reporting. J. Clean. Prod. 19, 99–107. doi:10.1016/j.jclepro.2010.01.004
Marimon, F., Alonso-Almeida, M. del M., Rodríguez, M. del P., Cortez Alejandro, K.A., 2012. The worldwide diffusion of the global reporting initiative: what is the point? J. Clean. Prod. 33, 132–144. doi:10.1016/j.jclepro.2012.04.017
Maxim, A., 2014. Sustainability assessment of electricity generation technologies using weighted multi-criteria decision analysis. Energy Policy 65, 284–297. doi:10.1016/j.enpol.2013.09.059
Morhardt, J.E., Baird, S., Freeman, K., 2002. Scoring corporate environmental and sustainability reports using GRI 2000, ISO 14031 and other criteria. Corp. Soc. Responsib. Environ. Manag. 9, 215–233. doi:10.1002/csr.26
Moss, A.R., Lansing, S.A., Tilley, D.R., Klavon, K.H., 2014. Assessing the sustainability of small-scale anaerobic digestion systems with the introduction of the emergy efficiency index (EEI) and adjusted yield ratio (AYR). Ecol. Eng. 64, 391–407. doi:10.1016/j.ecoleng.2013.12.008
Neely, A., Adams, C., Kennerley, M., 2002a. The Performance Prism: The Scorecard for Measuring and Managing Business Success. Pearson Education Limited, Harlow; London.

Neely, A., Bourne, M., Mills, J., Platts, K., Richards, H., 2002b. Getting the measure of your business. Cambridge University Press, Cambridge.
Neely, A., Gregory, M., Platts, K., 1995. Performance measurement system design: A literature review and research agenda. Int. J. Oper. Prod. Manag. 15, 80–116. doi:10.1108/01443579510083622
Ness, B., Urbel-Piirsalu, E., Anderberg, S., Olsson, L., 2007. Categorising tools for sustainability assessment. Ecol. Econ. 60, 498–508. doi:10.1016/j.ecolecon.2006.07.023
O'Donnell, F.J., Duffy, A.H.B., 2002. Modelling design development performance. Int. J. Oper. Prod. Manag. 22, 1198–1221. doi:10.1108/01443570210450301
O'Donnell, F.J., Duffy, A.H.B., 2005. Design Performance. Springer-Verlag, London.
Ofori-Boateng, C., Lee, K.T., 2014. An oil palm-based biorefinery concept for cellulosic ethanol and phytochemicals production: Sustainability evaluation using exergetic life cycle assessment. Appl. Therm. Eng. 62, 90–104. doi:10.1016/j.applthermaleng.2013.09.022
Onat, N., Bayar, H., 2010. The sustainability indicators of power production systems. Renew. Sustain. Energy Rev. 14, 3108–3115. doi:10.1016/j.rser.2010.07.022
Oxford English Dictionary, 2014. Oxford English Dictionary [Online]. URL http://www.oed.com/
Pacca, S., Sivaraman, D., Keoleian, G.A., 2007. Parameters affecting the life cycle performance of PV technologies and systems. Energy Policy 35, 3316–3326. doi:10.1016/j.enpol.2006.10.003
Park, P.-J., Lee, K.-M., Wimmer, W., 2005. Development of an Environmental Assessment Method for Consumer Electronics by combining Top-down and Bottom-up Approaches. Int. J. Life Cycle Assess. 11, 254–264. doi:10.1065/lca2005.05.205
Pierce, J.C., Budd, W.W., Lovrich Jr., N.P., 2011. Resilience and sustainability in US urban areas. Env. Polit. 20, 566–584.
PV Cycle UK, 2013. Recycling of Non-silicon Based PV [Online]. URL http://www.pvcycle.org.uk/pv-recycling/recycling-if-non-si/ (accessed 8.24.14).
Quental, N., Lourenço, J.M., da Silva, F.N., 2010. Sustainability: characteristics and scientific roots. Environ. Dev. Sustain. 13, 257–276. doi:10.1007/s10668-010-9260-x
Rahman, S.M.A., Masjuki, H.H., Kalam, M.A., Sanjid, A., Abedin, M.J., 2014. Assessment of emission and performance of compression ignition engine with varying injection timing. Renew. Sustain. Energy Rev. 35, 221–230. doi:10.1016/j.rser.2014.03.049
Raugei, M., Bargigli, S., Ulgiati, S., 2005. A multi-criteria life cycle assessment of molten carbonate fuel cells (MCFC)?a comparison to natural gas turbines. Int. J. Hydrogen Energy 30, 123–130. doi:10.1016/j.ijhydene.2004.04.009
Rosato, A., Sibilio, S., Ciampi, G., 2013. Energy, environmental and economic dynamic performance assessment of different micro-cogeneration systems in a residential application. Appl. Therm. Eng. 59, 599–617. doi:10.1016/j.applthermaleng.2013.06.022
Rosato, A., Sibilio, S., Scorpio, M., 2014a. Dynamic performance assessment of a residential building-integrated cogeneration system under different boundary conditions. Part I: Energy analysis. Energy Convers. Manag. 79, 731–748. doi:10.1016/j.enconman.2013.10.001
Rosato, A., Sibilio, S., Scorpio, M., 2014b. Dynamic performance assessment of a residential building-integrated cogeneration system under different boundary conditions. Part II: Environmental and economic analyses. Energy Convers. Manag. 79, 749–770. doi:10.1016/j.enconman.2013.09.058
Rosen, M.A., Dincer, I., 2001. Exergy as the confluence of energy, environment and sustainable development. Exergy, An Int. J. 1, 3–13. doi:10.1016/S1164-0235(01)00004-8
Rotella, G., Umbrello, D., Dillon Jr., O.W., Jawahir, I.S., 2012. Evaluation of Process Performance for Sustainable Hard Machining. J. Adv. Mech. Des. Syst. Manuf. 6, 989–998.
Russell-Smith, S. V., Lepech, M.D., Fruchter, R., Meyer, Y.B., 2014. Sustainable target value design: integrating life cycle assessment and target value design to improve building energy and environmental performance. J. Clean. Prod. doi:10.1016/j.jclepro.2014.03.025
Sage, A.P., 1992. Systems engineering. John Wiley, New York.
Schönsleben, P., Vodicka, M., Bunse, K., Ernst, F.O., 2010. The changing concept of sustainability and economic opportunities for energy-intensive industries. CIRP Ann. - Manuf. Technol. 59, 477–480. doi:10.1016/j.cirp.2010.03.121

Scientific Applications International Corporation, 2006. Life Cycle Impact Assessment, in: Life Cycle Assessment: Principles and Practice. National Risk Management Research Laboratory, Cincinnati, pp. 46–53.
Shah, V.P., Debella, D.C., Ries, R.J., 2008. Life cycle assessment of residential heating and cooling systems in four regions in the United States. Energy Build. 40, 503–513. doi:10.1016/j.enbuild.2007.04.004
Shahabi, M.P., McHugh, A., Anda, M., Ho, G., 2014. Environmental life cycle assessment of seawater reverse osmosis desalination plant powered by renewable energy. Renew. Energy 67, 53–58. doi:10.1016/j.renene.2013.11.050
Shearman, R., 1990. The Meaning and Ethics of Sustainability. Environ. Manage. 14, 1–8.
Silicon Valley Toxics Coalition, 2009. Toward a Just and Sustainable Solar Energy Industry.
Singh, G., Singh, A.P., Agarwal, A.K., 2014. Experimental investigations of combustion, performance and emission characterization of biodiesel fuelled HCCI engine using external mixture formation technique. Sustain. Energy Technol. Assessments 6, 116–128. doi:10.1016/j.seta.2014.01.002
Söğüt, Z., Oktay, Z., Karakoc, H., Hepbasli, A., 2012. Investigation of environmental and exergetic performance for coal-preparation units in cement production processes. Energy 46, 72–77. doi:10.1016/j.energy.2012.04.041
Standal, D., Utne, I.B., 2011. The hard choices of sustainability. Mar. Policy 35, 519–527. doi:10.1016/j.marpol.2011.01.001
Stasinopoulos, P., Smith, M.H., Hargroves, K., Desha, C., 2009. Whole System Design. An Integrated Approach to Sustainable Engineering. Earthscan, London.
Thiers, S., Peuportier, B., 2012. Energy and environmental assessment of two high energy performance residential buildings. Build. Environ. 51, 276–284. doi:10.1016/j.buildenv.2011.11.018
Uddin, M.S., Kumar, S., 2014. Energy, emissions and environmental impact analysis of wind turbine using life cycle assessment technique. J. Clean. Prod. 69, 153–164. doi:10.1016/j.jclepro.2014.01.073
Ulgiati, S., Ascione, M., Bargigli, S., Cherubini, F., Franzese, P.P., Raugei, M., Viglia, S., Zucaro, A., 2011. Material, energy and environmental performance of technological and social systems under a Life Cycle Assessment perspective. Ecol. Modell. 222, 176–189. doi:10.1016/j.ecolmodel.2010.09.005
Ulgiati, S., Raugei, M., Bargigli, S., 2006. Overcoming the inadequacy of single-criterion approaches to Life Cycle Assessment. Ecol. Modell. 190, 432–442. doi:10.1016/j.ecolmodel.2005.03.022
United Nations Development Programme, 2011. Human Development Report 2011. Palgrave Macmillan, Basingstoke.
Urban, R.A., Bakshi, B.R., Grubb, G.F., Baral, A., Mitsch, W.J., 2010. Towards sustainability of engineered processes: Designing self-reliant networks of technological–ecological systems. Comput. Chem. Eng. 34, 1413–1420. doi:10.1016/j.compchemeng.2010.02.026
Waheed, M.A., Oni, A.O., Adejuyigbe, S.B., Adewumi, B.A., 2014. Thermoeconomic and environmental assessment of a crude oil distillation unit of a Nigerian refinery. Appl. Therm. Eng. 66, 191–205. doi:10.1016/j.applthermaleng.2014.02.007
Wahl, D.C., Baxter, S., 2008. The Designer's Role in Facilitating Sustainable Solutions. Des. Issues 24, 72–83.
Wang, W., Duffy, A., Whitfield, I., Liu, S., Boyle, I., 2008. A design view of capability, in: Realising Network Enabled Capability Conference 2008, 13-14 October 2008, Leeds, UK. Leeds.
Wiersum, K.F., 1995. 200 Years of Sustainability in Forestry : Lessons from History. Environ. Manage. 19, 321–329.
World Commission on Environment and Development, 1987. Our common future. Oxford University Press, Oxford, New York.
Zhang, Y., Yang, Z., Liu, G., Yu, X., 2011. Emergy analysis of the urban metabolism of Beijing. Ecol. Modell. 222, 2377–2384. doi:10.1016/j.ecolmodel.2010.09.017

Appendix 3: Paper C

This appendix contains Paper C, which presents the findings of the inductive literature investigation undertaken to construct the S-Cycle and S-Loop models (Chapter 6). The paper is published in the Journal of Environmental Management, Volume 133, 2014 (full details of the article are provided in the list of appended papers at the beginning of the thesis. With respect to references and styles, the paper is presented here largely as it was formatted for submission to the journal. Owing to copyright restrictions, the published article cannot be included here; rather, the author's pre-publication manuscript is presented below.

Chapter 6 presents a summary of key points and findings from this paper. Note that owing to space limitations, certain tables and figures presented elsewhere in the thesis have been removed from the following paper. Where this is the case, readers are referred to the appropriate section of the thesis.

The Sustainability Cycle and Loop: models for a more unified understanding of sustainability

Laura Hay, Alex Duffy, R. I. Whitfield

Abstract

In spite of the considerable research on sustainability, reports suggest that we are barely any closer to a more sustainable society. As such, there is an urgent need to improve the effectiveness of human efforts towards sustainability. A clearer and more unified understanding of sustainability among different people and sectors could help facilitate this. This paper presents the results of an inductive literature investigation, aiming to develop models to explain the nature of sustainability in the Earth system, and how humans can effectively strive for it. The major contributions are two general and complementary models, that may be applied in any context to provide a common basis for understanding sustainability: the Sustainability Cycle (S-Cycle), and the Sustainability Loop (S-Loop). Literature spanning multiple sectors is examined from the perspective of three concepts, emerging as significant in relation to our aim. Systems are shown to provide the context for human action towards sustainability, and the nature of the Earth system and its sub-systems is explored. Activities are outlined as a fundamental target that humans need to sustain, since they produce the entities both needed and desired by society. The basic behaviour of activities operating in the Earth system is outlined. Finally, knowledge is positioned as the driver of human action towards sustainability, and the key components of knowledge involved are examined. The S-Cycle and S-Loop models are developed via a process of induction from the reviewed literature. The S-Cycle describes the operation of activities in a system from the perspective of sustainability. The sustainability of activities in a system depends upon the availability of resources, and the availability of resources depends upon the rate that activities consume and produce them. Humans may intervene in these dynamics via an iterative process of interpretation and action, described in the S-Loop model. The models are briefly applied to a system described in the literature. It is shown that the S-Loop may be used to guide efforts towards sustainability in a particular system of interest, by prescribing the basic activities involved. The S-Cycle may be applied complementary to the S-Loop, to support the interpretation of activity behaviour described in the latter. Given their general nature, the models provide the basis for a more unified understanding of sustainability. It is hoped that their use may go some way towards improving the effectiveness of human action towards sustainability.

Keywords: sustainability; sustainability goals; sustainability indicators; sustainability model; activity sustainability

1. Introduction

The increasing scale of human activity on the planet has led to the emergence of sustainability as a central aim for society. In its most basic form, sustainability can be defined as the ability to sustain (Kajikawa, 2008), maintain (Lele and Norgaard, 1996; Marcuse, 1998), or continue (Dempsey et al., 2011; Shearman, 1990) something over time. Historically, the term has been used in a technical sense within specific disciplines to refer generally to the maintenance or continuation of some process or system over time (Kajikawa et al., 2007). Today, sustainability is an issue of concern primarily because of the mounting evidence to suggest that human activity in the Earth system is following an unsustainable trajectory. According to (UNEP, 2012, p.xviii), the "Earth System provides the basis for all human societies and their economic activities" in the form of resources and waste processing capacity. However, research suggests that human activity is degrading the Earth system that it depends upon for its continued operation (Rockström et al., 2009; UNEP, 2012). Highlighting the potential magnitude of the problem, Ehrlich and Ehrlich (2013. p.1) suggest that supporting today's population, consuming resources at the same rate as the United States, "would take four to five more Earths." In response, much of current sustainability research focuses on the sustainability of human society as an integral part of the Earth system (Beddoe et al., 2009; Komiyama and Takeuchi, 2006; Voinov, 2007).

Lindsey (2011, p.561) remarks that the "worldwide movement toward a more sustainable society has caught fire in recent years." The rising significance of sustainability research is reflected the expanding size of the literature that documents it. Querying 'sustainab*' through the Web of Knowledge service for all years up until 2012 returns over 53,000 records in total – in contrast, conducting the same search for all years up until 1980 returns just 70 results. Within this literature, a plethora of goals, indicators, and targets intended to facilitate a shift towards sustainability may be identified (Jordan et al., 2010; Parris and Kates, 2003; Quental et al., 2011). However, recent reports highlight a lack of progress towards sustainability at the societal level (e.g. Eurostat, 2011; UNEP, 2012), suggestive of ineffectual human action. It seems that in spite of the considerable body of research on sustainability, we are barely any closer to a more sustainable society. So why is this?

One issue that appears to be impeding progress is the lack of a clear and unified understanding of sustainability among different people and sectors (Lindsey, 2011; Voinov, 2007). For example, Hannon and Callaghan (2011, p.877) argue that "the diffusion and popularity of the term sustainability with relatively little corresponding rigorous and grounded conceptualization may have created confusion over the basic concepts of sustainability." In turn, they suggest that the "lack of a unified and rigorous understanding of sustainability means that sustainability initiatives are often ineffectual," a point made in a business context but readily translatable to society as a whole. For example, Kajikawa (2008, p.218) remarks that people have different ideas on sustainability in different contexts and as a result, "solutions tend to be sustainable within [individual] sectors rather than across the whole of society." This is reflected in the sustainability research landscape, which remains fractured along disciplinary boundaries (Kajikawa et al. 2007; Kajikawa 2008) in spite of calls for transdisciplinary approaches (Bodini, 2012; Sneddon et al., 2006). For example, there exist distinct areas of research dedicated to sustainability in specific sectors, e.g. agriculture, development, forestry, fisheries, and so on (Kajikawa, 2008). Within each area, a range of context-specific sustainability definitions, goals, and indicators etc. may be identified (e.g. Eurostat, 2011; Standal and Utne, 2011; US Forest Service, 2010; Walter and Stützel, 2009). In summary, Lindsey (2011, p.561) remarks that, "While there seems to be considerable consensus that a more sustainable society is in the best interest of everyone, opinions regarding what sustainability really means and how to achieve it are as diverse as the entities striving for it." In response, he points to the need for "a consistent framework for human effectiveness in achieving sustainability."

There is an urgent need to improve the effectiveness of human efforts towards sustainability. A clearer and more unified understanding of sustainability among different people and sectors could help to facilitate this. Along these lines, this paper presents the results of an inductive literature investigation focusing on sustainability and human action towards it across society. The aim was to develop models to explain the nature of sustainability in the Earth system, and how humans in different sectors may effectively strive for it. Models may be viewed as "abstractions used by scientists and researchers to understand and explain natural phenomena or human behaviour phenomena" (Sim, 2000, p.17). In the context of sustainability, Kajikawa (2008, p.232) notes that "modeling is a fundamental and indispensable scientific activity." The major contributions made by this investigation are two general and complementary models, developed via a process of induction from the literature: (i) the Sustainability Cycle (S-Cycle), describing the operation of activities in a system from the perspective of sustainability; and (ii) the Sustainability Loop (S-Loop), describing a basic process that may lead humans towards sustainability.

Owing to the vastness of the sustainability literature, we focused our investigation on sources originating in sectors identified as major contributors to sustainability research: agriculture (Conway, 1986; Darnhofer et al., 2010; Hansen, 1996; Pretty, 2008; Tilman et al., 2002; Walter and Stützel, 2009), business (Dyllick and Hockerts, 2002; Figge and Hahn, 2005; Hahn and Figge, 2011; Hart and Milstein, 2003; Lo, 2010; Rainey, 2006), design (Chapman, 2011; Gagnon et al., 2012; Wahl and Baxter, 2008), development (Brown et al., 1987; Bodini, 2012; Burger and Christen, 2011; Dawson et al., 2010; Eurostat, 2011a; Holling, 2001; Jamieson, 1998; Lele and Norgaard, 1996; Rametsteiner et al., 2011; Shearman, 1990; UNDP, 2011; Vos, 2007; Vucetich and Nelson, 2010; Wackernagel and Yount, 1998; WCED, 1987), economics (Baumgärtner and Quaas, 2010; Brown and Ulgiati, 1997; Costanza and Daly, 1992; Daly, 1990; Derissen et al., 2011; Ekins et al., 2003; Heal, 2012; Neumayer, 2003; Odum, 1994; Solow, 1993), fisheries (Gaichas, 2008; Larkin, 1977; Norse et al., 2012; Standal and Utne, 2011), forestry (Hahn and Knoke, 2010; Noss, 1993; Pearce et al., 2003; Wiersum, 1995), urban studies (Dempsey et al., 2011; Maclaren, 1996; Marcuse, 1998), and sustainability science (Kajikawa 2008; Quental et al. 2010; Spangenberg 2011). We included literature from multiple sectors to gain a view that is as free from contextual nuances as possible.

Given our aim, we adopted an anthropocentric perspective throughout, although other perspectives are certainly possible (e.g. see Williams and Millington (2004) for an example). From our delimited corpus, three concepts emerged as significant for detailed investigation in relation to our aim of modelling to explain the nature of sustainability in the Earth system, and how humans in different sectors may effectively strive for it:

- *Systems*. As will be shown in Section 4, what is "sustainable" for one entity may in fact be detrimental to the sustainability of other entities that it is connected to (Alfaris et al., 2010; Voinov, 2007). As such, Bell and Morse (2008, p.110) suggest that, "In understanding sustainability […] we need to recognize and work with unities, of which we, as observers, are also part." In other words, humans should not focus on the sustainability of isolated entities, but rather on the sustainability of entities as interconnected parts of a wider system (Bell and Morse, 2008; Bodini, 2012; Fiksel, 2003). Ultimately, the entities that humans wish to sustain are parts of the Earth system, of which humans themselves are also integral components. Owing to the scale and complexity of the Earth system, humans focus on sustainability in a number of different sub-systems, e.g. agricultural systems (Conway, 1986; Darnhofer et al., 2010; Hansen, 1996; Pretty, 2008), economies (Costanza and Daly 1992; Solow 1993; Brown and Ulgiati 1997; Ekins et al. 2003; Neumayer 2003), and urban areas (Maclaren 1996; Dempsey et al. 2011) (explored more deeply in Section 3). Thus, it may be seen that systems provide the context for human action towards sustainability.
- *Activities.* As will be discussed in Section 2, the multiplicity of human values means that different people want to sustain different things (Lele and Norgaard, 1996; Lindsey, 2011; Chapman, 2011). Examples of sustainability targets identifiable in the literature include resources (e.g. Dyllick and Hockerts, 2002; Neumayer, 2003; Standal and Utne, 2011), social phenomena and standards (e.g. Heal, 2012; Vos, 2007; Wackernagel and Yount, 1998), and the life of organisms and non-organic entities (e.g. Brown et al., 1987; Goerner et al., 2009; Heal, 2012; Jamieson, 1998). From this perspective, developing a common understanding of the nature of sustainability appears to be a difficult task (Lindsey, 2011). In this paper, our approach is to consider that activities are a fundamental target that humans need to sustain. In a system, activities may be viewed as "the fundamental

elements that transform input to output" (O'Donnell and Duffy, 2005, p.56). For example, humans need production activities to transform raw materials into useful artefacts (Chapman, 2011), and socio-economic development activities to transform artefacts into intangible entities such as living standards and wellbeing (UNDP, 2011). We need certain natural activities to transform our waste products back into useful resources (Lindsey, 2011) such as water and minerals. At the most fundamental level, we need biological activities to transform food into energy, and air into the oxygen we need to live. Thus, in order to sustain a particular entity, we need to sustain the activities that produce that entity in the first place. Without activities, there would be no life and therefore no society to sustain. Like "system," "activity" is a general concept that may be translated to any context (O'Donnell and Duffy, 2005) (as shown in Section 4). Thus, discussing sustainability in terms of activities provides us with a general language that may be understood in any context.

- *Knowledge.* Knowledge may be viewed as a driver of human action, both generally and in efforts towards sustainability. For example, Newell (1982, p.100) describes knowledge generally as "a potential for generating action." In a similar vein, Meadows (1998, p.3) positions knowledge of "the discrepancy between the desired state or goal and the perceived state of [a] system" as a driver of human action towards sustainability. As we will show in Section 5, to make informed decisions in efforts towards sustainability, humans need knowledge on the system they are intervening in and the activities they are trying to manage. More fundamentally, they need to develop effective means to gather this knowledge. Thus, as is the case in other spheres, being equipped with adequate knowledge may be viewed as crucial to the effectiveness of human action towards sustainability.

In Sections 3, 4, and 5, we present the findings of a review of the literature (outlined previously) from the perspective of each of the above concepts. On the basis of these findings, we constructed the S-Cycle and S-Loop models via a process of induction. The S-Cycle model describes the Earth system and its sub-systems as being comprised of renewable and non-renewable resource stocks, that are consumed and replenished by both natural and human activities. These activities transform input flows of renewable and non-renewable resources into output flows of: (i) intended resources, i.e. entities intended for use in the activity itself; (ii) intended yield, i.e. entities to be yielded to the wider system, either to be used in other activities or to contribute to resource stocks in the system; and (iii) waste, i.e. entities with no utility to the activity, that may be used in other activities or contribute to waste accumulations in the system. The ability of activities in the system to continue to operate fundamentally depends upon the availability of resources in the system. In turn, the availability of resources in the system fundamentally depends upon the rate at which they are consumed and produced by activities. Humans may intervene in these dynamics by implementing sustainability goals and indicators for activities, as described in the S-Loop model below.

The S-Loop model describes human efforts towards sustainability as an iterative process of interpretation and action involving the aforementioned three concepts. In the S-Loop, humans interpret the behaviour of activities in a system to produce knowledge on: (i) their current behaviour; and (ii) how the activities should behave for sustainability, i.e. sustainability goal knowledge. This knowledge serves as a basis for suggesting and implementing actions that are expected to result in the activities fulfilling their sustainability goals. Humans then interpret the behaviour of activities after actions have been taken, by evaluating sustainability indicators to produce knowledge on resulting activity behaviour in relation to sustainability goals. This knowledge may then be used as a basis for suggesting and implementing further actions. For instance, if activities are found not to be on track to fulfil their sustainability goals, humans may suggest actions that are expected to result in the goals being fulfilled in future. Alternatively, they may use this knowledge as a basis from which to begin the whole process again in the context of a different system of interest, having learned from experience.

The S-Loop can provide guidance on how to intervene in a particular system of interest (e.g. businesses, production systems, and organisations generally) in efforts towards sustainability. A key activity described in the S-Loop model is interpreting the behaviour of activities in a particular system of interest, to produce knowledge on current behaviour and sustainability goals. The S-Cycle model can support this activity, by highlighting the aspects of activity behaviour that fundamentally affect sustainability in a system. Thus, the S-Cycle can be applied complementary to the S-Loop, to analyse and understand the behaviour of activities in a system of interest. More fundamentally, the S-Cycle can explain the nature of sustainability in the Earth system in general terms and thus, provides a common language for discussing sustainability both within and across different sectors. Given their general nature, the models provide the basis for a more unified understanding of sustainability among different people and sectors. Further research is under way to explore the validity and applications of the models. However, it is hoped that their use may go some way towards improving the effectiveness of human action towards sustainability.

The remainder of the paper is organised as follows. In Section 2, we briefly consider different definitions and interpretations of sustainability identifiable in the literature, and explicate the interpretation that guided our investigation. In Sections 3, 4, and 5, we present the findings of a literature review on human action towards sustainability from the perspective of systems, activities, and knowledge, as discussed above. In Section 6, we show how these findings were used to construct the S-Cycle and S-Loop models. A brief demonstration of the models is also provided. The paper concludes with a summary of the work in Section 7.

2. What is sustainability?

A definition of sustainability is often the starting point for human efforts towards sustainability (Hannon and Callaghan, 2011; van Zeijl-Rozema and Martens, 2010; Walter and Stützel, 2009). Indeed, if “sustainability” is our goal, then it seems reasonable to suggest that we need some grasp on what exactly this goal represents. As Bell and Morse (2008, p.11) exclaim, “how can we do something unless we know what we are trying to do?” In its most literal form, sustainability simply means the ability to sustain something (Kajikawa, 2008). To gain a deeper understanding of the term, authors have undertaken lexical examinations focusing primarily on the meaning and etymology of “sustain” (Brown et al., 1987; Jamieson, 1998; Kirsch, 2009; Lele and Norgaard, 1996; Shearman, 1990), leading to alternative definitions: the ability to maintain something (Lele and Norgaard, 1996; Marcuse, 1998), and the ability to continue something (Dempsey et al., 2011; Shearman, 1990). Voinov (2007, p.489) appears to suggest that these terms are essentially synonymous, writing that all definitions of sustainability “talk about maintenance, sustenance, continuity of a certain resource, system, condition, relationship.” Indeed, from the perspective of dictionary entries at least, the terms “sustain,” “maintain,” and “continue” hold similar meanings (OED, 2012). Thus, we shall employ them synonymously throughout this paper.

The lexical definitions above are rather abstract – they refer to sustaining something, without specifying what that thing is or how long it is to be sustained for. In order to move from these abstract interpretations of sustainability to a more concrete definition, humans decide what is to be sustained, and for how long (Lele and Norgaard, 1996; Solow, 1993; Vos, 2007). Lele and Norgaard (1996) argue that in executing such decisions, humans must make value judgements. In other words, as humans, what we choose to sustain and for how long depends upon what we value (Chapman, 2011; Lindsey, 2011; Liu et al., 2010). At the highest level, we seem to agree that we want human society to continue as an integral part of the Earth system. However, precisely what kind of society is a matter for considerable debate (Kajikawa, 2008; Parris and Kates, 2003). By specifying exactly what we want to sustain and for how long in a particular context, we may develop more specific definitions of sustainability (Lele and Norgaard, 1996). Vos (2007, p.335) remarks that specific definitions of sustainability “must number in the hundreds.” Given that different people have different value criteria and thus, will naturally consider different things as valuable sustainability targets, this is perhaps unsurprising.

Above, we have implicitly assumed that sustainability is an ability. That is, the ability to sustain is fundamentally an ability in the same vein as the ability to drive a car, the ability to read, and the ability to write (although these are all qualitatively different abilities). It would seem that the lexical definitions of sustainability as the ability to sustain, maintain, or continue something unequivocally point to this interpretation. However, alternative interpretations of sustainability emerge from the literature, including: a process of change (e.g. Kim and Oki, 2011; Wahl and Baxter, 2008); a property or attribute of an entity (e.g. Bodini, 2012; Wahl and Baxter, 2008); and a state of some kind (e.g. Goerner et al., 2009; Heal, 2012). All of these interpretations appear to refer to different "things." Before we can develop models to explain the nature of sustainability in the Earth system, and how humans may effectively strive for it, we need a clear grasp on what kind of "thing" sustainability actually is. To this end, in Section 2.1 we briefly explore the different interpretations of sustainability identifiable in the literature. In Section 2.2, we show how these different interpretations can be made more coherent by considering the nature of "ability" generally, and explicate the interpretation of sustainability that guided our investigation.

2.1 Interpretations of sustainability in the literature

In addition to interpretations of sustainability as an ability (e.g. Dempsey et al., 2011; Hansen, 1996; Kajikawa, 2008), sustainability may also be described as a process of change. In this vein, Kim and Oki (2011, p.248) remark that sustainability is a "dynamic process that requires building resilience and an ability to manage it wisely." Similarly, Wahl and Baxter (2008, p.72) describe sustainability as a "continuous process of learning and adaptation." Wahl and Baxter also highlight another interpretation: sustainability as a property or attribute of an entity. They refer to sustainability as "an emergent property of appropriate interactions and relationships among active participants in the complex cultural, social, and ecological processes that constitute life in the twenty-first century" (Wahl and Baxter, 2008, p.73). Along similar lines, Bodini (2012, p. 140) remarks that sustainability "is an overall attribute that emerges from the internal processes that characterize human–environmental systems." Yet another interpretation is sustainability as some kind of state of an entity. For instance, in the context of flow-networks Goerner et al. (2009, p. 77) suggest that "sustainability can reasonably be defined as the optimal balance of efficiency and resilience" in a flow-network, i.e. some optimal state of the network. In a similar vein, Heal (2012, p. 153) suggests that sustainability "is a potential dynamic equilibrium of some type," i.e. a state of equilibrium.

2.2 The nature of ability

Sustainability is a compound word: sustain + ability. Thus, it may seem rather incongruous to describe sustainability as anything other than an ability. However, examining the nature of "ability" generally suggests that the interpretations of sustainability presented in Section 2.1 are likely to be complementary rather than conflicting. For example, an ability may be described as a property of an entity, that is manifested to humans as behaviour that produces certain effects (Hubka and Eder, 1988; Wang et al., 2008). From this perspective, we may say that the sustainability of an entity is manifested to humans as behaviour that produces the effect of maintenance/continuation, either of the entity in question or some other target. What humans call "sustainability" may be viewed as a property of an entity that exhibits this kind of behaviour. Human cognizance of the property of sustainability results from an assessment of an entity's behaviour, showing that the entity can actually produce the effect of maintenance/continuation (Wang et al., 2008). Until this assessment is made, we may posit that an entity has the ability to sustain the chosen target, on the basis of our knowledge of the entity. But we cannot say that it actually has this ability until we have assessed its behaviour and confirmed that it can indeed sustain the target in question. This point is supported by authors in the sustainability literature. For instance, Costanza and Patten (1995, p.194) write that "determinations of sustainability can only be made after the fact." Similarly, Conway (1986, p.23) remarks that "measurement [of sustainability] is difficult and can often only be done retrospectively." Essentially, sustainability (particularly at the societal level) is often a long term goal, that we may never be able to say we have "attained". Rather, we may continually strive for it and keep track of our progress towards (or away from) it by assessing behaviour.

Above, we have shown that when considered as an ability, sustainability may simultaneously be viewed as a property of an entity (Wang et al., 2008). As discussed above, two further interpretations of the nature of sustainability may be identified in the literature: (i) a process of change (e.g. Kim and Oki, 2011; Wahl and Baxter, 2008), and (ii) a state of some kind (e.g. Goerner et al., 2009; Heal, 2012). Like "ability" and "property," we suggest that these interpretations simply describe different views on the sustainability concept. Firstly, much has been written on the need to transition towards sustainability (Parris and Kates, 2003; Quental et al., 2010). It may clearly be seen from the above that this is a behavioural direction – humans are trying to shift the current behaviour of entities towards the behaviour required for sustainability. With respect to (i), it is clear that in efforts towards sustainability, some kind of process of change is occurring with respect to the behaviour of certain entities. Secondly, as discussed, sustainability is manifested to humans as behaviour that produces the effect of sustenance/ maintenance/continuation (Wang et al., 2008). With respect to (ii), we may consider this manifestation as a kind of state of an entity. That is, the entity is perceived to be behaving in a particular manner (OED, 2012).

In summary, we interpret sustainability as an ability, that is in turn a property of an entity, and manifested to humans as behaviour that produces the effect of maintenance/continuation, either of the entity in question or some other target. In Section 1, it was shown that systems, activities, and knowledge emerge from the literature as key concepts in relation to our aim of modelling to explain the nature of sustainability in the Earth system, and how humans may effectively strive for it. In turn, the findings of a literature review conducted from the perspective of each of these concepts served as a basis for developing two general models via induction: (i) the S-Cycle, and (ii) the S-Loop (introduced in Section 6). Having outlined what we mean by "sustainability," we present the findings of this literature review in Sections 3, 4, and 5.

3. The systems context for sustainability

As discussed in Section 1, systems may be viewed as providing the context for human action towards sustainability. In this vein, Voinov (2007, p.488) suggests that sustainability may be viewed as "a human intervention that is imposed on a system as part of human activity and is totally controlled and managed by humans." Humans are primarily concerned with the sustainability of their society within the Earth system (Beddoe et al., 2009; Komiyama and Takeuchi, 2006; Voinov, 2007), although they tend to focus on different sub-systems of this overall system in order to reduce complexity. To provide insight into the context for human action towards sustainability, we examine and conceptualise the Earth system and its sub-systems in the following sections. In Section 3.1, the general concept of a system is defined, and the relationship between function, behaviour, and structure in a system is delineated. In Section 3.2, the Earth system is outlined. In turn, different sub-systems of the Earth system that commonly form the foci of human efforts towards sustainability are presented.

3.1 What is a system?

Like definitions of sustainability, definitions of "system" abound (Bell and Morse, 2008). However, on a basic level and in a generic sense, a system may be defined as "a collection of elements, also called parts [or components by certain authors], that are each interrelated with at least one other, and which possesses properties different from the collection of properties of the individual parts" (Thomé, 1993, p.4). Thomé (1993, p.5) remarks that systems "are in the eye of the beholder." In other words, systems exist in the "real" world, but must be defined by humans in order to be studied. The author explains that "an observer, through a conscious act of her/his own, chooses to delimit something, that is a system, from its environment." They suggest that "this act follows a purpose of the system that is not necessarily intrinsic to this system but that the observer has in mind." Meadows (2008, p.15) suggests that the terms "purpose" and "function" mean essentially the same thing, i.e. what the system is for (Gero and Kannengiesser, 2004). However, "function is generally used for a nonhuman system, [and] the word purpose for a human one." She goes on to state that this distinction "is not absolute, since so many systems have both human and nonhuman elements" (Meadows, 2008, p.15). We shall use the term "function" throughout this paper to refer to "what a system is for." A system may fulfil its function by exhibiting a certain purposeful behaviour (Hubka and Eder, 1988; Wang et al., 2008).

According to Meadows (2008, pp.1-2), a "central insight of systems theory" is the notion that a "system, to a large extent, causes its own behaviour." She writes that a "system may be buffeted, constricted, triggered, or driven by outside forces. But the system's response to these forces is characteristic of itself." Along these lines, Tully (1993, p.46) remarks that the behaviour of a system is "determined by its structure and the stimuli it actually receives." Essentially, system behaviour may be viewed as an emergent property (Tully, 1993). That is, a property that "is not determined solely from the properties of the system's parts, but which is additionally determined by the system's structure" (Thomé, 1993, p.7). Behaviour refers to what a system does and, as discussed above, how it achieves its functions (Gero and Kannengiesser, 2004; Wang et al., 2008). The structure of a system, on the other hand, refers to "what its components are, how they are connected, and what passes across those connections" (Tully, 1993, p.46). Therefore, it may be seen that the notion of "structure" encompasses both the components of a system, and the relationships among them (Gero and Kannengiesser, 2004; Meadows, 2008). The behaviour of a system is exhibited by its structure, i.e. by its components and relationships (Gero and Kannengiesser, 2004; Wang et al., 2008). That is, humans can "see" the behaviour of a system by observing what its interrelated components do in a particular environment. Hubka and Eder (1988, p.246) highlight that a particular behaviour "does not determine a unique structure." As such, the same kind of behaviour can be exhibited by systems with different structures.

To exemplify the concept of a system, let us consider the context of agriculture. In striving for agricultural sustainability, we may choose to define a particular farm as a system (Darnhofer et al., 2010). We may consider the function of the farm to be, for instance, supplying humans with food and materials (Walter and Stützel, 2009). We may draw a boundary, whereby everything falling within may be considered to be part of the farm, and everything lying outside as part of the farm's environment. A multitude of components may be contained within the system boundary, such as land, machinery, fuel, livestock, feedstock, plants, buildings, humans, and so on (Darnhofer et al., 2010). In turn, these components may be interrelated in a variety of ways. For example, fuel may be used to power machinery and heat buildings, humans may operate machinery to produce feedstock from plants that are harvested from the land, feedstock may be consumed by livestock, livestock may be housed in buildings, and so on. The farm's immediate environment may be a rural locality, containing other farms, villages, towns, etc. (Darnhofer et al., 2010). The purposeful behaviour exhibited by the system in relation to its function may include growing and harvesting certain crops intended for consumption by humans as food and materials, and breeding and selling livestock intended for slaughter and eventual consumption by humans (Tilman et al., 2002).

3.2 The Earth system

Thomé (1993, p.5) remarks that it is "hard to imagine anything that could not be regarded as a system." Skyttner (1996, p.32) highlights the work of Kenneth Boulding (1964), who suggests that, "Everything that exists, whether formal, existential, or psychological, is an organized system of matter, energy, and information." At the highest level, we may even view the whole universe as a system (Brown et al., 2004). Blanchard and Fabrycky (1981, p.5) highlight that, "Since every system is made up of components, any component can be broken down into smaller components. If two hierarchical levels are involved in a given system, the lower is conveniently called a subsystem." In this way, it may be seen that galaxies can be thought of as subsystems of the universe. In turn, galaxies may be broken down into stellar systems, which may then be broken down into solar systems, which may once again be broken down into subsystems such as the Sun and the individual planets (in the case of our own solar system). As discussed above, it may be seen that the Earth system provides the ultimate context for human action towards sustainability (UNEP, 2012).

The Earth system may be viewed as a socio-ecological system (Beddoe et al., 2009). In other words, a system where "society and nature are innately coupled" (Dawson et al., 2010, p.2844). As such, it may be seen that humans are integral components of the system. However, they may also intervene in the system and its subsystems (Beddoe et al., 2009; Dawson et al., 2010). Further, given certain assumptions regarding the negligibility of material inputs and outputs (e.g. owing to space travel and asteroids), the Earth system may be approximated as thermodynamically closed (Daly 1992; Wackernagel and Rees 1997; Cabezas et al. 2005). That is, no mass crosses the system boundary. Only energy crosses the boundary, in the form of heat and work interactions (Çengel and Turner, 2004). A basic function of the Earth system and its sub-systems is processing materials, energy, and information (MEI). Blanchard and Fabrycky (1981, p.4) highlight that some "motive force must be present to provide the alteration." In the context of the whole Earth system, it may be seen that ultimately, this motive force is provided by incoming electromagnetic radiation from the Sun (Stremke et al., 2011).

The Earth system may be broken down into a variety of "open, coupled, complex, interactive and non-linear dynamic [sub-]systems" (Dawson et al., 2010, p.2843). Major sub-systems of the Earth system considered in human efforts towards sustainability include: agricultural systems (e.g. Conway, 1986; Darnhofer et al., 2010; Hansen, 1996; Pretty, 2008); complex systems generally (e.g. Holling 2001; Voinov 2007; Goerner et al. 2009; Dawson et al. 2010; Bodini 2012); economies (e.g. Costanza and Daly 1992; Solow 1993; Brown and Ulgiati 1997; Ekins et al. 2003; Neumayer 2003); ecosystems (e.g. Brown et al. 1987; Gatto 1995; Goerner et al. 2009); organisms (e.g. Costanza and Daly 1992); urban areas (e.g. Maclaren 1996; Dempsey et al. 2011); and societies (e.g. Brown et al. 1987; Dempsey et al. 2011). These systems may be seen to exist at various hierarchical levels. For instance, a human (i.e. organism) may be viewed as a sub-system of a society, which in turn may be viewed as a sub-system of an ecosystem (Köhn, 1998). Given the size of the sustainability literature as discussed in Section 1, the range of systems presented here is not intended to be a comprehensive or absolute representation of all such entities studied in sustainability research. Rather, it is intended to convey those systems that emerge most prominently from the literature as key foci of sustainability research.

As discussed in Section 2, different people want to sustain different things within the Earth system (Lele and Norgaard, 1996; Lindsey, 2011; Chapman, 2011), leading to hundreds of different definitions of sustainability (Vos, 2007). From this perspective, developing a common understanding of sustainability seems to be a difficult task (Lindsey, 2011). In this paper, our approach is to consider that activities are a fundamental target that humans need to sustain. In Section 4, we introduce the general concept of an activity, illustrate the basic behaviour of activities in the Earth system, and show how humans can influence this behaviour towards what is required for sustainability within the system.

4. Sustainable activities

In Section 2, it was shown that sustainability may be generally defined as the ability to sustain (Kajikawa, 2008), maintain (Lele and Norgaard, 1996; Marcuse, 1998), or continue (Dempsey et al., 2011; Shearman, 1990) something. In Section 3, the context for human action towards sustainability, i.e. the Earth system and its sub-systems, was outlined. What humans choose to sustain within this system depends upon what they value (Chapman, 2011; Lindsey, 2011; Liu et al., 2010), as discussed in Section 2. Since different people have different value criteria (Reber, 2011), they want to sustain different things (Lele and Norgaard, 1996; Lindsey, 2011; Chapman, 2011). In turn, a plethora of specific definitions of sustainability may be identified in the literature, focusing on different targets to be sustained in different contexts (Vos, 2007). From this perspective, developing a common understanding of the nature of sustainability seems to be a difficult task (Lindsey, 2011). As discussed in Section 1, our approach in this paper is to consider that activities are a fundamental target that humans need to sustain.

In a system, activities may be viewed as "the fundamental elements that transform input to output" (O'Donnell and Duffy, 2005, p.56). For example, humans need production activities to transform raw materials into useful artefacts (Chapman, 2011), and socio-economic development activities to transform artefacts into intangible entities such as living standards and wellbeing (UNDP, 2011). We need certain natural activities to transform our waste products back into useful resources (Lindsey, 2011) such as water and minerals. At the most fundamental level, we need biological activities to transform food into energy, and air into the oxygen we need to live. Thus, in order to sustain a particular entity, we need to ensure the continued operation of the activities that produce that entity in the first place. Without activities, there would be no life and therefore no society to sustain. Like "system," "activity" is a general concept that may be translated to any context (as shown in the following sections). Thus, discussing sustainability in terms of activities provides us with a general language that may be understood in any context.

In the following sections, we introduce the concept of an activity in the context of the Earth system. In Section 4.1, an activity is defined as a physical or cognitive action that is directed by goals. It is shown that the sustainability of an activity in the Earth system may be considered to be manifested as behaviour that is conducive to the activity's continued operation within the system. In Section 4.2, the basic behaviour of activities operating in the Earth system is discussed. Finally, in Section 4.3, the kinds of relationships that may exist among activities in the Earth system are delineated. In turn, it is shown that sustainability may be viewed either as a property of an individual activity in a system, or an emergent property of a particular system of interest. Humans may influence activities in a system towards what is required for sustainability by implementing activity sustainability goals.

4.1 What is an activity?

An activity may be defined as a goal-directed physical or cognitive action, where a set of passive resources are used by active resources to produce an output that should satisfy the goal of the activity, as shown in Figure 1 (Boyle et al., 2009). Active resources may be viewed as resources that use other resources in activities and may "perform decision-making tasks," and passive resources as resources used by active resources (Boyle et al., 2009). For example, the information contained within defined goals may be considered to be a passive resource for use by active resources such as humans or intelligent software (Duffy, 2005). In a system, passive and active resources, and activity outputs, may be viewed as system components. The label of "passive resource," "active resource," or "output" that is attached to a particular system component depends upon the activities that it is involved in (explored more deeply in Section 4.2). In Section 3.1, it was shown that although systems exist in the "real" world, they must be defined by humans in order to be studied. The same point can be made regarding activities: although they operate in the "real" world, they must be defined by humans in order to be studied (O'Donnell and Duffy, 2005), e.g. by applying the formalism provided in Figure 1. From the work detailed in Duffy (2005, p. 65), it can be inferred that an active resource may be considered as "the means to carry out the activity," and a passive resource as providing "the conditions or elements upon which the means act." As such, it may be seen that the ability of an activity to continue to operate within a system, i.e. its sustainability, depends fundamentally upon the availability of passive and active resources in the system.

Fig. 1. *An activity, where active resources use passive resources to produce an output that meets the goal of the activity. The arrows indicate the direction of flow of material and/or cognitive entities* (see Figure 6-1, Section 6.3.1, Chapter 6 of thesis).

Human action towards sustainability in the Earth system focuses on a range of different activities. These include:

- agricultural activities (Tilman et al., 2002; Walter and Stützel, 2009);
- business activities (Dyllick and Hockerts 2002; Hahn and Figge 2011; Hart and Milstein 2003; Lo 2010; Rainey 2006);
- design activities (Chapman, 2011; Wahl and Baxter, 2008) and the overall design process (Gagnon et al., 2012), given that an activity may be viewed as the basic component of a process (O'Donnell and Duffy, 2005);
- the overarching process of socio-economic development (Burger and Christen 2011; Eurostat 2011a; Holling 2001; UNDP, 2011; Vos 2007; Vucetich and Nelson 2010; Wackernagel and Yount 1998; WCED 1987);
- the activity of fishing (Larkin 1977; Norse et al. 2012; Standal and Utne 2011);

- activities undertaken in the use of forests (Noss 1993; Wiersum 1995), e.g. timber harvesting (Pearce et al., 2003); and
- activities involved in the production of yield generally, e.g. economic activity (Ekins et al., 2003; Figge and Hahn, 2005).

Again, given the size of the sustainability literature as discussed in Section 1, the range of activities presented here is not a comprehensive or absolute account. Rather, it is intended to convey those activities that emerge most prominently from the literature as key foci of sustainability research.

In Section 3.1, it was shown that the behaviour of a system refers to what the system does (Gero and Kannengiesser, 2004; Wang et al., 2008). It is exhibited by the structure of the system (Gero and Kannengiesser, 2004; Wang et al., 2008), i.e. its components and relationships (Tully, 1993). That is, humans can "see" the behaviour of a system by observing what its interrelated components do in a particular environment. Similarly, humans may focus on the behaviour of activities operating in a certain system, i.e. what the activities do within the system (Wang et al., 2008). We may consider this behaviour to be exhibited by the particular set of system components (i.e. passive and active resources, and outputs) involved in the activity. The sustainability of an entity is manifested to humans as behaviour that produces the effect of maintenance/ continuation, either of the entity in question or some other target (Wang et al., 2008), as discussed in Section 2.2. As discussed above, in order to sustain the entities that humans value and that society depends upon, we need to ensure the continued operation of the activities that produce the entity in the first place. In other words, we need to ensure that these activities have the ability to continue operating over time. From this perspective, we may consider activity sustainability to be manifested as behaviour that produces the effect of continuation of the activity per se. In other words, behaviour that is conducive to the continued operation of the activity within the system. As we will show in Section 5.1, this behaviour is constrained by the physical laws and limits of the Earth system, and the moral and social standards of humans.

4.2 Activity behaviour

As shown in Section 2.2, the transition towards sustainability may be viewed as a behavioural direction. Thus, in seeking the sustainability of an activity in the Earth system, humans are attempting to shift its current behaviour towards the behaviour required for sustainability. That is, behaviour that is conducive to the activity's continued operation in the system. In doing so, humans may ensure the continued production of the entities that they value, and that society depends upon. To successfully facilitate a shift in activity behaviour, it is clearly necessary for humans to understand its basic nature. Along these lines, the behaviour of activities operating in the Earth system is outlined in the following paragraphs.

In the literature, the Earth system is typically viewed as containing various stocks of resources. According to Meadows (2008, p.17), a system stock is "a store, a quantity, an accumulation of material or information that has built up over time." Stocks of resources in the Earth system may be classed as either natural (e.g. forests, oceans, land, oil reserves, etc.) or artificial (e.g. economic capital stocks, industrial plant, information/knowledge databases, etc.) (Costanza and Daly 1992; Ekins 2011; Williams and Millington 2004). Further, these stocks may be classified as either renewable or non-renewable in nature (Brown and Ulgiati 1997; Campbell and Garmestani 2012; Daly 1990). That is, resource stocks that either regenerate over time (e.g. forests and oceans), or do not regenerate significantly along anthropological timescales (e.g. oil reserves), respectively (Daly, 1992).

An activity in the Earth system may use components from the above stocks as passive and active resources, to meet a need for resources as indicated by the goal of the activity. As discussed in Section 4.1, the sustainability of an activity in the Earth system fundamentally depends upon the availability of passive and active resources within the system. The term "resource" is defined thus: "A means of supplying a deficiency or need" (OED 2012). It may be seen that both natural and artificial system components may be used as resources in any type of activity. For example, natural activity has, over millions of years, produced crude oil that may be used as a passive resource in the anthropogenic activity of deep-sea drilling. Conversely, anthropogenic activity generates carbon dioxide that may be used as a passive resource by trees in the natural activity of photosynthesis. As discussed in Section 4.1, the active resources use the passive resources to produce outputs that should satisfy the goals of the activity, as shown in Figure 2.

The output of the activity shown in Figure 2 may be broken down into three kinds of components: intended yield, intended resources, and waste, as discussed below.

Yield production by activities:

The activity may produce components that are intended to be yielded to the wider system. These components may either contribute to resource stocks in the system, or they may be used directly as passive and/or active resources in other activities within the system (Brown and Ulgiati 1997; Campbell and Garmestani 2012; Ekins 2011; Liao et al. 2011). They are represented in Figure 3 as intended yield. For example, agricultural activity may produce outputs such as meat and vegetables as yield to be used by humans in the activities of cooking and eating (Kajikawa 2008; Metcalf and Widener 2011).

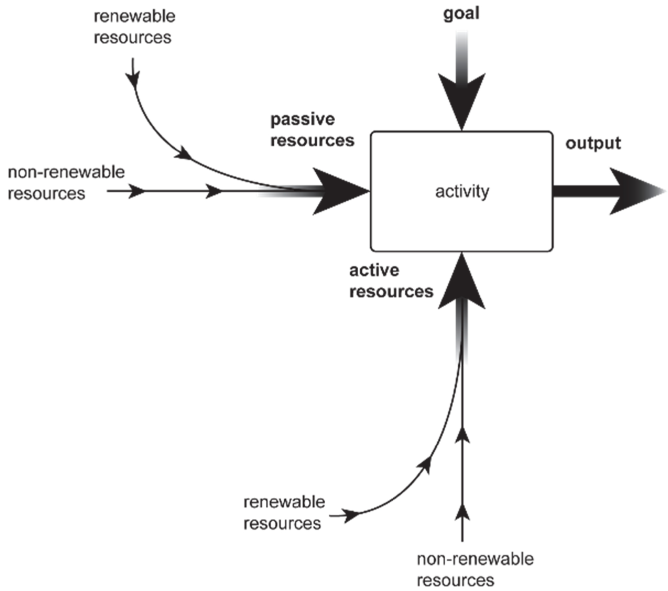


Fig. 2. *An activity operating within the Earth system, where active renewable and non-renewable resources originating in the system use passive renewable and non- renewable resources, also originating in the system. The arrows indicate the direction of flow of material and/or cognitive entities.*

Resource production by activities:

The activity may also produce components intended to be used as passive and/or active resources in the activity itself (Costanza and Daly 1992; Ekins 2011). These are represented in Figure 3 as intended resources. For example, economic activity generates goods and services as an output, a portion of which are intended for use as resources in economic activity itself to produce further goods and services (Ekins 2011; Eurostat 2010; Eurostat 2011a). It should be noted that certain parts of the intended resource stream may conventionally be considered to constitute waste, but are instead to be utilised in the activity as a resource (Marchettini et al. 2007; Yang et al. 2003; Zhang et al. 2011). The term "waste" is used here in a sense slightly modified to that offered by the OED: The by-products of an activity that have no utility to the activity (OED 2012). For example, used cooking oil may from certain perspectives be viewed as waste in relation to the activity of cooking food. However, in order to reduce the environmental impact of cooking food, this oil may be used in the activity as a biofuel (i.e. passive resource) to provide the energy required to heat the food.

Waste production by activities:

In addition to intended resources and yield, the activity may produce components that can be considered to be waste in relation to the activity (Barles 2010; Brown and Ulgiati 1997; Marchettini et al. 2007; Rosen et al. 2008; Zhang et al. 2011), as shown in Figure 3 below. That is, the fraction of the activity's output that is intended neither as yield nor resources and as such, has no utility in relation to the activity (OED 2012). For example, agricultural activity may produce greenhouse gases due to the use of fossil fuels as passive resources, which have no utility in relation to the activity itself and are not intended for use by other activities on Earth (Walter and Stützel, 2009). However, the terms "resource" and "waste" are defined here in relation to the activity under study. As such, components that may be classed as waste in relation to one activity may in fact represent resources to a different activity operating within the Earth system (Marchettini et al. 2007; Raut et al. 2011; Zhang et al. 2011). For example, an empty plastic bottle may be considered as waste in relation to the activity of drinking bottled water, but a passive resource in relation to the activity of recycling plastic.

Note that in the above paragraphs, we have focused primarily on physical examples of resources, yield, and waste. However, it should be noted that since the medium being transformed is MEI (Blanchard and Fabrycky, 1981), the labels of renewable and non-renewable passive and active resources, intended resources, intended yield, and waste may equally be applied to intangible, information-based entities such as knowledge, values, social norms, policies, etc.

Fig. 3. *An activity operating within the Earth system, where active renewable and non-renewable resources use passive renewable and non-renewable resources to produce yield, resources, and waste within the system. The arrows indicate the direction of flow of material and/or cognitive entities* (see Figure 6-2, Section 6.3.2, Chapter 6)

4.3 Sustainability as an emergent property

As discussed previously, in order to sustain entities valued by humans, we need to ensure the sustainability of the activities that produce these entities in the first place. That is, their ability to continue operating within the system. As an ability, sustainability may be viewed as a property of an entity that is manifested as behaviour that produces the effect of maintenance/continuation (Wang et al., 2008), either of the entity in question or some other target (discussed in Section 2.2). In Section 4.1, it was shown that the sustainability of an activity in the Earth system may be considered to be manifested as behaviour that is conducive to the activity's continued operation within the system. From this perspective, we may consider sustainability to be a property of an activity operating within the Earth system.

In Section 4.1, it was shown that a range of different activities form the foci of human efforts towards sustainability. Thus, humans are ultimately concerned with the sustainability of multiple activities in the Earth system, as opposed to one activity in particular. In Section 4.2, we illustrated the basic behaviour of activities operating within the Earth system by focusing on the behaviour of a single activity in isolation. However, as discussed in Section 4.2, certain outputs produced by one activity in the system may be used as resources by other activities in the system. In other words, activities in the Earth system may be coupled (Hubka and Eder, 1988; Turner, 2010; Yin and Xiang, 2009). Activities may be coupled in at least three ways, as shown in Figure 4 below.

Firstly, as discussed in Section 4.2, an activity may produce its own passive and active resources. In such a case, it may be said that the activity displays feedback – that is, part of its output (i.e. intended resources) is used as part of its input (i.e. passive and active resources) (Hubka and Eder, 1988). In short, the activity is coupled with itself. For example, in Figure 4, it may be seen that activity 1 displays feedback, represented by the flow of intended resources. Secondly, as discussed in Section 4.2, the yield or waste produced by one activity may be used as a passive or active resource by another activity in the system. In such a case, it may be said that the two activities are connected in series (Hubka and Eder, 1988). For instance, in Figure 4, it may be seen that the intended yield produced by activity 1 is used as a passive resource by activities 2 and 3. Thus, activity 1 is connected in series with both activities 2 and 3. Further, the waste produced by activity 1 is used as a passive resource by activity 4. Therefore, activity 1 is also connected in series with activity 4. Finally, an activity in the Earth system may share its input of passive or active resources with another activity in the system. In this case, it may be said that the activities are connected in parallel (Hubka and Eder, 1988). For example, in Figure 4, it may be seen that activities 2 and 3 share an input of passive resources originating from the output of activity 1 and thus, are connected in parallel.

Fig. 4. *Multiple activities operating in the Earth system, linked by three kinds of coupling relationship: feedback (represented by the flow of intended resources); connection in series (represented by the flow of waste); and connection in parallel (represented by the flow of intended yield)* (see Figure 6-3, Section 6.3.3, Chapter 6)

According to O'Donnell and Duffy (2005, p.57), a goal may be viewed as referring to "a future situation, which is perceived by the goal originator to be more desirable than the current situation." Given that activities are "goal-directed," it may be seen that humans can influence their behaviour towards what is required for sustainability by formulating and implementing certain activity goals (Eurostat, 2011; Parris and Kates, 2003; Quental et al., 2011). These may be termed "sustainability goals" (Ness et al., 2007, p.498). Owing to the relationships outlined above, sustainability goals implemented to influence the behaviour of one activity in the Earth system may have an indirect impact on the behaviour of other activities to which the activity in question is connected. With respect to sustainability, this impact may not necessarily be a positive one – the kind of behaviour that is conducive to the continued operation of one activity in the Earth system may in fact be detrimental to the sustainability of other activities in the system (Alfaris et al., 2010; Voinov, 2007). For example, consider activities 1 and 4 in Figure 4 above. We may set a sustainability goal for activity 1, focused on reducing the waste produced by the activity (more on sustainability goals in Section 5.1). However, it may be seen that activity 4 relies upon the waste output from activity 1 as a passive resource. As discussed in Section 4.1, an activity fundamentally depends upon resources for its continued operation. Thus, reducing the waste output of activity 1 may compromise the sustainability of activity 4, by reducing the availability of the passive resources it is dependent upon.

From the above, it may be seen that when seeking the sustainability of multiple activities in the Earth system, formulating and implementing sustainability goals for each activity in isolation is unlikely to be effective in bringing about the required behaviour. That is, behaviour that is conducive to the continued operation of the activities collectively. The relationships among the activities must also be taken into account when formulating the goals. As discussed in Section 3.1, the structure of a system refers to "what its components are, how they are connected, and what passes across those connections" (Tully, 1993, p.46). Following on from this, Hubka and Eder (1988, pp.255-257) suggest that we may view the structure of a system from two different perspectives: (i) its component structure, i.e. "structure consisting of components and their relationships" as described above; and (ii) its function structure, i.e. "structure consisting of functions and their relationships, […] structure of activities." If we consider that a particular set of interconnected activities within the Earth system can be partitioned as a sub-system, then it may be seen that sustainability can be described as an emergent property of a particular system of interest (Bodini, 2012; Godfrey, 2010; Wahl and Baxter, 2008). That is, a property that is "not determined solely from the properties of the system's parts, but which is additionally determined by the system's structure (i.e., by the way the parts are connected to form the system)" (Thomé, 1993, p.7). Even if all activities in a system may be said to have the property of sustainability individually, there is no guarantee that the system as a whole also has this property.

As discussed in Section 4.1, the sustainability of an activity in the Earth system may be considered to be manifested as behaviour that is conducive to the activity's continued operation within the system. In turn, the sustainability of a system may be considered to be manifested as behaviour that is conducive to the continued operation of the system as a whole within its wider environment. In Section 3.1, it was shown that system behaviour per se may be viewed as an emergent property (Tully, 1993). Thus, for sustainability to emerge in a system, the behaviour of individual activities within the system must contribute to the kind of system behaviour described above. As such, it may be seen that to successfully shift a system toward the behaviour required for sustainability, it is possible that certain activities in the system may have to cease operation. For example, certain authors suggest that in order to achieve sustainability of the global economic system within the Earth system, the activity of economic growth needs to be halted (Daly, 1990).

In the literature, sustainability may be described as an emergent property of the whole Earth system, including human society as an integral part. For example, Wahl and Baxter (2008, p. 73) remark that sustainability may be viewed as an emergent property of "the complex dynamic system that contains culture and nature." As shown in Section 3.2, a range of different sub-systems of the Earth system are considered in human efforts towards sustainability. Accordingly, sustainability may also be positioned as an emergent property of sub-systems of the Earth system. In this vein, Bodini (2012, p. 140) describes sustainability as "an overall attribute that emerges from the internal processes that characterize human–environmental systems." In the context of the built environment, Godfrey (2010, p.219) suggests that sustainability "may be seen as an emergent property of the complex systems involved."

The emergent nature of sustainability in the Earth system and its sub-systems may be problematic for humans. As shown above, when seeking sustainability in a system, knowledge on the relationships between the activities in the system is required when formulating sustainability goals. However, in certain cases, it may be difficult for humans to decipher these relationships (Komiyama and Takeuchi, 2006; Quental et al., 2010). Bodini (2012, p. 140) suggests that in large-scale economic, social, and environmental systems, relationships reach such a high degree of complexity that "our perception of cause and effects is confounded." As a result, it may be difficult to predict the impact that sustainability goals will actually have on the behaviour of individual activities and in turn, the system of interest as a whole.

In summary, we may view sustainability as a property from two perspectives:

i. A property of an individual activity in a system, manifested as behaviour that is conducive to the activity's continued operation within the system. That is, the ability of an activity to continue to operate within a system.
ii. An emergent property of a particular system of interest, manifested as behaviour that is conducive to the continued operation of the system as a whole within its environment. That is, the ability of a system to continue operating within its environment. In order for sustainability to emerge in a system, the behaviour of all activities in the system must contribute to this kind of system behaviour (given that system behaviour per se may be viewed as an emergent property (Tully, 1993)).

As discussed above, humans may influence the behaviour of activities in the Earth system and its sub-systems towards what is required for sustainability by implementing sustainability goals (Ness et al., 2007; O'Donnell and Duffy, 2005). A goal refers to a future situation that is considered to be more desirable than the current one, and may be viewed as a component of human knowledge (O'Donnell and Duffy, 2005). Thus, it may be seen that in formulating sustainability goals for activities in the Earth system and its sub-systems, humans are interpreting their current behaviour to produce knowledge on how they should behave with respect to sustainability in the system of interest (Derissen et al., 2011). In this vein, the production and use of knowledge in human efforts towards sustainability is examined in Section 5.

5. Sustainability knowledge

As discussed in Section 1, knowledge may be viewed as a driver of human action, both generally and in efforts towards sustainability. For example, Newell (1982, p.100) describes knowledge generally as "a potential for generating action." In a similar vein, Meadows (1998, p.3) positions knowledge of "the discrepancy between the desired state or goal and the perceived state of [a] system" as a driver of human action towards sustainability. In the following sections, we examine key components of knowledge involved in human action towards sustainability. Note that throughout, we employ the term "knowledge" in a broad sense to include "expert knowledge," but also less concrete elements such as “implicit theories on how the physical world behaves,” “outcome foci,” “experiences,” (Reber, 2011) and also perceptions (Gero and Kannengiesser, 2004).

As discussed in Section 4.3, humans may influence the behaviour of activities in a system towards what is required for sustainability by implementing sustainability goals (Eurostat, 2011; Parris and Kates, 2003; Quental et al., 2011). Sustainability goals, like all goals, refer to a future situation that is considered to be more desirable than the current one (O’Donnell and Duffy, 2005), and may be viewed as key components of knowledge involved in efforts towards sustainability. As discussed in Section 5.1 below, sustainability goals are formulated on the basis of how humans perceive the behaviour of an activity, i.e. knowledge on current behaviour. Humans take action to implement goals and bring about a shift in behaviour on the basis of these two components of knowledge.

In addition to formulating and implementing sustainability goals, it is clearly also necessary to determine whether or not they are being fulfilled (Derissen et al., 2011; Eurostat, 2011a; Ness et al., 2007; van Zeijl-Rozema and Martens, 2010). To do so, humans need knowledge on the behaviour of activities in relation to sustainability goals, after the goals have been implemented (Jordan et al., 2010; van Zeijl-Rozema and Martens, 2010). As we will show in Section 5.2 below, the process of sustainability assessment (SA) may be viewed as the primary means by which humans gain such knowledge. Humans define or select indicators to assess the behaviour of an activity in relation to its sustainability goals, and then evaluate these indicators to gain knowledge on actual behaviour. Measures may also be selected to provide a holistic view on the behaviour of systems from the perspective of sustainability.

5.1 Sustainability goals

As discussed above, sustainability goals, like all goals, refer to a future situation that is considered to be more desirable than the current one. They may be viewed as components of knowledge, describing how an activity should behave with respect to sustainability in a particular system of interest (Ness et al., 2007; O’Donnell and Duffy, 2005). In order to formulate sustainability goals for an activity in a system, humans must interpret its current behaviour (Jordan et al., 2010; Walter and Stützel, 2009). In Section 4.2, it was shown that the use and production of resources, the production of yield, and the production of waste may be viewed as basic aspects of the behaviour of activities operating in the Earth system. Humans may interpret these aspects of a particular activity’s behaviour, to produce knowledge on current behaviour and to formulate sustainability goals for the activity (Eurostat, 2011a; Meadows, 1998; Parris and Kates, 2003; Walter and Stützel, 2009). On the basis of what they know about the activity’s behaviour, humans can suggest actions to be taken with respect to the system components involved in the activity, that are expected to result in the activity fulfilling its sustainability goals. To actually implement the goals, humans then carry out these actions (Eurostat, 2011a; Parris and Kates, 2003). For instance, if humans formulate the goal of “minimise fossil fuel consumption” for agricultural activity within a farming system, they may take action to allocate alternative renewable passive resources to the activity so that it fulfils the goal.

As an example, the work of Daly (1990) may be seen to point to a number of sustainability goals. The goals focus on resource use and waste production, and are intended to influence the behaviour of human activity generally towards sustainability in the Earth system. Firstly, Daly suggests that non-renewable resources “cannot be maintained intact short of nonuse.” That is, since they are not believed to be regenerated significantly along anthropological timescales of thousands of years (Daly, 1992), depletion of non-renewable resource stocks may be considered to be irreversible as shown in case (a) in Figure 5. Given that like all activities, human activities depend fundamentally upon resources for their continued operation (discussed in Section 4.1), they should not use non-renewable resources. The eventual total depletion of non-renewable resource stocks would compromise the sustainability of human activity generally in the Earth system. To implement this goal (in highly simplified terms), humans may allocate renewable resources to their activities to replace any non-renewable resources that are currently used.

With respect to renewable resources, Daly (1990a, p. 2) argues that "harvest rates should equal regeneration rates." In other words, using renewable resources faster than stocks are regenerated may lead to depletion of renewable resource stocks (Campbell and Garmestani, 2012), as shown in case (b) in Figure 5. Again, because of human activities' reliance upon resources for their continued operation, they should use renewable resources at rates equal to or less than the regeneration rate of resource stocks to avoid depletion, as illustrated in cases (c) and (d) in Figure 5 respectively. To implement this goal (again, in highly simplified terms), humans may take action to reduce the rate at which their activities consume renewable resources. Note that in addition to consuming renewable resources, it is also activities (both anthropogenic and natural) that regenerate the stocks of such resources in the Earth system. As shown in Section 4.2, activities produce yield, i.e. useful components that are intended to be yielded to the wider system. These components may be used directly as resources in other activities within the system, or they may contribute to resource stocks in the system (Brown and Ulgiati 1997; Campbell and Garmestani 2012; Ekins 2011; Liao et al. 2011).

Finally, with respect to waste production, Daly (1990a, p. 2) writes that for sustainability, "waste emission rates should equal the natural assimilative capacities of the ecosystems into which the wastes are emitted." Emitting more waste than can be processed within the Earth system at a given time may lead to accumulations of waste within the system, as shown in Figure 6. In other words, the Earth system may become polluted (Zhang et al., 2011). If waste accumulates in the Earth system, then in addition to resources, an activity may also draw in waste as an unintended input as shown in Figure 6. In turn, this may have some detrimental effect on the activity that compromises its ability to continue operating.

For example, the activity of driving a vehicle may produce waste gases that are noxious to humans. Collectively, these kinds of activities across society may produce noxious gases in excess of what can be processed in a timely fashion by natural activities. As a result, the gases are believed to accumulate in the air surrounding urban areas in the form of smog. In turn, human beings may unintentionally draw in these gases as an input to the activity of breathing. Since the gases are noxious to humans, this action may damage the lungs of the human being, which may be viewed as an active resource in the activity of breathing. If the lungs are damaged to a large enough extent, then the activity of breathing will cease to continue, i.e. the sustainability of the activity will be compromised. Given the potentially detrimental effects of excess waste on the sustainability of activities, human activities should produce waste at rates less than or equal to the rate that other activities in the Earth system can process it (given that waste in relation to one activity may be used as a resource in other activities as discussed in Section 4.2). To implement this goal (once again, in highly simplified terms), humans may take action to reduce the rate at which their activities produce waste.

Fig. 5. *An activity consuming resources at removal rate R_{rem} from a physical stock with regeneration rate R_{regen}. Depending on the relative magnitudes of R_{rem} and R_{regen}, the stock will be depleted, maintained, or increased* (see Figure 3-4, Section 3.4, Chapter 3 of thesis)

From the above example based on the work of Daly (1990), it may be seen that one set of considerations governing the formulation of sustainability goals is the physical laws and limits of the Earth system, e.g. the laws of thermodynamics, biological limits, and ecological limits. Walter and Stützel (2009, p. 1276) delineate sustainability goals for agriculture that may be seen to pertain to resource use, yield production, and waste production as highlighted in square brackets below. They write that "to be sustainable, agriculture must:

- supply humanity with food and fibre of sufficient quantity and quality [yield production goal];
- not endanger Earth's life support systems (such as the climate system and the functioning of ecosystems) or natural resources (including biotic and abiotic resources, soils and biodiversity) [resource use and waste production goals];
- allow producers to make a secure livelihood [yield production goal];
- contribute to rural development and the enhancement of rural communities;

- ensure the health of workers, rural populations and consumers;
- be equitable, just and produce in a socially accepted way."

These goals may be seen to highlight another aspect considered when formulating sustainability goals: the moral and social impacts of behaviour (Eurostat, 2011a; Parris and Kates, 2003). Voinov (2007, p.495) suggests that "sustainability is all about livelihood for humans as part of the ecosystem. We do not talk about sustainability of ecosystems in the absence of humans." From this perspective, it may be seen that humans strive for sustainability, but not at the expense of human society and wellbeing. Therefore, in formulating sustainability goals for activities, it is not sufficient to influence activity behaviour (outlined in Section 4.2) on the basis of the physical laws and limits of the Earth system alone. Additionally, the moral and social impacts of the resulting behaviour must be considered (Kajikawa, 2008). For example, we may influence the behaviour of agricultural activity so that it uses fewer non-renewable resources to produce yield for humans (e.g. food and materials), in order to ensure its continued operation in the Earth system. However, if this resulting behaviour involves the exploitation of humans through unpaid labour and excessive working hours, then according to the prevailing moral and social standards of numerous societies, it would likely be considered unacceptable (even if it is physically sustainable).

From the above, it may be seen that in addition to the physical laws and limits of the Earth system, the formulation of sustainability goals is also governed by the moral and social standards of humans. In Section 4.3, we suggested that in the context of activities and systems, sustainability may be viewed from two different perspectives: (i) the ability of an activity to continue operating within a system; and (ii) the ability of a particular system of interest to continue operating within its environment. However, it may now be seen that from a human perspective, it is not sufficient for an activity or system to simply "continue operating" – they must continue operating in a manner that is socially acceptable. In this vein, Vucetich and Nelson (2010, pp.539-540) suggest that sustainability can be either "virtuous" or "vulgar," depending upon the ethical standards of those seeking it. They argue that, "Progress in understanding and achieving sustainability requires addressing it as both a scientific and an ethical issue."

Fig. 6. *An activity producing waste within the Earth system, at rate W_{prod}, to be processed as a passive resource at rate W_{proc} by a different activity within the system. The arrows indicate the direction of flow of material and/or cognitive entities* (see Figure 3-5, Section 3.4, Chapter 3 of thesis).

5.2 Sustainability assessment

As discussed in Section 4.1, humans may influence the behaviour of activities towards what is required for sustainability via sustainability goals (Eurostat, 2011; Parris and Kates, 2003; Quental et al., 2011). These are formulated on the basis of the (i) physical laws and limits of the Earth system (Daly, 1990), and (ii) moral and social standards of humans (Kajikawa, 2008; Walter and Stützel, 2009), as shown in Section 5.1. In turn, these goals are implemented by humans who suggest and then carry out actions that are expected to result in the activity fulfilling its goals (Eurostat, 2011a; Parris and Kates, 2003). After implementation, it is clearly necessary to ascertain whether or not the goals are being fulfilled. Given that sustainability is often a long term goal that we may never actually attain (as discussed in Section 2.2), it is at least necessary to monitor whether or not the activity in question is on track to fulfil its sustainability goals, i.e. whether its behaviour is moving in the desired direction. To do so, humans need to interpret its behaviour after sustainability goals have been implemented, to produce knowledge on how it behaves in relation to its goals (Jordan et al., 2010; van Zeijl-Rozema and Martens, 2010). In the context of sustainability, these efforts may be termed "sustainability assessment" (Bodini, 2012; Ness et al., 2007).

As shown in Section 5.1, sustainability goals focus on: (i) the use and production of resources, the production of yield, and the production of waste by activities within the physical constraints of the Earth system; and (ii) the moral and social impacts of this behaviour. Therefore, to assess an activity's behaviour in relation to sustainability goals, it is necessary to at the very least define measures that will provide a window on these aspects when evaluated (Wang et al., 2008). Along these lines, McCool and Stankey (2004, p.298) write of the need to link "specific measurable variables" to sustainability goals. Measures employed to evaluate behaviour in sustainability assessment may generally be referred to as sustainability indicators (SIs) (Ness et al. 2007; Jordan et al. 2010; Ramos and Caeiro 2010; Rametsteiner et al. 2011; van Zeijl-Rozema and Martens 2010; Singh et al. 2012). SIs need not necessarily be quantitative in nature. For instance, Meadows (1998, p.9) distinguishes between objective and subjective SIs. She writes that the former are those that are "sensed by instruments outside the individual – thermometers, voltmeters, counters, dials, rulers. They can be verified by others. They can be expressed in numbers." In contrast, she remarks that subjective SIs are those that "are sensed only within the individual by means that may not be easily explained and in units that are probably not numerical." In short: "Objective indicators primarily measure quantity. Subjective indicators primarily measure quality."

Analysing the range of indicators identifiable in the literature reveals that they may be broadly split into four categories, which are briefly delineated below. A categorisation of sustainability indicators and the approaches used to evaluate them is shown in Figure 7.

Fig. 7. *Hierarchy showing major categories of sustainability indicators identifiable in the literature, examples of specific indicators, assessment approaches associated with each category, and the main behavioural aspects covered by indicators in each category* (see Figure 3-7, Section 3.5.1, Chapter 3 of thesis)

Hak et al. (2012, p. 46) suggest that although it is not possible to put an absolute figure on the number of indicators currently in use, "we can assume the existence of hundreds of various indices and sets of indicators or even several thousands of such metrics if individual indicators are included." As such, the categories provided below are not claimed to be exhaustive. Rather, based on the literature, they are intended to represent the indicator types most commonly encountered in sustainability assessment research:

- *Accounting indices (AIs)*, which focus mainly upon the resource use, yield production, waste production, and social impacts of development and economic activities in the Earth system (Galli et al., 2012; Ness et al., 2007; Singh et al., 2012). AIs are typically evaluated retrospectively through natural resource accounting (Galli et al., 2012), national wealth accounting (Alfsen and Greaker, 2007), and green national accounting (World Bank, 2010a) approaches. Examples include the Ecological Footprint (Galli et al., 2012; Wackernagel and Yount, 1998), the Adjusted Net Savings index (World Bank 2010a), and the Genuine Progress Indicator (Posner and Costanza, 2011).
- *Energetic and physical flow indicators (EPFIs)*, which focus mainly upon the resource use and yield production behaviour of production activities in the Earth system (Brown and Ulgiati, 1997), and the behaviour of production systems (Coppola et al., 2009; Liao et al., 2011) and regional systems (Campbell and Garmestani, 2012; Gasparatos et al., 2009a,b). EPFIs are typically evaluated retrospectively through energy analysis (Ertesvag, 2005; Liao et al., 2011), exergy analysis (Gasparatos et al., 2009b), emergy accounting (Campbell and Garmestani, 2012; Liu et al., 2012), and material flow analysis (Eurostat, 2011b; Ness et al., 2007) approaches. Examples include energy efficiency (Liao et al., 2011), exergy efficiency (Gasparatos et al., 2009b; Rosen et al., 2008), percent renewable emergy (Brown and Ulgiati, 1997; Campbell and Garmestani, 2012), and resource productivity (Eurostat, 2011a; Eurostat, 2011b).
- *Sustainable development indicators (SDIs)*, focusing primarily upon the resource use, yield production, waste production, and social impacts of development activities in the Earth system (Eurostat, 2011a; Ness et al., 2007; Pülzl et al., 2011; Ramos and Caeiro, 2010). SDIs are typically evaluated retrospectively through progress monitoring (Eurostat, 2011a; van Zeijl-Rozema and Martens, 2010) and prospectively through impact assessment (European Commission, 2009; De Smedt, 2010) approaches. Examples include the Eurostat set of SDIs (Eurostat, 2011a), and the United Nations Commission on Sustainable Development's set of over one hundred Indicators of Sustainable Development (UN, 2007).
- *Ecological indicators (EIs)*, which are holistic measures focusing upon the resource use and yield production behaviour of whole systems (Bodini, 2012; Ulanowicz et al., 2009). EIs are typically evaluated retrospectively through ecological network analysis (Bodini, 2012;

Li and Yang, 2011). Examples include ascendency (Bodini, 2012; Li and Yang, 2011; Ulanowicz, 1980; Ulanowicz et al., 2009), total system throughput (Bodini, 2012; Ulanowicz, 1980; Ulanowicz et al., 2009), and overhead (Bodini, 2012; Ulanowicz, 1980; Ulanowicz et al., 2009).

Meadows (1998, p.10) highlights that, "When a system is extremely complex, it takes trial, error, and learning to produce a serviceable set of indicators." The definition and selection of SIs for activities in a particular system of interest is by no means an easy task. Firstly, there may be a range of potential SIs that could be used to assess the behaviour of an activity in relation to sustainability goals (Meadows, 1998). As such, Meadows (1998, p.9) highlights that the "very choice of an indicator is based upon some value, some inner human purpose that tells us what is important to measure." In turn, authors have emphasised the importance of involving multiple stakeholders in discussions on SIs (Celino and Concilio 2010; Garmendia and Stagl 2010; Robinson et al. 2011; Yang et al. 2011), including both expert stakeholders (e.g. natural scientists, sociologists, and engineers), and citizen stakeholders and their representatives (e.g. product users, local inhabitants, and politicians), to account for different values and perspectives (Pülzl et al. 2011; Rametsteiner et al. 2011). However, these differences mean that considerable negotiation may be involved in efforts to define or select SIs, which can be time consuming and fraught with intractable disagreements (Meadows, 1998).

Secondly, the choice of SIs may have an unintended and undesired impact on the behaviour of activities in a system. In this vein, Meadows (1998, p.3) remarks that, "When indicators are poorly chosen, they can cause serious malfunctions." For example, measures of CO2 emissions may be employed to assess the behaviour of businesses in relation to sustainability goals focused on reducing the level of CO2 produced (Eurostat, 2011a). Logically, the intention would seem to be that if we measure the amount of CO2 being emitted by businesses in relation to this goal, then businesses will reduce their CO2 emissions over time in order to meet the goal. However, certain decision makers react by offsetting their businesses' CO2 emissions. That is, rather than taking action to reduce their CO2 emissions, they take action to "cancel out" their CO2 emissions by, for example, planting extra trees to process CO2, or investing in carbon sequestration schemes (Norgaard, 2010). It may be argued that actually reducing the CO2 emitted is more desriable behaviour than offsetting with respect to sustainability (Norgaard, 2010). Measuring CO2 emissions seems like an obvious choice in relation to a goal to reduce the level of CO2 produced. Nonetheless, in doing so, we have created an unintended and arguably undesirable behaviour among businesses within the Earth system. Meadows (1998, p.10) remarks that there is "no shame in having a wrong model or a misleading indicator, only in clinging to it in the face of contradictory evidence." Thus, the process of defining and selecting SIs for activities in a system must be "evolutionary." The "necessary process is one of learning."

Sustainability assessment may be conducted at a range of scales, from local to global (Ness et al., 2007) as shown in Figure 8. Essentially, as we increase the scale of assessment from local to global, we are extending the boundary of the system of interest within which the behaviour of activities is interpreted (Ulgiati et al., 2011). For example, let us return to the context of agriculture, and consider the activity of crop production with a sustainability goal to "minimise non-renewable resource (NRR) consumption." At the local scale, we may assess only the direct inputs of NRRs required for operation of the activity, e.g. the inputs of petrol and oil for machinery. At the regional scale, however, we may additionally assess certain indirect inputs of NRRs to the activity, e.g. the NRRs that were consumed in extracting raw materials and converting them into petrol and oil for machinery. Finally, at the global scale, we may also assess the inputs to the activity directly from the biosphere (i.e. ecosystem services), e.g. the actual raw materials extracted from non-renewable stocks such as oil fields to produce petrol and oil (Ulgiati et al., 2011). With each increase in scale, the boundary of the system of interest is extended to include inputs originating from more activities and resource stocks than were considered at the previous scale. Thus, we may evaluate the same SI at different scales, and obtain different results. As such, Ulgiati et al. (2011, p.177) remark that the "value of a given indicator is only 'true' at the scale at which it is calculated." Furthermore, they highlight the importance of scale when interpreting the behaviour of an activity:

"if a process evaluation is performed at a small scale, its actual performance may not be well understood and may be overestimated due to a lack of inclusion of some large-scale impacts."

Fig. 8. *The varying spatial scale of sustainability assessment. The x-axis represents the scale of assessment, ranging from local, up to regional and global, whilst the y-axis represents the extent of the boundary of the system of interest for interpreting activity behaviour* (see Figure 3-9, Section 3.5.1, Chapter 3 of thesis).

In addition to spatial scale, time is another factor that may influence the way that activity behaviour is interpreted during sustainability assessment. For instance, Bell and Morse (2008, p. 16) highlight that from the perspective of sustainability, the behaviour of an entity may fluctuate considerably over long time periods. As such, depending upon the intervals at which this behaviour is assessed, "the interpretation of the trend [from the perspective of sustainability] in each block of time may be quite different" to one another, and to the interpretation of the behaviour of the system over multiple intervals i.e. in the longer term. They argue that the "choice of the starting point" or baseline for a sustainability assessment effort "can influence the results." As discussed in Section 2.3, sustainability is often a long term goal, that we may never be able to say that we have "attained". Rather, we may track our progress towards or away from it by continually assessing behaviour. As such, authors emphasise the need to adopt both long- and short-term perspectives in sustainability assessment (Ness et al., 2007). Assessment may be carried out retrospectively to produce knowledge on actual behaviour, or prospectively to produce knowledge on potential future behaviour (Ness et al. 2007; Rametsteiner et al. 2011). Given its future-oriented nature, the information obtained on behaviour through prospective sustainability assessment may be viewed as inherently uncertain (Upham et al., 2011). As such, authors comment on the need to acknowledge and manage uncertainty in prospective sustainability assessment (Benoît et al., 2009; De Lara and Martinet, 2009; Upham et al., 2011).

In summary, sustainability assessment consists of: (i) defining/selecting SIs to assess the behaviour of activities in a particular system of interest, in relation to their sustainability goals; and then (ii) evaluating these SIs to produce knowledge on the behaviour of the activities in question. Based on the above discussion, the overarching sustainability assessment process is represented graphically in Figure 9. Knowledge on behaviour obtained through the evaluation of SIs may be used in the execution of decisions relating to sustainability (Ness et al. 2007; De Smedt 2010; Heijungs et al. 2010; Ramos and Caeiro 2010; Rametsteiner et al. 2011; Singh et al. 2012), and thus be used to determine an appropriate course of action to be taken with respect to the sustainability of an activity or a whole system (Boyle et al., 2012). For instance, upon interpretation, the values obtained for a set of SIs selected to assess activities in a particular system of interest system may show that the activities are not on track to fulfil their sustainability goals. On the basis of this knowledge, humans may suggest and implement actions that are intended to shift the behaviour of the activities in the desired direction.

Fig. 9. *The sustainability assessment process, beginning with sustainability goals for an activity and consisting of the activities of: defining or selecting indicators, and evaluating indicators to obtain indicator values. The process may draw upon both expert and citizen knowledge throughout* (see Figure 3-10, Section 3.5.1, Chapter 3).

6. The Sustainability Cycle and Loop

As discussed in Section 1, the investigation documented in this paper aimed to develop models to explain the nature of sustainability in the Earth system, and how humans in different sectors may effectively strive for it. Three concepts initially emerged from the literature as significant for detailed investigation in relation to this aim:

- *systems*, as the context for human action towards sustainability;
- *activities*, as the most fundamental target that humans need to sustain within the Earth system; and
- *knowledge*, as the driver of human action towards sustainability.

The findings of a review of the sustainability literature from the perspective of the above three concepts were presented in Sections 3, 4, and 5. The corpus examined included sources from multiple sectors (outlined in Section 1), to gain a view that is as free from contextual nuances as possible. In Section 3, the Earth system was characterised as the ultimate context for human action towards sustainability, and different sub-systems of this overall system were discussed. In Section 4, the concept of an activity was defined in the context of the Earth system. It was shown that sustainability may be viewed either as a property of an individual activity in a system, or an emergent property of a particular system of interest. Humans may influence the behaviour of activities in a system towards what is required for sustainability by implementing activity sustainability goals. Finally, in Section 5, it was shown that humans formulate sustainability goals by interpreting the behaviour of activities in a particular system of interest. The formulation of these goals is governed by (i) the physical laws and limits of the Earth system, and (ii) the moral and social standards of humans. The goals are implemented via actions that produce effects on the system components involved in the activities, resulting in a change in activity behaviour. To determine if the goals are being fulfilled or not, humans interpret activity behaviour after they have been implemented by defining and evaluating SIs.

In the following sections, we show how the findings of the literature investigation briefly summarised above were used to develop two models via a process of induction: (i) the Sustainability Cycle (S-Cycle), describing the operation of activities in a system from the perspective of sustainability; and (ii) the Sustainability Loop (S-Loop), describing a basic process that may lead humans towards sustainability. In Section 6.1, we develop the S-Cycle model on the basis of the literature on systems and activities covered in Sections 3 and 4. In Section 6.2, we introduce the S-Loop model. First, we highlight a basic process followed by humans striving for sustainability that emerges from the literature covered in Section 5. This may be described as an iterative process of interpretation and action, involving the concepts of systems, activities, and knowledge reviewed in Sections 3, 4, and 5. Next, we show that humans striving for sustainability may be considered to operate between two different "worlds": the external world, where activities and systems exist; and the interpreted world, where knowledge exists. We then develop the S-Loop model by describing the iterative process in the context of the external and interpreted worlds. Finally, in Section 6.3, we provide a brief demonstration of the models by applying them to a bioethanol production system described in the literature.

6.1 The S-Cycle model

As discussed throughout the paper, activities may be viewed as a fundamental target that humans need to sustain within the Earth system. In a system, activities may be viewed as "the fundamental elements that transform input to output" (O'Donnell and Duffy, 2005, p.56). For example, humans need production activities to transform raw materials into useful artefacts (Chapman, 2011), and socio-economic development activities to transform goods and services into intangible entities such as living standards and wellbeing (UNDP, 2011). We need certain natural activities to transform our waste products back into useful resources (Lindsey, 2011) such as water and minerals. At the most fundamental level, we need biological activities to transform food into energy, and air into the oxygen we need to live. Thus, in order to sustain a particular entity, we need to sustain the activities that produce that entity within the Earth system.

Like all systems, the Earth system can be viewed as "an organized system of matter, energy, and information" (Skyttner, 1996, p.32). In Section 3.2, it was shown that this system may be approximated as a thermodynamically closed system (Daly 1992; Wackernagel and Rees 1997; Cabezas et al. 2005), whose primary external energy source is the Sun (Stremke et al., 2011) as shown in Figure 10 below. Processing MEI may be viewed as a basic function of the system (Bodini, 2012; Brown et al., 2004; Cabezas et al., 2005; Ulanowicz, 1980). The Earth system may also be described as a socio-ecological system, i.e. one where "society and nature are innately coupled" (Dawson et al., 2010, p.2844). Therefore, human beings themselves may be viewed as components of the system (Beddoe et al., 2009). As discussed in Section 4.2, the Earth system contains stocks of natural and artificial components (Costanza and Daly 1992; Ekins 2011; Williams and Millington 2004), that may be classed as either renewable or non-renewable in nature (Brown and Ulgiati 1997; Campbell and Garmestani 2012; Daly 1990), again shown in Figure 10.

The S-Cycle model describes the operation of activities in the Earth system from the perspective of sustainability. The model is presented in Figure 11, and is described here in relation to the literature that it was induced from. In Section 4.2, it was shown that an activity can be defined as a goal-directed physical or cognitive action, where a set of passive resources are used by active resources to produce an output that should satisfy the goal of the activity (Boyle et al., 2009). Activities may use components from the renewable and non-renewable resource stocks in the system as passive and active resources, to produce an output consisting of three kinds of components, again shown in Figure 11: intended yield, i.e. components intended to be yielded to the wider system, that may be used directly as resources in other activities in the system, or may contribute to resource stocks in the system (Brown and Ulgiati 1997; Campbell and Garmestani 2012; Ekins 2011; Liao et al. 2011); intended resources, i.e. components intended to be used in the activity itself as passive and active resources (Costanza and Daly 1992; Ekins 2011); and waste, i.e. components that are intended neither as yield nor resources and thus, have no utility in relation to the activity (Barles 2010; Brown and Ulgiati 1997; Marchettini et al. 2007; Rosen et al. 2008; Zhang et al. 2011). Therefore, it may be seen that the sustainability of activities in the Earth system, i.e. their ability to continue to operate, depends fundamentally upon the availability of passive and active resources in the system. In turn, as discussed in Section 5.1, the availability of resources in the system depends upon the rate at which activities in the system consume and produce them. Consuming renewable resources faster than stocks are regenerated will lead to depletion of the stocks, and consuming non-renewable resources at any rate will deplete stocks since they are not regenerated significantly along anthropological timescales (Daly, 1990).

Fig. 10. *The Earth system, represented as a closed system whose primary external energy source is electromagnetic radiation from the Sun* (see Figure 6-4, Section 6.5.1, Chapter 6 of thesis)

In Section 4.3, it was shown that in addition to being viewed as a property of an individual activity in a system, sustainability may also be viewed as an emergent property of a particular system of interest (Bodini, 2012; Godfrey, 2010; Wahl and Baxter, 2008), i.e. a sub-system of the Earth system. For sustainability to emerge in a system, the behaviour of all activities in the system must contribute to the continued operation of the system within its environment (given that system behaviour per se may be viewed as an emergent property (Tully, 1993), as discussed in Section 3.1). These activities are likely to be coupled with one another, often in complex ways (Hubka and Eder, 1988; Turner, 2010; Yin and Xiang, 2009) as shown in Section 4.3. We may represent the total activity operating in a system in precisely the same way as we represent an individual activity (O'Donnell and Duffy, 2005), i.e. using the formalism first provided in Figure 1 in Section 4.1. Thus, the S-Cycle model presented in Figure 11 may be interpreted as describing the operation of an individual activity in the Earth system, or the total system activity, i.e. the aggregate of all natural and anthropogenic activities operating in the system at a given time.

Fig. 11. *The Sustainability Cycle (S-Cycle) model, describing the operation of activities in a system from the perspective of sustainability* (see Figure 6-5, Section 6.5.1, Chapter 6).

The S-Cycle model may be used as a tool to support the analysis of activities in a particular system of interest from the perspective of sustainability, as will be demonstrated in Section 6.3. In Figure 11, the system boundary is represented as that of the whole Earth system. However, the S-Cycle model is generic – it describes the operation of activities in a system in completely general terms (e.g. it does not make reference to specific kinds of resources, yield, and waste, only the stocks and flows of these kinds of entities generally). Thus, we may represent the system boundary in Figure 11 as that of any particular system of interest within the Earth system. In short: we may apply the S-Cycle model to any system at any level. The location of the system boundary will determine the specific activities, stocks, and flows to be studied.

6.2 The S-Loop model

The S-Cycle model, introduced in Section 6.1, illustrates that the sustainability of activities in the Earth system depends fundamentally upon the availability of resources in the system. In turn, the availability of resources in the system depends upon the rate at which activities in the system consume and produce them. In Section 5, it was shown that humans may intervene in these dynamics by implementing sustainability goals to influence the behaviour of activities in a particular system of interest, and then assessing the resulting behaviour. Considering the literature covered in Section 5 holistically reveals a general process undertaken by humans striving for sustainability in different sectors, consisting of the following basic activities:

- interpret the behaviour of activities in a particular system of interest within the Earth system (Jordan et al., 2010; Walter and Stützel, 2009), to produce knowledge on their current behaviour, and how the activities should behave with respect to sustainability (Derissen et al., 2011) – that is, knowledge on sustainability goals (O'Donnell and Duffy, 2005);
- implement sustainability goals by suggesting and taking actions that produce effects on the system components involved in the activities, and are expected to result in the activities fulfilling their goals (Eurostat, 2011a; Parris and Kates, 2003);
- determine if activities have fulfilled, or are on track to fulfil sustainability goals by assessing their behaviour after the goals have been implemented, to produce knowledge on that behaviour (Jordan et al., 2010; Ness et al., 2007; van Zeijl-Rozema and Martens, 2010); and
- on the basis of this knowledge, suggest and take actions regarding the sustainability of the activities and/or the system of interest as a whole (Ness et al. 2007; De Smedt 2010; Heijungs et al. 2010; Ramos and Caeiro 2010; Rametsteiner et al. 2011; Singh et al. 2012), e.g. if activities are not on track to fulfil their sustainability goals, humans may suggest and take actions to ensure that they are fulfilled in future, or they may begin the whole process again in the context of a different system, having learned from experience.

It may be seen that this process is essentially iterative: humans interpret the behaviour of activities in a system to produce knowledge, and then on the basis of this knowledge, take action to alter the behaviour of the activities and the overall system (given that system behaviour may be viewed as an emergent property, as discussed in Section 3.1). They then interpret the resulting behaviour to produce further knowledge and on the basis of this, suggest further actions to be taken. In other words: knowledge on behaviour determines the actions taken by humans striving for sustainability, and the actions taken by humans striving for sustainability result in the production of new knowledge on behaviour that determines further actions to be taken by humans, and so on and so forth.

According to Gero and Kannengiesser (2004, p.378), interpretation "transforms variables, which are sensed in the external world into the interpretations of sensory experiences, percepts and concepts that compose the interpreted world." They suggest that action may be viewed as "a transformation of an expected concept into an external representation." The result of action is "an effect, which brings about a change in the external world." Thus, it may be argued that humans striving for sustainability, via the iterative process of interpretation and action delineated above, operate between two different "worlds": (i) the external world, which may be viewed as the world "composed of representations outside" of a human (Gero and Kannengiesser, 2004, p.377) i.e. the world that is extrinsic to the human mind; and (ii) the interpreted world, which may be viewed as the world composed of "sensory experiences, percepts and concepts" (Gero and Kannengiesser, 2004, p.377) i.e. the inner mental world of a human. Clearly, different people may interpret representations in the external world in different ways and thus, the interpreted worlds of different people may be quite dissimilar in nature. As Meadows (1998, p.8) highlights, "people of different worldviews live literally in different worlds." This is arguably one of the reasons for the considerable variety in the targets we wish to sustain (Section 2), interpretations of sustainability (Section 2.1), sustainability goals (Section 5.1), and sustainability indicators (Section 5.2). In fact, it is worthwhile considering that the work reported in this paper represents the authors' interpretation of certain external representations, i.e. the sustainability literature. Other authors may have different interpretations of the same literature.

Above, Gero and Kannengiesser (2004) refer to both interpretation and action as the transforming of one thing into another. As highlighted throughout this paper, activities may be viewed as "the fundamental elements that transform input to output" (O'Donnell and Duffy, 2005, p.56). Therefore, it may be seen that both interpretation and action, as carried out in human efforts towards sustainability, may be viewed as activities, in precisely the same sense as the activities we are trying to maintain. For example, humans, as active resources, may undertake interpretation of an activity's behaviour with the goal of producing knowledge on that behaviour. They may use observations of behaviour as passive resources, to produce knowledge on behaviour as an output that satisfies the goal of the interpretation activity (the activity of interpretation is explored further below). Similarly, humans acting as active resources may use knowledge on activity sustainability goals as a passive resource in implementation activities, with the goal of altering activity behaviour so that sustainability goals are fulfilled. Thus, it may be seen that in human efforts towards sustainability, two sets of activities are involved: (i) the activities whose operation we are trying to maintain; and (ii) the activities we undertake in order to manage the behaviour of (i).

To characterise the external and interpreted worlds from a sustainability perspective, we may map the concepts of systems, activities, and knowledge to each world by considering the activity of human interpretation. Firstly, systems may be considered to exist in the external world. However, as highlighted in Section 3.1, systems "are in the eye of the beholder" (Thomé, 1993, p.4). As such, whilst they exist in the external world, systems may be considered to be defined for study in the interpreted world. That is, humans interpret the world around them to produce knowledge on a particular system of interest, as shown in Figure 12. Thus, systems may be considered to exist in the external world, but knowledge on the systems under study may be viewed as existing in the interpreted world, again shown in Figure 12.

Like systems, activities may be considered to operate in the external world. However, as shown in Section 4.1, activities must also be defined for study by humans (O'Donnell and Duffy, 2005), e.g. by applying the formalism provided in Figure 1 in Section 4.1. Therefore, in the same manner as humans define systems, they interpret the world around them to produce knowledge on activities in a particular system of interest. As such, activities may be viewed as existing in the external world, but knowledge on the activities under study exists in the interpreted world, as shown in Figure 12.

Finally, as shown above, humans interpret the external world to produce knowledge on that world that is held within the human mind. To provide further examples, humans interpret the behaviour of activities to produce knowledge on their current behaviour and how they should behave with respect to sustainability (i.e. knowledge on sustainability goals), and their behaviour in relation to sustainability goals (shown in Figure 12 above). As such, knowledge may be viewed as existing solely within the interpreted world. However, note that knowledge may be represented in the external world (Newell, 1982). For example, in this paper, knowledge on the operation of activities in the Earth system and its sub-systems from the perspective of sustainability has been represented in the form of the S-Cycle model (Figure 11), that exists in the external world. Furthermore, knowledge existing in the interpreted world may be transformed into effects in the external world via action, as highlighted by Gero and Kannengiesser (2004) above.

In the S-Loop model, systems (Figure 10) and activities (Figure 11) are represented in the external world, whilst key components of knowledge employed in human action towards sustainability (Figure 12) are represented in the interpreted world. These three entities, i.e. systems, activities, and knowledge, are linked via the iterative process of interpretation and action outlined previously. The entities are presented at different levels so that they may be positioned relative to one another, according to their roles in the iterative process. The model is presented in Figure 13, and is described in relation to the literature it was induced from below.

As shown in the S-Loop model, the Earth system, like all systems, exhibits behaviour, i.e. it "does something". This behaviour is exhibited by the structure of the system (Gero and Kannengiesser, 2004; Wang et al., 2008), i.e. by its components and relationships (Tully, 1993) (discussed in Section 3.1). In turn, humans may focus on the behaviour of activities operating in the system. The behaviour of an activity may be viewed as the behaviour exhibited by the particular set of system components (i.e. passive and active resources, and outputs) involved in the activity (discussed in Section 4.1). In Section 3.2, it was shown that humans per se may be viewed as integral components of the Earth system (Beddoe et al., 2009; Dawson et al., 2010). Thus, we may consider humans to exist as components of the Earth system at the system level in the S-Loop model. In turn, given that interpretation and action may be viewed as activities as discussed above (Gero and Kannengiesser, 2004), it may be seen that humans carry out interpretation and actions at the activity level in the S-Loop. Humans may be viewed as active resources in these activities.

In the S-Loop model, the iterative process that emerges from the literature covered in Section 5 (outlined above) is described as follows. Humans interpret the behaviour of activities in a particular system of interest (i.e. sub-system of the Earth system) in the external world (Jordan et al., 2010; Walter and Stützel, 2009), to produce knowledge on current behaviour and how the activities should behave with respect to sustainability, i.e. knowledge on sustainability goals (Ness et al., 2007; O'Donnell and Duffy, 2005) (formulated on the basis of (i) the physical laws and limits of the Earth system (Daly, 1990), and (ii) the moral and social standards of humans (Kajikawa, 2008; Walter and Stützel, 2009), as discussed in Section 5.1). Both of these knowledge elements exist at the knowledge level in the interpreted world. On the basis of this knowledge, humans may suggest actions to be taken, that are expected to result in the activities fulfilling their goals. They may then actually take action at the activity level of the external world (Eurostat, 2011a; Parris and Kates, 2003), to produce effects on the system components involved in the activities (existing at the system level of the external world). These effects bring about a change in the behaviour of the activities at the activity level of the external world (discussed in Section 5.1). To determine if activities have fulfilled, or are on track to fulfil their sustainability goals, humans interpret activity behaviour after the goals have been implemented by defining and evaluating SIs (Ness et al. 2007; Jordan et al. 2010; Ramos and Caeiro 2010; Rametsteiner et al. 2011; van Zeijl-Rozema and Martens 2010; Singh et al. 2012). In other words, they carry out sustainability assessment (Bodini, 2012; Ness et al., 2007) at the activity level of the external world (discussed in Section 5.2). Like knowledge on current behaviour and sustainability goals, knowledge on post-action activity behaviour exists at the knowledge level in the interpreted world. On the basis of the latter component of knowledge, humans may again suggest actions to be taken regarding the sustainability of the activities and/or the system of interest as a whole (given that sustainability may be viewed as an emergent property of a system (Bodini, 2012; Godfrey, 2010; Wahl and Baxter, 2008), as discussed in Section 4.3). For example, if activities are found not to be on track to fulfil their sustainability goals, humans may suggest actions that are expected to result in the goals being fulfilled in future. Alternatively, they may use this knowledge as a basis from which to begin the whole process again in the context of a different system of interest, having learned from experience.

Fig. 12. *The activity of interpretation, where observations of the external world are used as a passive resource by humans (i.e. active resources), to produce knowledge that exists in the interpreted world* (see Figure 6-6, Section 6.5.2, Chapter 6).

As will be demonstrated in Section 6.3, the S-Loop model may be applied to guide efforts towards sustainability in the context of a particular system of interest. A key activity described in the S-Loop is interpreting the behaviour of activities in a system to produce knowledge on current behaviour and sustainability goals. Since it describes the operation of activities in a system from the perspective of sustainability, the S-Cycle model may be used to guide this interpretation activity. Thus, the S-Cycle model may be applied complementary to the S-Loop model, to support the interpretation activities described in the latter.

Fig. 13. *The Sustainability Loop (S-Loop) model, describing human efforts towards sustainability as an iterative process of knowledge production and action, involving systems, activities, and knowledge* (see Figure 6-7, Section 6.5.2, Chapter 6).

6.3 The S-Cycle and S-Loop models in practice

Research is currently under way to explore the validity of the S-Cycle and S-Loop models in depth, and their applicability and usefulness in practice. Nonetheless, to illustrate their intended use, a brief demonstration is provided in this section by applying the models to a system described in Ulgiati et al. (2011, p.182): a production system for the industrial conversion of corn into bioethanol. The authors provide an energy systems diagram for the system, presented in Figure 14. This diagram, along with its accompanying description, provided the majority of the data required to briefly apply the S-Cycle and S-Loop models; however, certain data were extracted from a table of SIs provided on p.181 of Ulgiati et al. (2011). As we show below, the S-Loop model may be applied to provide guidance on how to shift the system towards sustainability, whilst the S-Cycle model may be applied to support interpretation of the behaviour of activities in the system.

According to the S-Loop model, humans seeking sustainability in a particular system of interest (SOI) must first interpret the behaviour of activities operating in the system. This activity should yield knowledge on current activity behaviour, and activity sustainability goals. To carry out this task, we may apply the S-Cycle model to the production system described in Ulgiati et al. (2011, pp.180-182). Firstly, we will define the boundary of the SOI to include the bioethanol plant, and also the resource stocks providing its direct inputs as described in the energy systems diagram in Figure 14 above. Next, we must define the activities whose behaviour we will focus on within the SOI. As shown in Figure 14, Ulgiati et al. (2011, p.182) describe a number of interconnected "process steps" within the production system. Using the S-Cycle model, each of these process steps may be represented as an activity. For example, in Figure 14, it may be seen that DDGS drying has the following inputs: electricity, flue gases, goods and machinery, labour and services, and distilled corn. The output of this process step consists of warm gases, and DDGS. Assuming that labour and machinery use electricity, flue gases, goods and services, and distilled corn to produce DDGS, we may represent DDGS drying as an activity as shown in Figure 15. Labour and machinery may be classed as active resources (i.e. resources that use other resources in an activity (Boyle et al., 2009)), whilst electricity, flue gases, goods and services, and distilled corn may be classed as passive resources (i.e. resources used by active resources in an activity (Boyle et al., 2009)). DDGS represents the output of the activity, and "produce DDGS" may be viewed as a high-level goal of the activity.

Fig. 14. *Energy systems diagram of a bioethanol production system (from Ulgiati et al., 2011)* (see Figure 7-4, Section 7.1.2, Chapter 7).

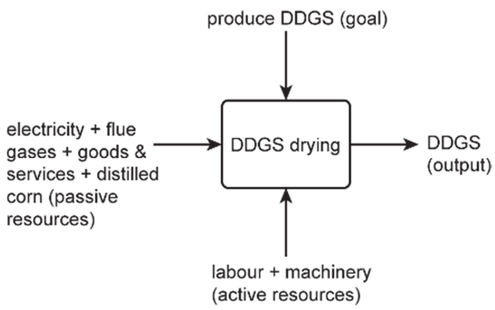


Fig. 15. *DDGS drying from Ulgiati et al. (2011) represented as an activity.*

Although we may represent each of the process steps as an individual activity using the S-Cycle model, this would make for a rather in-depth treatment of the SOI that would likely exceed the necessary space limitations of a journal article. Therefore, we may instead represent the aggregate of these activities, i.e. the activity of "bioethanol production" as shown in Figure 16. Using the S-Cycle model, we may interpret the behaviour of this activity within the SOI as shown in Figure 16. The activity is carried out by labour, machinery, enzymes, and yeasts (renewable active resources), that use air, water, corn and residues, electricity, and goods and services (renewable passive resources), along with coal (non-renewable passive resource), to produce an output consisting of: ethanol and DDGS (intended yield); high pressure steam, low pressure steam, electricity, flue gases, low pressure water condensate, and warm gases (intended resources); and solid emissions and greenhouse gases (waste). Note that the intended resources were identified as the inputs to process steps that originate from other process steps included in the overall activity of bioethanol production. That is, resources produced by the bioethanol production activity that are intended for use in the activity itself. Note also that the bioethanol production activity does not use any non-renewable active resources, does not produce any yield that may be considered to be non-renewable, and does not produce any intended active resources (only intended passive resources).

We may now interpret the behaviour of the bioethanol production activity, represented in Figure 16, to set sustainability goals for the activity. For example, we may formulate the following goals, among others:

1. Minimise coal use (since activities should not use non-renewable resources (Daly, 1990), as discussed in Section 5.1).
2. Minimise solid emissions (since activities should not produce excessive waste (Daly, 1990), as discussed in Section 5.1).
3. Minimise greenhouse gas emissions (for the same reason as goal 2 above).
4. Maximise the fraction of the electricity input that comes from the intended resources stream (to improve the activity's ability to continue operating in the event of disruption to the external electricity supply).
5. Ensure that ethanol produced meets the quality standards of humans (since any ethanol that does not meet these standards may have to be disposed of, i.e. represents waste and also, to eliminate any negative social impacts that may arise from the continued production of poor quality ethanol).

Fig. 16. *Interpretation of the behaviour of a bioethanol production activity using the S-Cycle model* (see Figure 7-4, Section 7.1.2, Chapter 7 of thesis).

Next, the S-Loop model prescribes that we must suggest and then implement actions that are expected to result in the activity fulfilling its sustainability goals. Without access to the actual system, it is rather difficult to suggest realistic actions. Furthermore, it is not possible to demonstrate the implementation of these actions here. However, for the purposes of this simple analysis, the following actions may be generally expected to result in the fulfilment of the above goals:

- To fulfil goals 1 and 3, we may install a renewable energy production system (e.g. a solar system) within the bioethanol plant to replace or reduce the input of coal.
- To fulfil goal 2, we may set up a scheme whereby the solid emissions from the plant are captured and recycled or stored.
- To fulfil goal 4, we may increase the internal energy production of the activity by installing electricity production equipment with a higher output capacity in the bioethanol plant.
- To fulfil goal 5, we may ensure that equipment in the plant is cleaned regularly, that adequate training is provided for human resources, and that the best quality yeast and enzymes are used in the plant.

Finally, according to the S-Loop model, we must interpret the post-action behaviour of the bioethanol production activity by carrying out sustainability assessment. That is, by defining SIs that allow us to assess the behaviour of the activity in relation to its sustainability goals, and then evaluating these SIs to produce knowledge on that behaviour. Ulgiati et al. (2011, p.181) provide a set of SIs for bioethanol production, along with SI values. Some of these may be used to assess the behaviour of the bioethanol production activity (represented in Figure 16) in relation to the sustainability goals defined above. In other cases, example SIs have been defined below. Again, without access to the actual system, it is not possible to evaluate these SIs to produce knowledge on activity behaviour, and there is no guarantee that these SIs would be measurable in practice. They are intended as examples only.

- To assess activity behaviour in relation to goal 1, we may, for instance, define the SI 'tons of coal consumed per unit of bioethanol produced.'
- To assess behaviour in relation to goal 2, we may define the SI 'grams of solid emissions per unit of bioethanol produced' (Ulgiati et al., 2011).

- To assess behaviour in relation to goal 3, we may define the SI 'grams of CO2 equivalent produced per gram of bioethanol produced' (Ulgiati et al., 2011).
- To assess behaviour in relation to goal 4, we may define the SI 'internally produced electricity consumed as a fraction of the total electricity input per annum.'
- To assess behaviour in relation to goal 5, we may define the SI 'number of satisfied customers per 1000 customers.' Alternatively, we may define a qualitative, subjective indicator such as 'perceived quality of ethanol by customers.'

If we were to evaluate the SIs suggested above, we may be able to determine whether or not the bioethanol production activity is on track to fulfil its sustainability goals or not, and suggest an appropriate course of action in this respect. For example, if we evaluated the SI 'grams of solid emissions per unit of bioethanol produced' over a period of several months and found that the value of the SI was continually rising, this may indicate that the activity is not on track to fulfil goal 2 above. In turn, we may suggest and take action to, for instance, accelerate the implementation of a scheme to capture and recycle or store solid emissions (outlined above).

7. Conclusion

In spite of a considerable body of research on sustainability, recent reports suggest that we are barely any closer to a more sustainable society (Eurostat, 2011; UNEP, 2012). There is an urgent need to improve the effectiveness of human efforts towards sustainability. A clearer and more unified understanding of sustainability among different people and sectors could help to facilitate this (Hannon and Callaghan, 2011; Lindsey, 2011). Along these lines, this paper has presented the results of an inductive literature investigation focusing on sustainability and human action towards it across society. The aim was to develop models to explain the nature of sustainability in the Earth system, and how humans in different sectors may effectively strive for it. The major contributions made by the investigation are two general and complementary models, developed via a process of induction from the literature: (i) the Sustainability Cycle (S-Cycle), describing the operation of activities in a system from the perspective of sustainability; and (ii) the Sustainability Loop (S-Loop), describing a basic process that may lead humans towards sustainability in the context of a particular system of interest.

Literature from multiple sectors identified as major contributors to sustainability research was selected for review, to gain a view that is as free from contextual nuances as possible. From this literature, three concepts emerged as significant for detailed investigation in relation to our aim: (i) systems, as the context for human action towards sustainability (Bell and Morse, 2008; Bodini, 2012; Fiksel, 2003); (ii) activities, as a fundamental target that humans need to sustain within the Earth system (given their instrumental role in producing the entities both needed and desired by society (O'Donnell and Duffy, 2005)); and (iii) knowledge, as the driver of human action towards sustainability (Meadows, 1998; Newell, 1982). In Section 3, the Earth system was characterised as the ultimate context for human action towards sustainability (UNEP, 2012), and different sub-systems of this overall system were discussed. In Section 4, the concept of an activity was introduced, and the basic behaviour of activities operating in the Earth system was outlined. It was shown that sustainability may be viewed either as a property of an individual activity in a system, or an emergent property of a particular system of interest (Bodini, 2012; Godfrey, 2010; Wahl and Baxter, 2008). Humans may influence the behaviour of activities in a system towards what is required for sustainability by implementing activity sustainability goals (Eurostat, 2011; Parris and Kates, 2003; Quental et al., 2011). Finally, in Section 5, it was shown that humans formulate sustainability goals by interpreting the behaviour of activities in a particular system of interest. The formulation of these goals is governed by (i) the physical laws and limits of the Earth system (Daly, 1990), and (ii) the moral and social standards of humans (Kajikawa, 2008; Walter and Stützel, 2009). The goals are implemented via actions (Eurostat, 2011a; Parris and Kates, 2003) that produce effects on the system components involved in the activities, resulting in a change in activity behaviour. To determine if the goals are being fulfilled or not, humans interpret activity behaviour after they have been implemented by defining and evaluating SIs (Ness et al. 2007;

Jordan et al. 2010; Ramos and Caeiro 2010; Rametsteiner et al. 2011; van Zeijl-Rozema and Martens 2010; Singh et al. 2012).

In Sections 6.1 and 6.2, the S-Cycle and S-Loop models were introduced and discussed in relation to the literature that they were induced from. The S-Cycle model describes the Earth system and its sub-systems as being comprised of renewable and non-renewable resource stocks, that are consumed and replenished by both natural and human activities. These activities transform input flows of renewable and non-renewable passive and active resources into output flows of: (i) intended resources, i.e. entities intended for use in the activity itself (Costanza and Daly 1992; Ekins 2011); (ii) intended yield, i.e. entities to be yielded to the wider system (Brown and Ulgiati 1997; Campbell and Garmestani 2012; Ekins 2011; Liao et al. 2011), either to be used in other activities or to contribute to resource stocks in the system; and (iii) waste, i.e. entities with no utility to the activity (Barles 2010; Brown and Ulgiati 1997; Marchettini et al. 2007; Rosen et al. 2008; Zhang et al. 2011), that may be used in other activities or contribute to waste accumulations in the system. The ability of activities in the system to continue to operate (i.e. their sustainability) fundamentally depends upon the availability of resources in the system. In turn, the availability of resources in the system fundamentally depends upon the rate at which they are consumed and replenished by activities. Humans may intervene in these dynamics by implementing sustainability goals and indicators for activities, as described in the S-Loop model below.

The S-Loop model describes human efforts towards sustainability as an iterative process of interpretation and action involving the aforementioned three concepts. In the S-Loop, humans interpret the behaviour of activities in a system to produce knowledge on: (i) their current behaviour (Meadows, 1998); and (ii) how the activities should behave for sustainability (Derissen et al., 2011), i.e. sustainability goal knowledge (O'Donnell and Duffy, 2005). This knowledge serves as a basis for suggesting and implementing actions that are expected to result in the activities fulfilling their sustainability goals. Humans then interpret the behaviour of activities after actions have been taken, by evaluating sustainability indicators to produce knowledge on resulting activity behaviour in relation to sustainability goals (Jordan et al., 2010; Ness et al., 2007; van Zeijl-Rozema and Martens, 2010). This knowledge may then be used as a basis for suggesting and implementing further actions. For instance, if activities are found not to be on track to fulfil their sustainability goals, humans may suggest actions that are expected to result in the goals being fulfilled in future. Alternatively, they may use this knowledge as a basis from which to begin the whole process again in the context of a different system of interest, having learned from experience.

In Section 6.3, a brief demonstration of the models was provided by applying them to a bioethanol production system described in the literature (Ulgiati et al., 2011). It was shown that the S-Loop model may be used to guide efforts towards sustainability in the context of a particular system of interest, by prescribing the basic activities that should be undertaken. A key activity described in the S-Loop model is interpreting the behaviour of activities in a particular system of interest, to produce knowledge on current behaviour and sustainability goals. The S-Cycle model can support this activity, by highlighting the aspects of activity behaviour that fundamentally affect sustainability in a system. Thus, as shown in Section 6.3, the S-Cycle model may be applied complementary to the S-Loop model, to support the interpretation activities described in the latter. More fundamentally, the S-Cycle can explain the nature of sustainability in the Earth system in general terms (i.e. in terms of systems and activities), and thus, provides a common language for discussing sustainability both within and across different sectors. Given their general nature, the models provide the basis for a more unified understanding of sustainability among different people and sectors. Further research is under way to explore the validity and applications of the models. However, it is hoped that their use may go some way towards improving the effectiveness of human action towards sustainability.

Acknowledgements

The authors gratefully acknowledge the University of Strathclyde for funding the research documented in this paper through the award of a University of Strathclyde Research Studentship.

References

Alfaris, A., Siddiqi, A., Rizk, C., de Weck, O., Svetinovic, D., 2010. Hierarchical Decomposition and Multidomain Formulation for the Design of Complex Sustainable Systems. J. Mech. Des. 132, 091003–1 – 091003–13.
Alfsen, K.H., Greaker, M., 2007. From natural resources and environmental accounting to construction of indicators for sustainable development. Ecol. Econ. 61, 600–610. doi:10.1016/j.ecolecon.2006.06.017
Barles, S., 2010. Society, energy and materials: the contribution of urban metabolism studies to sustainable urban development issues. J. Environ. Plan. Manag. 53, 439–455. doi:10.1080/09640561003703772
Baumgärtner, S., Quaas, M., 2010. What is sustainability economics? Ecol. Econ. 69, 445–450. doi:10.1016/j.ecolecon.2009.11.019
Beddoe, R., Costanza, R., Farley, J., Garza, E., Kent, J., Kubiszewski, I., Martinez, L., McCowen, T., Murphy, K., Myers, N., Ogden, Z., Stapleton, K., Woodward, J., 2009. Overcoming systemic roadblocks to sustainability: the evolutionary redesign of worldviews, institutions, and technologies. Proc. Natl. Acad. Sci. U. S. A. 106, 2483–2489. doi:10.1073/pnas.0812570106
Bell, S., Morse, S., 2008. Sustainability indicators: measuring the immeasurable?, 2nd ed. Earthscan, London.
Benoît, C., Mazjin, B., Andrews, E.S., Barthel, L.-P., Ciroth, A., Cucuzzella, C., Gensch, C.O., 2009. Guidelines for Social Life Cycle Assessment of Products. United Nations Environment Programme, Druk in de weer, Belgium.
Blanchard, B.S., Fabrycky, W.J., 1981. Systems Engineering and Analysis. Prentice-Hall, Inc., Englewood Cliffs, New Jersey.
Bodini, A., 2012. Building a systemic environmental monitoring and indicators for sustainability: What has the ecological network approach to offer? Ecol. Indic. 15, 140–148. doi:10.1016/j.ecolind.2011.09.032
Boyle, I.M., Duffy, A.H.B., Whitfield, R.I., Liu, S., 2009. Towards an understanding of the impact of resources on the design process, in: 17th International Conference on Engineering Design (ICED `09). The Design Society, Stanford.
Boyle, I.M., Duffy, A.H.B., Whitfield, R.I., Liu, S., 2012. The impact of resources on decision making. Artif. Intell. Eng. Des. Anal. Manuf. 26, 407–423.
Brown, B.J., Hanson, M.E., Liverman, D.M., Merideth, R.W., 1987. Global sustainability: Toward definition. Environ. Manage. 11, 713–719. doi:10.1007/BF01867238
Brown, M.., Ulgiati, S., 1997. Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation. Ecol. Eng. 9, 51–69. doi:10.1016/S0925-8574(97)00033-5
Brown, M.T., Odum, H.T., Jorgensen, S.., 2004. Energy hierarchy and transformity in the universe. Ecol. Modell. 178, 17–28. doi:10.1016/j.ecolmodel.2003.12.002
Burger, P., Christen, M., 2011. Towards a capability approach of sustainability. J. Clean. Prod. 19, 787–795. doi:10.1016/j.jclepro.2010.06.019
Cabezas, H., Pawlowski, C.W., Mayer, A.L., Hoagland, N.T., 2005. Sustainable systems theory: ecological and other aspects. J. Clean. Prod. 13, 455–467. doi:10.1016/j.jclepro.2003.09.011
Campbell, D.E., Garmestani, A.S., 2012. An energy systems view of sustainability: emergy evaluation of the San Luis Basin, Colorado. J. Environ. Manage. 95, 72–97. doi:10.1016/j.jenvman.2011.07.028
Celino, A., Concilio, G., 2010. Explorative Nature of Negotiation in Participatory Decision Making for Sustainability. Gr. Decis. Negot. 20, 255–270. doi:10.1007/s10726-010-9197-3
Çengel, Y.A., Turner, R.H., 2004. Fundamentals of thermal-fluid sciences, 2nd ed. McGraw-Hill, Boston, London.
Chapman, J., 2011. Emotionally Durable Design, 3rd ed. Earthscan, London, Washington DC.
Conway, G.R., 1986. Agroecosystem analysis for research and development. Winrock International, Bangkok.
Coppola, F., Bastianoni, S., Østergård, H., 2009. Sustainability of bioethanol production from wheat with recycled residues as evaluated by Emergy assessment. Biomass and Bioenergy 33, 1626–1642. doi:10.1016/j.biombioe.2009.08.003

Costanza, R., Daly, H.E., 1992. Natural Capital and Sustainable Development. Conserv. Biol. 6, 37–46. doi:10.1046/j.1523-1739.1992.610037.x

Costanza, R., Patten, B.C., 1995. Defining and predicting sustainability. Ecol. Econ. 15, 193–196. doi:10.1016/0921-8009(95)00048-8

Daly, H.E., 1990. Toward some operational principles of sustainable development. Ecol. Econ. 2, 1–6. doi:10.1016/0921-8009(90)90010-R

Daly, H.E., 1992. Steady-state economics, 2nd ed. Earthscan, London.

Darnhofer, I., Fairweather, J., Moller, H., 2010. Assessing a farm's sustainability: insights from resilience thinking. Int. J. Agric. Sustain. 8, 186–198.

Dawson, T.P., Rounsevell, M.D.A., Kluvánková-Oravská, T., Chobotová, V., Stirling, A., 2010. Dynamic properties of complex adaptive ecosystems: implications for the sustainability of service provision. Biodivers. Conserv. 19, 2843–2853. doi:10.1007/s10531-010-9892-z

De Lara, M., Martinet, V., 2009. Multi-criteria dynamic decision under uncertainty: a stochastic viability analysis and an application to sustainable fishery management. Math. Biosci. 217, 118–24. doi:10.1016/j.mbs.2008.11.003

De Smedt, P., 2010. The Use of Impact Assessment Tools to Support Sustainable Policy Objectives in Europe. Ecol. Soc. 15.

Dempsey, N., Bramley, G., Power, S., Brown, C., 2011. The social dimension of sustainable development: Defining urban social sustainability. Sustain. Dev. 19, 289–300. doi:10.1002/sd.417

Derissen, S., Quaas, M.F., Baumgärtner, S., 2011. The relationship between resilience and sustainability of ecological-economic systems. Ecol. Econ. 70, 1121–1128. doi:10.1016/j.ecolecon.2011.01.003

Duffy, A., 2005. Design process and performance, in: Clarkson, J., Huhtala, M. (Eds.), Engineering Design - Theory and Practice, A Symposium in Honour of Ken Wallace. Engineering Design Centre, University Of Cambridge, pp. 76–85.

Dyllick, T., Hockerts, K., 2002. Beyond the business case for corporate sustainability. Bus. Strateg. Environ. 11, 130–141.

Ehrlich, P.R., Ehrlich, A.H., 2013. Can a collapse of global civilization be avoided? Proc. Biol. Sci. 280, 20122845. doi:10.1098/rspb.2012.2845

Ekins, P., 2011. Environmental sustainability: From environmental valuation to the sustainability gap. Prog. Phys. Geogr. 35, 629–651. doi:10.1177/0309133311423186

Ekins, P., Simon, S., Deutsch, L., Folke, C., De Groot, R., 2003. A framework for the practical application of the concepts of critical natural capital and strong sustainability. Ecol. Econ. 44, 165–185. doi:10.1016/S0921-8009(02)00272-0

Ertesvag, I.S., 2005. Energy, exergy, and extended-exergy analysis of the Norwegian society 2000. Energy 30, 649–675. doi:10.1016/j.energy.2004.05.025

European Commission, 2009. Commission Impact Assessment Guidelines [Online]. URL http://ec.europa.eu/governance/impact/commission_guidelines/commission_guidelines_en.htm (accessed 5.18.12).

Eurostat, 2010. Eurostat Quality Profile - Gross Domestic Product (GDP) per capita in Purchasing Power Standards (PPS) [Online]. Eurostat Qual. Profile - Gross Domest. Prod. per capita Purch. Power Stand. URL http://epp.eurostat.ec.europa.eu/portal/page/portal/sdi/files/QP GDP per capita in PPS.pdf (accessed 7.18.12).

Eurostat, 2011a. Sustainable development in the European Union - 2011 monitoring report of the EU sustainable development strategy. Publications Office of the European Union, Luxembourg. doi:10.2785/1538

Eurostat, 2011b. Material flow accounts - Statistics Explained [Online]. URL http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Material_flow_accounts (accessed 5.25.12).

Figge, F., Hahn, T., 2005. The Cost of Sustainability Capital and the Creation of Sustainable Value by Companies. J. Ind. Ecol. 9, 47–58.

Fiksel, J., 2003. Designing Resilient, Sustainable Systems. Environ. Sci. Technol. 37, 5330–5339. doi:10.1021/es0344819

Gagnon, B., Leduc, R., Savard, L., 2012. From a conventional to a sustainable engineering design process: different shades of sustainability. J. Eng. Des. 23, 49–74. doi:10.1080/09544828.2010.516246
Gaichas, S.K., 2008. A context for ecosystem-based fishery management: Developing concepts of ecosystems and sustainability. Mar. Policy 32, 393–401. doi:10.1016/j.marpol.2007.08.002
Galli, A., Kitzes, J., Niccolucci, V., Wackernagel, M., Wada, Y., Marchettini, N., 2012. Assessing the global environmental consequences of economic growth through the Ecological Footprint: A focus on China and India. Ecol. Indic. 17, 99–107. doi:10.1016/j.ecolind.2011.04.022
Garmendia, E., Stagl, S., 2010. Public participation for sustainability and social learning: Concepts and lessons from three case studies in Europe. Ecol. Econ. 69, 1712–1722. doi:10.1016/j.ecolecon.2010.03.027
Gasparatos, A., El-Haram, M., Horner, M., 2009a. Assessing the sustainability of the UK society using thermodynamic concepts: Part 1. Renew. Sustain. Energy Rev. 13, 1074–1081. doi:10.1016/j.rser.2008.03.004
Gasparatos, A., El-Haram, M., Horner, M., 2009b. Assessing the sustainability of the UK society using thermodynamic concepts: Part 2. Renew. Sustain. Energy Rev. 13, 956–970. doi:10.1016/j.rser.2008.03.005
Gatto, M., 1995. Sustainability: Is it a well defined concept? Ecol. Appl. 5, 1181–1183.
Gero, J.S., Kannengiesser, U., 2004. The situated function–behaviour–structure framework. Des. Stud. 25, 373–391. doi:10.1016/j.destud.2003.10.010
Godfrey, P., 2010. Using systems thinking to learn to deliver sustainable built environments. Civ. Eng. Environ. Syst. 27, 219–230. doi:10.1080/10286608.2010.482656
Goerner, S.J., Lietaer, B., Ulanowicz, R.E., 2009. Quantifying economic sustainability: Implications for free-enterprise theory, policy and practice. Ecol. Econ. 69, 76–81. doi:10.1016/j.ecolecon.2009.07.018
Hahn, T., Figge, F., 2011. Beyond the Bounded Instrumentality in Current Corporate Sustainability Research: Toward an Inclusive Notion of Profitability. J. Bus. Ethics 104, 325–345. doi:10.1007/s10551-011-0911-0
Hahn, W.A., Knoke, T., 2010. Sustainable development and sustainable forestry: analogies, differences, and the role of flexibility. Eur. J. For. Res. 129, 787–801.
Hak, T., Kovanda, J., Weinzettel, J., 2012. A method to assess the relevance of sustainability indicators: Application to the indicator set of the Czech Republic's Sustainable Development Strategy. Ecol. Indic. 17, 46–57. doi:10.1016/j.ecolind.2011.04.034
Hannon, A., Callaghan, E.G., 2011. Definitions and organizational practice of sustainability in the for-profit sector of Nova Scotia. J. Clean. Prod. 19, 877–884. doi:10.1016/j.jclepro.2010.11.003
Hansen, J.W., 1996. Is agricultural sustainability a useful concept? Agric. Syst. 50, 117–143.
Hart, S.L., Milstein, M.B., 2003. Creating sustainable value. Acad. Manag. Exec. 17, 56–69.
Heal, G., 2012. Reflections - Defining and Measuring Sustainability. Rev. Environ. Econ. Policy 6, 147–163.
Heijungs, R., Huppes, G., Guinée, J.B., 2010. Life cycle assessment and sustainability analysis of products, materials and technologies. Toward a scientific framework for sustainability life cycle analysis. Polym. Degrad. Stab. 95, 422–428. doi:10.1016/j.polymdegradstab.2009.11.010
Holling, C.S., 2001. Understanding the Complexity of Economic, Ecological, and Social Systems. Ecosystems 4, 390–405. doi:10.1007/s10021-001-0101-5
Hubka, V., Eder, W.E., 1988. Theory of Technical Systems, 2nd ed. Springer-Verlag, Berlin, Heidelberg, New York.
Jamieson, D., 1998. Sustainability and beyond. Ecol. Econ. 24, 183–192. doi:10.1016/S0921-8009(97)00142-0
Jordan, S.J., Hayes, S.E., Yoskowitz, D., Smith, L.M., Summers, J.K., Russell, M., Benson, W.H., 2010. Accounting for natural resources and environmental sustainability: linking ecosystem services to human well-being. Environ. Sci. Technol. 44, 1530–6. doi:10.1021/es902597u
Kajikawa, Y., 2008. Research core and framework of sustainability science. Sustain. Sci. 3, 215–239. doi:10.1007/s11625-008-0053-1
Kajikawa, Y., Ohno, J., Takeda, Y., Matsushima, K., Komiyama, H., 2007. Creating an academic landscape of sustainability science: an analysis of the citation network. Sustain. Sci. 2, 221–231. doi:10.1007/s11625-007-0027-8

Kim, J., Oki, T., 2011. Visioneering: an essential framework in sustainability science. Sustain. Sci. 6, 247–251. doi:10.1007/s11625-011-0130-8
Kirsch, S., 2009. Sustainable Mining. Dialect. Anthropol. 34, 87–93. doi:10.1007/s10624-009-9113-x
Köhn, J., 1998. Thinking in terms of system hierarchies and velocities. What makes development sustainable? Ecol. Econ. 26, 173–187. doi:10.1016/S0921-8009(97)00102-X
Komiyama, H., Takeuchi, K., 2006. Sustainability science: building a new discipline. Sustain. Sci. 1, 1–6. doi:10.1007/s11625-006-0007-4
Larkin, P.A., 1977. An Epitaph for the Concept of Maximum Sustained Yield. Trans. Am. Fish. Soc. 106, 1–11.
Lele, S., Norgaard, R.B., 1996. Sustainability and the Scientist's Burden. Conserv. Biol. 10, 354–365. doi:10.1046/j.1523-1739.1996.10020354.x
Li, Y., Yang, Z.F., 2011. Quantifying the sustainability of water use systems: Calculating the balance between network efficiency and resilience. Ecol. Modell. 222, 1771–1780. doi:10.1016/j.ecolmodel.2011.03.001
Liao, W., Heijungs, R., Huppes, G., 2011. Is bioethanol a sustainable energy source? An energy-, exergy-, and emergy-based thermodynamic system analysis. Renew. Energy 36, 3487–3479. doi:10.1016/j.renene.2011.05.030
Lindsey, T.C., 2011. Sustainable principles: common values for achieving sustainability. J. Clean. Prod. 19, 561–565. doi:10.1016/j.jclepro.2010.10.014
Liu, J., Lin, B.-L., Sagisaka, M., 2012. Sustainability assessment of bioethanol and petroleum fuel production in Japan based on emergy analysis. Energy Policy 44, 23–33. doi:10.1016/j.enpol.2011.12.022
Liu, S., Costanza, R., Farber, S., Troy, A., 2010. Valuing ecosystem services: theory, practice, and the need for a transdisciplinary synthesis. Ann. N. Y. Acad. Sci. 1185, 54–78. doi:10.1111/j.1749-6632.2009.05167.x
Lo, S.-F., 2010. Performance evaluation for sustainable business: a profitability and marketability framework. Corp. Soc. Responsib. Environ. Manag. 17, 311–319. doi:10.1002/csr.214
Maclaren, V.W., 1996. Urban Sustainability Reporting. J. Am. Plan. Assoc. 62, 184–202.
Marchettini, N., Ridolfi, R., Rustici, M., 2007. An environmental analysis for comparing waste management options and strategies. Waste Manag. 27, 562–71.
Marcuse, P., 1998. Sustainability is not enough. Environ. Urban. 10, 103–112.
McCool, S.F., Stankey, G.H., 2004. Indicators of sustainability: challenges and opportunities at the interface of science and policy. Environ. Manage. 33, 294–305. doi:10.1007/s00267-003-0084-4
Meadows, D., 1998. Indicators and information systems for sustainable development. Hartland.
Meadows, D.H., 2008. Thinking in Systems - A Primer. London.
Metcalf, S.S., Widener, M.J., 2011. Growing Buffalo's capacity for local food: A systems framework for sustainable agriculture. Appl. Geogr. 31, 1242–1251. doi:10.1016/j.apgeog.2011.01.008
Ness, B., Urbel-Piirsalu, E., Anderberg, S., Olsson, L., 2007. Categorising tools for sustainability assessment. Ecol. Econ. 60, 498–508. doi:10.1016/j.ecolecon.2006.07.023
Neumayer, E., 2003. Weak versus strong sustainability : exploring the limits of two opposing paradigms, 2nd ed. Edward Elgar, Cheltenham, UK; Northampton, MA.
Newell, A., 1982. The knowledge level. Artif. Intell. 18, 87–127. doi:10.1016/0004-3702(82)90012-1
Norgaard, R.B., 2010. Ecosystem services: From eye-opening metaphor to complexity blinder. Ecol. Econ. 69, 1219–1227. doi:10.1016/j.ecolecon.2009.11.009
Norse, E.A., Brooke, S., Cheung, W.W.L., Clark, M.R., Ekeland, I., Froese, R., Gjerde, K.M., Haedrich, R.L., Heppell, S.S., Morato, T., Morgan, L.E., Pauly, D., Sumaila, R., Watson, R., 2012. Sustainability of deep-sea fisheries. Mar. Policy 36, 307–320. doi:10.1016/j.marpol.2011.06.008
Noss, R.F., 1993. Sustainable Forestry or Sustainable Forests?, in: Aplet, G.H., Johnson, N., Olson, J.T., Sample, V.A. (Eds.), Defining Sustainable Forestry. Island Press, Washington D.C., pp. 17–43.
O'Donnell, F.J., Duffy, A.H.B., 2005. Design Performance. Springer-Verlag, London.
Odum, H.T., 1994. The emergy of natural capital, in: Jansson, A., Hammer, M., Folke, C., Costanza, R. (Eds.), Investing in Natural Capital - The Ecological Economics Approach to Sustainability. Island Press, Washington D.C., pp. 200–214.
Oxford English Dictionary, 2014. Oxford English Dictionary [Online]. URL http://www.oed.com/

Parris, T.M., Kates, R.W., 2003. Characterizing a sustainability transition: goals, targets, trends, and driving forces. Proc. Natl. Acad. Sci. U. S. A. 100, 8068–73. doi:10.1073/pnas.1231336100

Pearce, D., Putz, F.E., Vanclay, J.K., 2003. Sustainable forestry in the tropics: panacea or folly? For. Ecol. Manage. 172, 229–247.

Posner, S.M., Costanza, R., 2011. A summary of ISEW and GPI studies at multiple scales and new estimates for Baltimore City, Baltimore County, and the State of Maryland. Ecol. Econ. 70, 1972–1980. doi:10.1016/j.ecolecon.2011.05.004

Pretty, J., 2008. Agricultural sustainability: concepts, principles and evidence. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 363, 447–65.

Pülzl, H., Prokofieva, I., Berg, S., Rametsteiner, E., Aggestam, F., Wolfslehner, B., 2011. Indicator development in sustainability impact assessment: balancing theory and practice. Eur. J. For. Res. 131, 35–46. doi:10.1007/s10342-011-0547-8

Quental, N., Lourenço, J.M., da Silva, F.N., 2010. Sustainability: characteristics and scientific roots. Environ. Dev. Sustain. 13, 257–276. doi:10.1007/s10668-010-9260-x

Quental, N., Lourenço, J.M., da Silva, F.N., 2011. Sustainable Development Policy: Goals, Targets and Political Cycles. Sustain. Dev. 19, 15–29. doi:10.1002/sd.416

Rainey, D.L., 2006. Sustainable business development : inventing the future through strategy, innovation, and leadership. Cambridge University Press, Cambridge; New York.

Rametsteiner, E., Pülzl, H., Alkan-Olsson, J., Frederiksen, P., 2011. Sustainability indicator development—Science or political negotiation? Ecol. Indic. 11, 61–70. doi:10.1016/j.ecolind.2009.06.009

Ramos, T.B., Caeiro, S., 2010. Meta-performance evaluation of sustainability indicators. Ecol. Indic. 10, 157–166. doi:10.1016/j.ecolind.2009.04.008

Raut, S.P., Ralegaonkar, R.V., Mandavgane, S.A., 2011. Development of sustainable construction material using industrial and agricultural solid waste: A review of waste-create bricks. Constr. Build. Mater. 25, 4037–4042.

Reber, M., 2011. A theory of value in design. University of Strathclyde.

Robinson, J., Burch, S., Talwar, S., O'Shea, M., Walsh, M., 2011. Envisioning sustainability: Recent progress in the use of participatory backcasting approaches for sustainability research. Technol. Forecast. Soc. Change 78, 756–768. doi:10.1016/j.techfore.2010.12.006

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A., 2009. A safe operating space for humanity. Nature 461, 472–5. doi:10.1038/461472a

Rosen, M.A., Dincer, I., Kanoglu, M., 2008. Role of exergy in increasing efficiency and sustainability and reducing environmental impact. Energy Policy 36, 128–137. doi:10.1016/j.enpol.2007.09.006

Shearman, R., 1990. The Meaning and Ethics of Sustainability. Environ. Manage. 14, 1–8.

Sim, S.K., 2000. Modelling Learning in Design. University of Strathclyde.

Singh, R.K., Murty, H.R., Gupta, S.K., Dikshit, A.K., 2012. An overview of sustainability assessment methodologies. Ecol. Indic. 15, 281–299. doi:10.1016/j.ecolind.2011.01.007

Skyttner, L., 1996. General Systems Theory - An Introduction. Macmillan Press Ltd, Basingstoke; London.

Sneddon, C., Howarth, R., Norgaard, R., 2006. Sustainable development in a post-Brundtland world. Ecol. Econ. 57, 253–268. doi:10.1016/j.ecolecon.2005.04.013

Solow, R., 1993. An almost practical step toward sustainability. Resour. Policy 19, 162–172.

Spangenberg, J.H., 2011. Sustainability science: a review, an analysis and some empirical lessons. Environ. Conserv. 38, 275–287. doi:10.1017/S0376892911000270

Standal, D., Utne, I.B., 2011. The hard choices of sustainability. Mar. Policy 35, 519–527. doi:10.1016/j.marpol.2011.01.001

Stremke, S., van den Dobbelsteen, A., Koh, J., 2011. Exergy landscapes: exploration of second-law thinking towards sustainable landscape design. Int. J. Exergy 8, 148–174.

Thomé, B., 1993. Definition and Scope of Systems Engineering, in: Thomé, B. (Ed.), Systems Engineering: Principles and Practice of Computer-Based Systems Engineering. John Wiley & Sons Ltd., Chichester, pp. 1–23.

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418, 671–7.
Tully, C., 1993. System Development Activity, in: Thomé, B. (Ed.), Systems Engineering: Principles and Practice of Computer-Based Systems Engineering. John Wiley & Sons Ltd., Chichester, pp. 45–80.
Turner, B.L., 2010. Vulnerability and resilience: Coalescing or paralleling approaches for sustainability science? Glob. Environ. Chang. 20, 570–576. doi:10.1016/j.gloenvcha.2010.07.003
Ulanowicz, R., Goerner, S., Lietaer, B., Gomez, R., 2009. Quantifying sustainability: Resilience, efficiency and the return of information theory. Ecol. Complex. 6, 27–36. doi:10.1016/j.ecocom.2008.10.005
Ulanowicz, R.E., 1980. An Hypothesis on the Development of Natural Communities. J. Theor. Biol. 85, 223–245.
Ulgiati, S., Ascione, M., Bargigli, S., Cherubini, F., Franzese, P.P., Raugei, M., Viglia, S., Zucaro, A., 2011. Material, energy and environmental performance of technological and social systems under a Life Cycle Assessment perspective. Ecol. Modell. 222, 176–189. doi:10.1016/j.ecolmodel.2010.09.005
United Nations, 2007. Indicators of Sustainable Development: Guidelines and Methodologies. United Nations, New York.
United Nations Development Programme, 2011. Human Development Report 2011. Palgrave Macmillan, Basingstoke.
United Nations Environment Programme, 2012. GEO5 - Environment for the future we want. United Nations Environment Programme, Valletta, Malta.
United States Department of Agriculture Forest Service, 2010. National Report on Sustainable Forests - 2010. Unknown.
Upham, P., Riesch, H., Tomei, J., Thornley, P., 2011. The sustainability of forestry biomass supply for EU bioenergy: A post-normal approach to environmental risk and uncertainty. Environ. Sci. Policy 14, 510–518. doi:10.1016/j.envsci.2011.02.010
Van Zeijl-Rozema, A., Martens, P., 2010. An adaptive indicator framework for monitoring regional sustainable development - a case study of the INSURE project in Limburg, The Netherlands. Sustain. Sci. Pract. Policy 6, 6–17.
Voinov, A., 2007. Understanding and communicating sustainability: global versus regional perspectives. Environ. Dev. Sustain. 10, 487–501. doi:10.1007/s10668-006-9076-x
Vos, R.O., 2007. Defining sustainability: a conceptual orientation. J. Chem. Technol. Biotechnol. 82, 334–339. doi:10.1002/jctb.1675
Vucetich, J.A., Nelson, M.P., 2010. Sustainability: Virtuous or Vulgar? Bioscience 60, 539–544. doi:10.1525/bio.2010.60.7.9
Wackernagel, M., Rees, W.E., 1997. Perceptual and structural barriers to investing in natural capital: Economics from an ecological footprint perspective. Ecol. Econ. 20, 3–24. doi:10.1016/S0921-8009(96)00077-8
Wackernagel, M., Yount, D.J., 1998. The Ecological Footprint: an Indicator of Progress Toward Regional Sustainability. Environ. Monit. Assess. 51, 511–529.
Wahl, D.C., Baxter, S., 2008. The Designer's Role in Facilitating Sustainable Solutions. Des. Issues 24, 72–83.
Walter, C., Stützel, H., 2009. A new method for assessing the sustainability of land-use systems (I): Identifying the relevant issues. Ecol. Econ. 68, 1275–1287. doi:10.1016/j.ecolecon.2008.11.016
Wang, W., Duffy, A., Whitfield, I., Liu, S., Boyle, I., 2008. A design view of capability, in: Realising Network Enabled Capability Conference 2008, 13-14 October 2008, Leeds, UK. Leeds.
Wiersum, K.F., 1995. 200 Years of Sustainability in Forestry : Lessons from History. Environ. Manage. 19, 321–329.
Williams, C.C., Millington, A.C., 2004. The diverse and contested meanings of sustainable development. Geogr. J. 170, 99–104.
World Bank, 2010. Adjusted net saving - a proxy for sustainability.
World Commission on Environment and Development, 1987. Our common future. Oxford University Press, Oxford, New York.

Yang, C.-M., Li, J.-J., Chiang, H.-C., 2011. Stakeholders' perspective on the sustainable utilization of marine protected areas in Green Island, Taiwan. Ocean Coast. Manag. 54, 771–780. doi:10.1016/j.ocecoaman.2011.08.006

Yang, H., Li, Y., Shen, J., Hu, S., 2003. Evaluating waste treatment, recycle and reuse in industrial system: an application of the eMergy approach. Ecol. Modell. 160, 13–21.

Yin, R., Xiang, Q., 2009. An integrative approach to modeling land-use changes: multiple facets of agriculture in the Upper Yangtze basin. Sustain. Sci. 5, 9–18. doi:10.1007/s11625-009-0093-1

Zhang, X., Deng, S., Zhang, Y., Yang, G., Li, L., Qi, H., Xiao, H., Wu, J., Wang, Y., Shen, F., 2011. Emergy evaluation of the impact of waste exchanges on the sustainability of industrial systems. Ecol. Eng. 37, 206–216. doi:10.1016/j.ecoleng.2010.10.001

Appendix 4: Paper D

This appendix contains Paper D, which documents case study 2 (CS1) carried out as part of the evaluation of the S-Cycle model (Section 7.1.3.2, Chapter 7). The paper is a technical report written for BAE Systems, who developed the generic chilled water (CW) system modelled during the study. The report has been reformatted for inclusion here, owing to space limitations.

Section 7.1.3.2 presents a summary of the key aspects of the approach adopted to model and interpret the CW system, which are reported in full in this paper. Additionally, the findings presented in the paper are reported in various sections throughout Chapter 8. The full set of IDEF0 diagrams discussed in Section 7.1.3.2 are presented at the end of the paper. Note that owing to space limitations, certain tables and figures presented elsewhere in the thesis have been removed from the following paper. Where this is the case, readers are referred to the appropriate section of the thesis.

For the meaning of abbreviations, please see Section 6 of the paper where a full list is provided.

A model of the chilled water system and its sustainability

Laura Hay

1. Introduction

The modern warship is an example of a large scale, complex system of systems, where a range of closely interdependent systems contribute to the overall performance and capabilities of the ship as a whole. The array of physical equipment comprising these systems generates considerable waste heat, even under typical operating conditions; under the onerous conditions a warship may be expected to face, the thermal load only increases. The chilled water (CW) system carries out the function of removing this heat, by producing a flow of chilled water that is circulated throughout the ship to be used as a cooling medium. The heat absorbed by the cooling medium is eventually transferred to a flow of sea water that is dumped overboard, rejecting the heat to the sea.

If waste heat is not promptly removed from equipment and rejected to the environment, the capabilities of the ship as a whole may be compromised through the failure of critical systems. Furthermore, in hot climates or an NBC shutdown, a lack of cooling can cause extreme discomfort for the ship's staff, in turn reducing their personal capabilities. As such, the CW system is a critical and fundamental system, and its effective design and operation hinge upon a clear understanding of its behaviour. This report is intended to contribute to such an understanding, by presenting a model describing the behaviour of the CW system in terms of key system activities.

The CW system model was developed as part of a study on system sustainability, conducted under the BAE Systems-University of Strathclyde Strategic Partnership and funded by a University of Strathclyde Research Studentship. In the context of technical systems such as a warship and its constituent sub-systems, sustainability typically refers to the system's ability to continue producing its intended output within the constraints of the wider system that supports it. Specifically, CW system sustainability may be understood as the CW system's ability to continue producing a flow of chilled water over time. Since the continued operation of a warship at sea is critically dependent upon this chilled water output, CW system sustainability is a prominent concern with respect to the broader issue of platform sustainability. As such, the CW system model is presented from two perspectives in this report: (i) a general systems perspective, describing the major activities performed by the system; and (ii) a sustainability perspective. To present the model from the latter perspective, a sustainability model known as the S-Cycle was applied to identify the renewable and non-renewable resources used by the system to produce the chilled water flow, and the waste produced alongside this intended output.

The CW system study had two primary aims:

1. To model the behaviour of the CW system for BAE Systems.
2. To test and evaluate the S-Cycle model, developed as part of PhD research at the University of Strathclyde.

The major objectives carried out to achieve this aim were as follows. A timeline for the study is presented in Figure 1.

1. Using appropriate methods, construct and evaluate a model of the CW system.
2. Apply the S-Cycle model to interpret the CW system model from a sustainability perspective.
3. Elicit opinions on the S-Cycle model and the chilled water system work from systems experts.
4. Disseminate the major findings of the study in a report and presentation for BAE Systems.

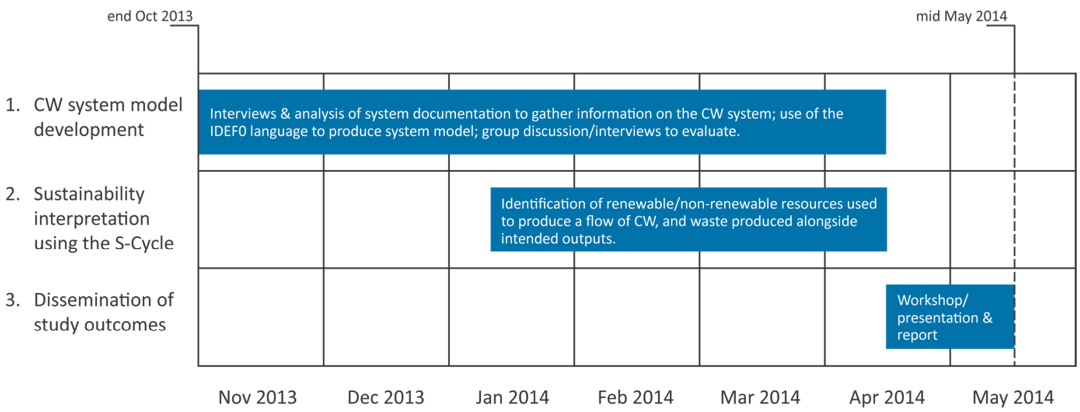


Figure 1. CW system study timeline

In Section 2, the scope of the work conducted to model the CW system is discussed, before the modelling approach is outlined and the CW system model itself presented. In Section 3, the S-Cycle model is introduced and explained. The process by which it was applied to the CW system is briefly outlined, and the resulting sustainability interpretation of the CW system model is presented. Section 4 provides a brief discussion on the potential future directions of the work reported, and the report concludes with a summary in Section 5.

2. The chilled water system model

2.1 Scope of the work

Considering the whole product life cycle, the scope of the work conducted to model the CW system is restricted to the *life in service* phase. The design, manufacture, and disposal of the system were not considered. Within this life cycle phase, the work focused solely on the *operation* of the system, and excluded its maintenance and repair. Thus, the CW system model presented in Section 2.4 describes the system's behaviour during normal operation[12]. The original intention was that the work would take a through-life perspective and focus on the full life in service of the system, i.e. focusing on both the operation and maintenance/ repair of the system. However, owing largely to the time constraints of PhD research, it was decided to limit the scope as described above. Note that future work may seek to extend the scope to include maintenance, as discussed in Section 4.2.

[12] "Normal operation" spans the full range of: (i) potential operational states the ship may be subject to at sea, e.g. action stations, defence stations, NBC shutdown, and peacetime cruising; and (ii) potential climatic conditions it may experience both at sea and in the dock, e.g. temperate, arctic, tropics, and Gulf conditions.

In the interests of ensuring that the CW system model would be applicable across multiple platforms, the work did not focus on any specific CW system. The focus was on the *functions* carried out by CW systems on marine platforms generally, rather than specific physical components (e.g. particular types of CW plants, pumps, etc.).

2.2 Modelling approach

A modelling language called IDEF0 was chosen to represent the CW system. Using this language, a system is modelled in terms of the major activities (i.e. functions) it performs, the inputs and mechanisms required for successful execution of these activities, the outputs produced as a result of the activities, and the controls that govern these outputs. The two key elements of the language are: (i) *boxes*, which represent activities; and (ii) *arrows*, which represent the inputs, mechanisms, outputs, and controls associated with each activity. The IDEF0 activity representation is shown in Figure 2.

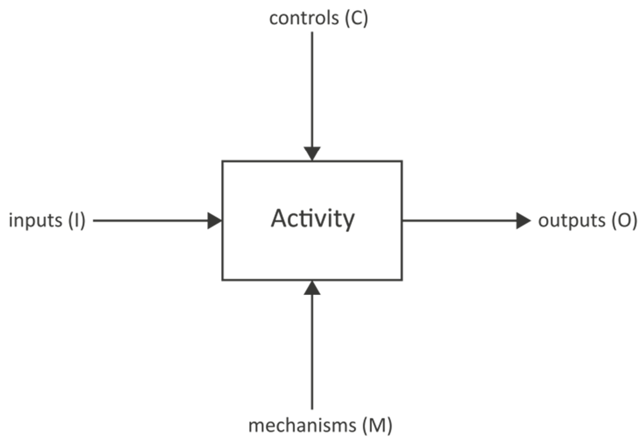


Figure 2. IDEF0 activity representation

The different types of arrow are defined as follows:

- *mechanisms* carry out processing to produce outputs, e.g. the compressors in the CW system;
- *inputs* are the materials, energy and information processed by the mechanisms, e.g. the electricity and refrigerant used by the CW system;
- *outputs* are the things produced via a system activity, e.g. chilled water from the activity of 'chill cooling medium'; and
- *controls* are the conditions that govern the production of outputs.

The major rationale behind the selection of the IDEF0 language is that it provides the model developer with the means to describe a complex system (such as the CW system) in gradually increasing levels of detail, without overwhelming readers of the model (as shown in Section 2.3).

The modelling process revolved around gathering, structuring, and representing the information outlined above for the CW system. The process consisted of three stages: (1) development of a draft model; (2) refinement of the model; and (3) finalisation of the model. Stage (1) focused primarily upon distilling a large amount of information on the CW system into a basic model. Stages (2) and (3) focused more upon editing and evaluating this model in response to feedback from CW system experts, to ensure that the final model was acceptable as a valid representation of the system. As shown in Figure 3 and described in Table 1 overleaf, three major tasks were carried out within each of these phases: (i) information gathering; (ii) analysis; and (iii) model building. The primary sources of information were engineers/designers and engineering managers familiar with the CW system, whilst the major methods employed to gather this information were unstructured interviews and group discussion sessions. Analysis of system documentation also yielded useful information.

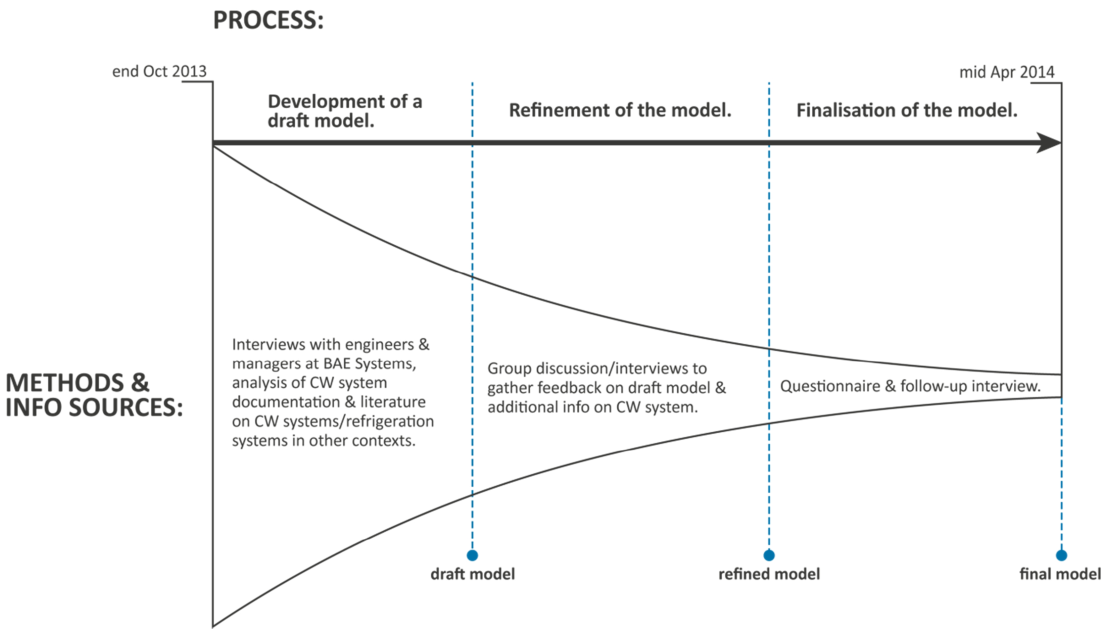


Figure 3. The modelling process

Table 1. Stages and tasks involved in the modelling process

Stage	Information gathering	Analysis	Model building
1. Draft model.	Physical and functional descriptions of the CW system were gathered using the following methods and sources: • unstructured, one-to-one interviews with designers/ engineers and managers familiar with the CW system; • system documentation, e.g. NES and DefStans relating to chilled water, T45 CW system op. stat., and generic layouts and schematics; and • non-BAE Systems documentation on CW systems in buildings and non-military marine vehicles, and refrigeration systems generally.	Physical and functional descriptions were analysed to define: • the major activities carried out by the CW system; • the inputs, outputs, mechanisms, and controls associated with each activity; and • the key relationships among the activities, e.g. cases where the output of one activity is used as the input to another.	Textual descriptions of activities, inputs/outputs/ mechanisms/controls were translated to boxes and arrows in the IDEF0 language. These were then structured according to the key relationships identified, to form a draft model of the CW system.
2. Model refinement.	Opinions on the correctness and completeness of the draft model were gathered using the following methods and sources:	The visual and textual output from the discussion sessions was analysed, alongside the additional system descriptions	The layout and structure of the IDEF0 model was updated to reflect changes in the activities, inputs/outputs/

	• semi-structured group discussion sessions with designers/engineers and managers, focusing on specific parts of the model depending upon participants' expertise (e.g. the session focusing on the "chilling" activity involved CW plant experts); • semi-structured one-to-one discussion sessions focusing on specific parts of the model in cases where a group discussion was not possible • (suggested corrections and deletions were recorded visually by drawing on A3 print-outs of the model, and textually via written notes). Additionally, further physical and functional descriptions of the CW system that had been missed during stage 1 were gathered during these sessions. Finally, a physical CW system was visually inspected aboard HMS Duncan in Portsmouth.	gathered, to refine: • the major activities carried out by the CW system; • the inputs, outputs, mechanisms, and controls associated with each activity; and • the key relationships among the activities.	mechanisms/ controls, and key relationships, yielding a refined CW system model.
3. Model finalisation.	Opinions on the correctness and completeness of the refined model were gathered using the following methods and sources: • a questionnaire distributed to two engineers working in modelling and simulation, sent out alongside PowerPoint slides detailing the changes made to the model during refinement – respondents were	The questionnaire responses were analysed to determine the final refinements required to the activities, inputs/ outputs/mechanisms/ controls, and key relationships as outlined above.	Following analysis of the questionnaire responses, minor changes were made to the layout and structure of the IDEF0 to reflect the refinements, yielding the final CW system model. Following implementation of the above changes, the interview served as a 'final check' on the correctness and completeness of the CW system model.

	asked to either indicate agreement with the changes, or suggest further corrections; and • an unstructured, one-to-one interview with the Principal Engineer for modelling and simulation.		

2.3 Structure of the chilled water system model

As mentioned in Section 2.2, the IDEF0 language provides the means to describe a complex system in gradually increasing detail. Accordingly, the full CW system model is a hierarchical set of diagrams, describing system activities and their relationships at different levels of decomposition. The key activities carried out by the CW system are first represented in a high-level diagram. As required, each activity in this diagram is then decomposed into its constituent sub-activities in a lower-level diagram, to provide a more detailed description of the system behaviour represented by the parent activity. The decomposition of activities in this way continues until a sufficiently detailed view of the system's behaviour has been provided.

All diagrams in the CW system model have a unique number, shown in the bottom left hand corner of the diagram (see Figure 4 overleaf for an example). Throughout the model, any activity that has been decomposed in a sub-diagram will be denoted with a number at its bottom right-hand corner (Figure 4). This number is the number of the diagram detailing the decomposition (again, see Figure 4).

As shown in Figure 5, the overall activity carried out by the CW system is described as *remove waste heat from equipment aboard ship*. This activity is represented in the A-0 diagram, which is the highest level in the model. In turn, the A-0 diagram is the parent of the A0 diagram, where the activity described in A-0 is decomposed into five key sub-activities carried out by the CW system: (1) *absorb waste heat from CW users*; (2) *control and configure CW system*; (3) *accumulate and store cooling medium*; (4) *circulate cooling medium in CW system*; and (5) *chill cooling medium*. Of these activities, (2), (4), and (5) are then decomposed further in lower-level diagrams.

Figure 4. Tracing the decomposition of activities in an IDEF0 model (see Figure 7-9, Section 7.1.3.2, Chapter 7 of thesis)

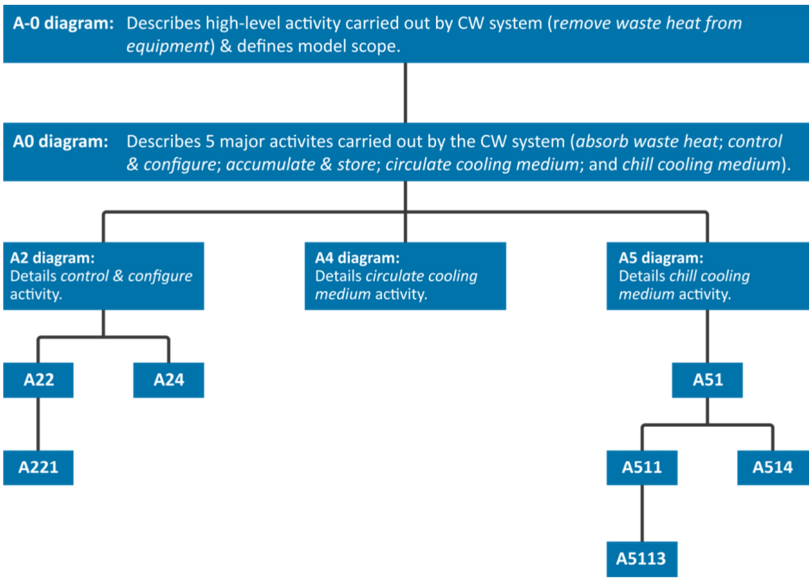


Figure 5. Overall structure of the CW system model

2.4 Activities in the CW system model

In the following sub-sections, the activities represented within the diagrams of the CW system model are briefly explained. Please refer to the end of this report for copies of the diagrams themselves.

2.4.1 A-0 diagram: Chilled water system operation

As mentioned in Section 2.3, the A-0 diagram is the top-most diagram in the CW system model, and therefore provides the highest level view on the behaviour of the system during its operation. This diagram defines the purpose, viewpoint, and scope of the whole model. As discussed in Section 2.1, the focus of the model is on the normal operation of the system (across the full range of potential operational states and climatic conditions). Lying outside of this scope are related systems and processes that support the operation of the CW system, including: the natural systems that provide inputs and receive outputs (i.e. the sea and atmosphere); other systems on board the ship that provide inputs (e.g. power systems); domestic systems on board the ship that maintain the wellbeing and personal capabilities of human operators; training processes that ensure operators have the knowledge required to operate the system; and maintenance and repair processes that keep the system in working order. As discussed in Section 1, the CW system produces a flow of chilled water that is circulated throughout the ship to be used as a cooling medium by equipment. The mechanisms by which heat is transferred from equipment to the CW flow are included in the model, but the operation of the equipment itself is excluded. The heat transfer mechanisms may be viewed as the interface between the CW system and the other systems on board the ship that use the CW flow produced.

2.4.2 A0 diagram: Remove waste heat from equipment aboard the ship

The A0 diagram describes the major activities carried out by the chilled water system in order to remove waste heat from equipment aboard the ship. This diagram is a decomposition of the high-level activity presented in the A-0 diagram. The *circulate* activity maintains and directs the CW flow between CW users and the CW plants. The *chill* activity produces the supply temperature (i.e. changes the temperature of the CW flow from warm to cool), whilst the *absorb waste heat* activity produces the return temperature (i.e. changes the temperature of the CW flow from cool to warm). The *accumulate & store* activity stores additional water, and allows water to flow between the CW circulation system and the header tanks when required. The magnitude and direction of this flow depends upon whether there is an insufficient or excessive volume of water in the CW circulation system. Insufficient volume may result from water losses (i.e. leaks), whilst excessive volume may result from an increase in the return temperature, causing thermal expansion of the water. The former will trigger flow from the header tanks into the circulation system to fill the pipework, whilst the latter will trigger movement in the opposite direction so that excessive flow in the pipework is absorbed by the header tanks.

The A0 diagram highlights that the *control & configure* activity is key to the correct operation of the CW system, as it produces the majority of the controls for the other activities. If this activity cannot be performed correctly, the operation of the system as a whole will be negatively impacted. For example, in the event of action damage to part of the system, it may be necessary to re-configure the CW flow path in order to isolate the damaged section and maintain a CW flow for critical equipment. If this cannot be carried out correctly, the key output of the *circulate* activity, i.e. the CW flow between users and CW plants, may be lost. The *control & configure* activity itself depends upon information on CW system state provided by instrumentation throughout the CW system, and human knowledge of how the system works. Thus, a lack of either (e.g. due to faulty instrumentation and a lack of adequate training for operators, respectively) may prevent the *control & configure* activity being performed correctly. As such, these two controls – i.e. human knowledge and information on CW system state – may be viewed as fundamental to the operation of the CW system as a whole. In addition to human knowledge of how the system works, knowledge of the current and desired operational state of the ship also plays a role. This is because different operational states require different CW system configurations. For example, in low threat situations, a single CW plant may supply all equipment with the flow path configured as a single ring main. However, at action stations, the ring main may be split into sections and multiple plants will be online to supply different areas. Thus, a human operator may take action to re-configure the system on the basis of knowledge that the ship is moving from one operational state to another.

2.4.3 A2 diagram: Control and configure the chilled water system

The A2 diagram describes the activities carried out in order to control and configure the CW system. This diagram is a decomposition of the *control & configure* activity in the A0 diagram (see Section 2.4.2). The system may be controlled and configured in one of two ways: (i) remotely, as described by the *remote control via PMS* activity; or (ii) locally. To control the system remotely, humans in the control room use the human control interface to trigger control signals that are sent to equipment throughout the CW system via the PMS. To control the system locally, humans use control mechanisms positioned locally at equipment e.g. valve handles, pump starters, and the local control panels on the CW plants. Included in these local control mechanisms are the mechanisms that allow the equipment to be switched from remote to local control mode. Note that the cooling capacity of the CW plants cannot be controlled locally by human operators. Rather, this parameter is controlled automatically by an in-built PLC that uses information on the return temperature of the CW flow to adjust the position of the TEx valve, and settings on either the compressor or the CW sea water pump (depending on the type of CW plant).

2.4.4 A22 diagram: Start/stop one or more chilled water plants

As discussed in Section 2.4.2, the different operational states that the ship may potentially be subject to require different CW system configurations. That is, different numbers of pumps and CW plants online, and different CW flow paths as determined by the position of valves in the circulation system. The A22 diagram simply decomposes the activity *start/stop CW plants* described in the A2 diagram (see Section 2.4.3), to illustrate that each plant may be brought online independently of the others.

2.4.5 A221 diagram: Start/stop a single chilled water plant

The A221 diagram describes the activities carried out in order to start/stop a single CW plant. This diagram is a decomposition of the activity *start/stop CW plant 1* in the A22 diagram (see Section

2.4.4). Note that each of the other activities in the A22 diagram may be decomposed in the same way (not shown to avoid repetition). The key relationship shown in this diagram is the dependency between the CW sea water system and the compressor in in a CW plant. The compressor cannot be started until the CW sea water system has been configured to provide a supply of sea water to cool the condenser associated with the compressor. To configure the CW sea water system, the valves connecting the CW sea water pump with the condenser must be correctly aligned, and the pump must be turned on. As discussed in Section 2.4.3, this may be done remotely or locally.

2.4.6 A24 diagram: Start/stop one or more chilled water circulation pumps

As discussed in Section 2.4.2, the different operational states that the ship may potentially be subject to require different CW system configurations. That is, different numbers of pumps and CW plants online, and different CW flow paths as determined by the position of valves in the circulation system. The A24 diagram simply decomposes the activity *start/stop CW circ. pumps* described in the A2 diagram (see Section 2.4.3), to illustrate that each pump may be brought online independently of the others.

2.4.7 A4 diagram: Circulate cooling medium in the chilled water system

The A4 diagram describes the activities carried out in order to circulate the cooling medium within the CW system, between the CW plants where it is chilled, and the CW users where it is used for cooling. This diagram is a decomposition of the activity *circulate cooling medium in CWS* described in the A0 diagram (see Section 2.4.2). In the CW system, heat is transferred from equipment to the cooling medium flow according to the following equation:

$$\dot{Q} = \dot{m} C_p \Delta T \qquad \textbf{Equation 1}$$

…where $\dot{Q}$ is the amount of heat transferred to the cooling medium per second, $\dot{m}$ is the cooling medium flow rate, C_p is the specific heat capacity of the cooling medium (i.e. demineralised water), and ΔT is the difference between the supply and return temperatures. Of these variables, one of the most fundamentally important is the cooling medium flow rate. If flow rates are disrupted, the CW system's effectiveness at removing waste heat from equipment may be reduced. The cooling medium flow rate is produced by the activity *maintain flow of cooling medium in CWS*, and its magnitude depends upon the number of CW circulation pumps online at a given time, and the pressure losses in the CW flow path (due to e.g. valves and fittings, bends in pipework, etc.).

Large air bubbles in the CW circulation system (e.g. from filling and routine maintenance) are one potential source of disruption to flow rates. Not only can these physically block the flow path, but they may also reduce the performance of the CW circulation pumps. When the bubbles are sucked into the pumps, they are transformed into many microscopic bubbles by the action of the impeller – the air becomes entrained in the cooling medium. This reduces the CW system's effectiveness in two ways. Firstly, the heat transfer properties of the cooling medium are negatively impacted – i.e. the value of C_p in Equation 1 is reduced. Secondly, once the entrained air has travelled around the circulation system, it is sucked back into the pumps where it is exposed to low pressure. This causes the air to be rapidly released from the cooling medium, which can in turn cause cavitation in the pumps. To mitigate this problem, a new piece of equipment known as a vacuum degasser has been trialled on two Royal Navy warships. This is represented as a mechanism for the activity *remove air from cooling medium*. The degasser removes water from the return side of the circulation system, exposes it to an underpressure to release the entrained air, and then returns the degassed water to the flow in the circulation system. The waste air is then vented to the atmosphere. The degasser will only turn on when it senses a concentration of undissolved gases in the cooling medium above a certain threshold level, and turns off once the level drops back below the threshold.

As discussed in Section 2.4.2, the ability to control and configure the CW system (represented via the *control & configure* activity in the A0 diagram) depends upon both human knowledge, and information on the CW system state provided by instrumentation throughout the system. The provisioning of information on the state of equipment in the CW circulation system in this way is represented by the activity *provide info on state of CW circ. sys.*

2.4.8 A5 diagram: Chill cooling medium using one or more chilled water plants

As discussed in Section 2.4.2, the different operational states that the ship may potentially be subject to require different CW system configurations. That is, different numbers of pumps and CW plants online, and different CW flow paths as determined by the position of valves in the circulation system. The A5 diagram simply decomposes the activity *chill cooling medium* in the A0 diagram (see Section 2.4.2) to show that this may involve one or more CW plants at a given time.

2.4.9 A51 diagram: Chill cooling medium using a single chilled water plant

The A51 diagram describes the activities carried out by a single CW plant to chill the cooling medium. In other words, it describes the internal workings of a CW plant. This diagram is a decomposition of the activity *chill cooling medium using CW plant 1* in the A5 diagram (see Section 2.4.8). Note that each of the other activities in the A5 diagram may be decomposed in the same way (not shown to avoid repetition). This also applies to the A511, A5113, and A514 diagrams discussed in Sections 2.4.10 – 2.4.12.

The CW plants operate a vapour-compression refrigeration cycle. Each plant may be split into two parts: (i) the high pressure (HP) side, consisting of the compressor, condenser, and associated valves, fittings, and pipework; and (ii) the low pressure (LP) side, consisting of the evaporator and associated valves, fittings, and pipework. The HP and LP equipment carry out different elements of the refrigeration cycle, as follows. Heat is first transferred from the cooling medium to the refrigerant flow via evaporation of the refrigerant in the evaporator. This is represented by the activity *remove heat from cooling medium*, carried out by the LP equipment. The low pressure, low temperature vapour leaving the evaporator is then sucked into the compressor, where its pressure and temperature are increased. The high pressure, high temperature vapour leaving the compressor then travels through the condenser, where heat is transferred from the refrigerant flow to a flow of sea water (provided by the plant's associated CW sea water system) via condensation. This is represented by the activity *reject heat from cooling medium to sea*, carried out by the HP equipment. The high pressure, high temperature liquid refrigerant leaving the condenser then flows to the thermostatic expansion (TEx) valve, where the flow rate is metered to ensure that the evaporator receives the correct amount of refrigerant for complete evaporation to occur. A key relationship described in the A51 diagram is therefore the one existing between the flow rate of refrigerant into and out of the TEx valve, i.e. the relationship between the input and output of the activity, *meter flow of refrig. in CWP 1*.

2.4.10 A511 diagram: Reject waste heat to the sea using a single chilled water plant

The A511 diagram describes the activities carried out by a single CW plant to reject waste heat to the sea. This diagram is a decomposition of the activity *reject heat from cooling medium to sea* in the A51 diagram, and simply describes the operation of the HP equipment (discussed in Section 2.4.9) in more detail.

As discussed in Section 2.4.2, the ability to control and configure the CW system (represented via the *control & configure* activity in the A0 diagram) depends upon both human knowledge, and information on the CW system state provided by instrumentation throughout the system. The provisioning of information on the state of HP CW plant equipment in this way is represented by the activity *provide info on state of HP CWP 1 equip.*

2.4.11 A5113 diagram: Transfer heat from refrigerant to sea water using a single chilled water plant

The A5113 diagram describes the activities carried out by a single CW plant to transfer heat from the refrigerant flow to the sea water flow through the condenser, via condensation of the refrigerant. This diagram is a decomposition of the activity *transfer heat from refrig. to sea water* in the A511 diagram. The diagram provides a more detailed view on the operation of the CW sea water system, which provides the flow of sea water used to cool the condenser and facilitate condensation of the refrigerant flowing through it. The flow of sea water is maintained by the CW sea water pump, and the flow is directed through the condenser and eventually overboard by various valves, fittings, and pipework.

As discussed in Section 2.4.2, the ability to control and configure the CW system (represented via the *control & configure* activity in the A0 diagram) depends upon both human knowledge, and information on the CW system state provided by instrumentation throughout the system. The provisioning of information on the state of the CW sea water system equipment in this way is represented by the activity *provide info on state of CWP 1 CWSW sys.*

2.4.12 A514 diagram: Remove heat from the cooling medium using a single chilled water plant

The A514 diagram describes the activities carried out by a single CW plant to remove heat from the cooling medium. This diagram is a decomposition of the activity *remove heat from cooling medium* in the A51 diagram, and simply describes the operation of the LP equipment (discussed in Section 2.4.9) in more detail.

As discussed in Section 2.4.2, the ability to control and configure the CW system (represented via the *control & configure* activity in the A0 diagram) depends upon both human knowledge, and information on the CW system state provided by instrumentation throughout the system. The provisioning of information on the state of LP CW plant equipment in this way is represented by the activity *provide info on state of LP CWP 1 equip.*

3. Sustainability interpretation of the CW system model

As discussed in Section 1, the CW system model presented in Section 2 was developed as part of a study on system sustainability. This study centred on the use of a sustainability model known as the S-Cycle, which describes the behaviour of a technical system from a sustainability perspective. In addition to modelling the CW system, a major aim of the study was to test and evaluate the S-Cycle model by applying it to a complex technical system. The CW system model provided the basis for this exercise. The following sections introduce the S-Cycle model (Section 3.1), explain how it was applied to the CW system, and present the resulting sustainability interpretation of the system's behaviour (Section 3.2).

3.1 The S-Cycle model

In its most literal form, sustainability simply means "the ability to sustain something," over some time period. Several variants on this definition exist, including the ability to continue and the ability to maintain something. In the context of technical systems, sustainability typically refers to the system's ability to continue producing its intended output within the constraints of the wider system that supports it. As discussed throughout this report, the key output produced by the CW system on a ship is a flow of chilled water for use as a cooling medium by equipment. Thus, CW system sustainability may be defined as the system's ability to continue producing a flow of chilled water for equipment over time.

The S-Cycle model (shown in Figure 6) is a model describing the behaviour of a technical system from a sustainability perspective. Like the IDEF0 language used to model the CW system, the S-Cycle adopts an "activity" formalism to represent technical system behaviour. The S-Cycle shows that the sustained production of intended output within a wider system of interest (SOI) depends fundamentally upon the availability of resources (i.e. inputs and mechanisms). If the required resources are not available, the production of output by the technical system will cease. Resources may be classed as either renewable or non-renewable. That is, resources that originate from stocks that regenerate over time, and stocks that do not regenerate over time, respectively. Additionally, the S-Cycle shows that a technical system may produce its own resources (i.e. inputs and/or mechanisms), to reduce its reliance upon external resource stocks and achieve a degree of self-sufficiency. These are referred to as *intended resources* in the S-Cycle. Finally, the S-Cycle illustrates that technical systems also produce waste alongside their intended output. This waste is received by the wider SOI, where it is processed.

Figure 6. The S-Cycle model (see Figure 6-5, Section 6.5.1, Chapter 6)

Since the sustained production of output by a technical system depends upon the availability of resources, certain constraints on their use must be fulfilled in order for the system to be sustainable. Firstly, because non-renewable stocks do not regenerate over time, they should not be used for the production of intended output as their continued availability cannot be guaranteed. Secondly, although renewable resource stocks do regenerate over time, a stock will still be depleted if it is consumed faster than the regeneration rate. Thus, for sustainability, renewable resources should not be used faster than stocks can regenerate. The production of waste by a technical system must also be constrained in order for the system to be sustainable. A build-up of waste can be harmful for key resources involved in an activity. For example, the major waste output produced by a compressor is heat energy. If a compressor is allowed to overheat during operation, its internal components will be damaged and it will eventually cease to produce its intended output. Therefore, for sustainability, a technical system should not produce waste faster than it can be processed within the system's wider environment. Essentially, to be sustainable, a technical system's behaviour must meet both its conventional performance criteria, *and* sustainability performance criteria.

3.2 Applying the S-Cycle model to the CW system

The S-Cycle is intended to support the modelling and analysis of a technical system's behaviour from a sustainability perspective, by highlighting the fundamental aspects of behaviour that contribute to system sustainability: the use of renewable and non-renewable resources; the production and use of intended resources; the production of intended output; and the production of waste. During the study reported herein, the S-Cycle was applied to the CW system model to develop a sustainability interpretation of the system's behaviour. That is, a version of the CW system model that clearly shows the renewable and non-renewable resources used, the intended resources produced and used, the intended output produced, and the waste produced alongside this. This version of the system model provided the data required for validation of the S-Cycle model, as well as insights into the CW system's sustainability.

As discussed in Section 3.1, the S-Cycle places the behaviour of a technical system within the context of a wider SOI. Thus, the first step in applying the S-Cycle to the CW system was to define the SOI for interpreting its behaviour. This is discussed in Section 3.2.1 below. In Section 3.2.2, the major elements of the interpretation are summarised and briefly discussed. Please refer to Appendix 2 for copies of the interpreted IDEF0 diagrams themselves. The work on CW system sustainability was presented and discussed at an interactive evaluation workshop held at Scotstoun on 30 April 2014, involving engineers, designers, and managers from BAE Systems.

3.2.1 The system of interest for interpreting behaviour

In any attempt to model or analyse sustainability, the boundary of the SOI defines what resource stocks will be considered. To determine whether a particular resource is renewable or non-renewable, it is necessary to trace the resource back to the stock it originates from *within the SOI boundary*. At the highest level, the SOI may be defined as the whole Earth system. At this level, resources must be traced all the way back to the natural stocks that they ultimately derive from (e.g. crude oil stocks, ocean stocks, mineral deposits, etc.) in order to determine renewability.

However, owing largely to time constraints on the study, a more manageable SOI was defined for interpreting the CW system behaviour: the ship at sea (Figure 7). Within this boundary, the stocks that must be considered are: the sea the ship sails on (natural stock); the atmosphere surrounding the ship (natural stock); and the man-made stocks aboard the ship, e.g. refrigerant, oil, diesel in the ship's fuel tank, and physical equipment.

A crucial issue to emerge from the CW system study with respect to the use of the S-Cycle model is the fundamental importance of *space and time*, and the difficulties these aspects may cause decision makers. As discussed above, the SOI was defined as the ship at sea, which included a number of natural and man-made stocks. It was then assumed that the ship would be at sea for approximately 90 days. In turn, this is the time period across which sustainability was modelled. However, when applying the S-Cycle model, it became apparent that different spatial and temporal boundaries may lead to different interpretations of what is renewable and non-renewable. For example, consider the oil used to lubricate the compressors in the CW plants within the CW system. As shown in Table 2, this may be interpreted as either renewable or non-renewable within different boundaries. Given that the use of non-renewable resources is unsustainable (see Section 3.1), this highlights that a very different view on the CW system's sustainability may be obtained depending on the spatial and temporal boundaries of the interpretation. Thus, when applying the S-Cycle model, it is critical that both the SOI *and* the timescale across which sustainability is being considered are clearly defined. Further work will seek to develop guidance on how to rigorously define these aspects when applying the S-Cycle model to a technical system.

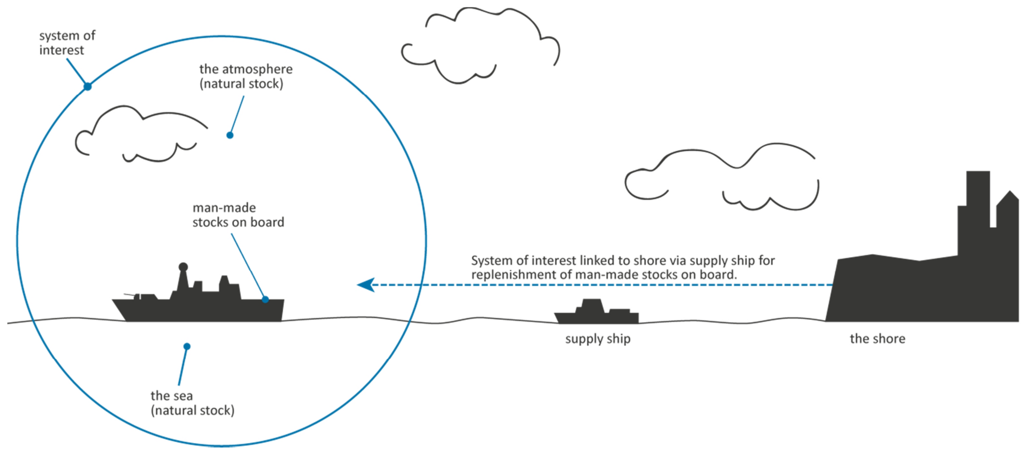


Figure 7. The wider system of interest for interpreting CW system behaviour

Table 2. The changing renewability of oil as an input to the compressor in a CW plant (see Table 8-9, Section 8.2.1, Chapter 8 of thesis)

Another salient issue to emerge from the study was the importance of transparency regarding any assumptions made when defining the SOI. For instance, a key assumption made in defining the above SOI is that it is connected to the shore by a supply ship that may carry out replenishment at sea (RAS) if needed (see Figure 7). Thus, although resource stocks on the shore were not themselves considered to be part of the SOI, certain stocks *within* the SOI may be replenished by a supply ship that takes resources from the shore stocks and transports them to the ship at sea. Note that future work may either: (i) exclude the supply ship and focus on the period *in between* RAS, since it is desirable to conserve resources during this period by using them as efficiently and effectively as possible; or (ii) focus on a specific ship and more rigorously define the frequency of RAS by considering the ship's operational plan.

3.2.2 Summary of the sustainability interpretation

After defining the SOI, the S-Cycle was applied to each activity described in the CW system model in order to classify the inputs, mechanisms, and outputs as renewable resources, non-renewable resources, intended resources, intended outputs, or waste. The S-Cycle currently focuses on the *physical* aspects of a technical system, i.e. materials and energy. Since the controls in the CW system model are informational in nature, they were excluded from the interpretation. Similarly, any informational inputs and outputs were excluded. Future work may seek to extend the applicability of the S-Cycle model to information systems.

Although every activity in the CW system model (with the exception of information-provisioning activities) was interpreted using the S-Cycle, only the major activities, i.e. those described in the A0 diagram, are listed in Table 3. An exception is the activity *compress flow of refrig. from evaporator*, which is described in the A511 diagram and provides the only example of intended resources identified in the CW system. Thus, it is also listed below. Please refer to Appendix 2 for the interpreted IDEF0 diagrams, where the interpretation of each activity in the CW system model may be examined. Note that the interpretation of inputs, mechanisms, and outputs was checked by engineers/designers and engineering managers from BAE Systems at the evaluation workshop held on 30 April 2014.

As discussed in Section 3.1, CW system sustainability may be defined as the system's ability to continue producing a flow of chilled water for equipment over time. As such, the intended output to be sustained is the "CW flow & supply temp" produced by the *chill cooling medium* activity in the A0 diagram. As described in the S-Cycle, the sustained production of this intended output depends upon renewable and non-renewable resources. Additionally, the CW system produces limited intended resources for its own use. Lastly, the system produce wastes alongside its intended output of a flow of chilled water. Each of these aspects of behaviour is briefly discussed below:

Use of renewable and non-renewable resources:

The CW system was found to rely on a mixture of both renewable and non-renewable resources: the majority of inputs were classed as renewable, whilst most of the mechanisms were interpreted as non-renewable. Most of the inputs originate from either renewable natural resource stocks (e.g. the sea water used to cool the condenser), or from stocks on board the ship that may be replenished at sea (e.g. refrigerant and oil for the compressors – see Section 3.2.1 for discussion on the assumptions made regarding replenishment at sea). Two exceptions were the human control interface (HCI) and local control mechanisms, inputs that are transformed by humans attempting to control and re-configure the system. These were interpreted as non-renewable, as they cannot be replaced at sea in the event of damage or failure. Most of the mechanisms in the CW system model are items of equipment that comprise the CW system (e.g. pumps, CW plants, header tanks, pipework, valves, etc.). Like the HCI and local control mechanisms, if these are lost whilst the ship is at sea, they cannot be replaced. However, equipment such as pumps and CW plants may have associated spares on board. Therefore, although it may not be possible to replace e.g. a whole CW plant in the event of catastrophic damage, it may be possible to maintain the functioning of the equipment in response to more minor issues. Nonetheless, the equipment itself is still interpreted as non-renewable, since the total stock of e.g. CW plants on board cannot be replenished whilst the ship is at sea. Only one mechanism in the CW system model was interpreted as renewable – humans who operate the system. Although rare, the ship's staff can be replenished at sea in the same way as the inputs discussed above if necessary.

Production and use of intended resources:

Just one instance of intended resources was identified in the CW system model. During operation of the CW plants, the oil used to lubricate the compressor becomes mixed with the refrigerant being compressed inside the compressor. Any oil entrained in the refrigerant flowing out of the compressor is extracted and re-injected to the crankcase by the compressor's oil system. This oil is then re-used as a lubricant. As such, it may be viewed as a resource that is produced by the activity *compress flow of refrig. from evaporator* in the A511 diagram for its own use – i.e. an intended resource, as shown in Figure 8 below.

Figure 8. Production of intended resources by the compressor (see Figure 8-1, Section 8.1.2.2, Chapter 8 of thesis)

Production of waste:

The majority of the waste outputs identified in the CW system model took the form of energy and material losses in the pumping and chilling equipment. Energy losses include waste heat, noise, and vibration generated by compressors and pumps, whilst material losses include refrigerant leaks from CW plants and water leaks from the CW circulation system. In addition to losses, two further waste outputs were identified: air that is removed from the CW circulation system by vacuum degassers and vented to the atmosphere (discussed from a systems perspective in Section 2.4.7, and further below); and the flow of sea water that carries waste heat overboard after passing through the condenser in the CW plants.

In addition to the above, a type of input that is not currently described in the S-Cycle model was identified: an unwanted input. That is, an input that is not a resource, and therefore does not contribute usefully to the production of intended output. In this case, the unwanted input was air bubbles to the activity *circulate cooling medium in CWS* (described in the A0 diagram, and decomposed in the A4 diagram – see Sections 2.4.2 and 2.4.7, respectively). As discussed in Section 2.4.7, air bubbles become entrained in the air via the action of the pump impellers, a process that disrupts the flow rate produced by the activity. The correct flow rate is crucial for the effective operation of the CW system as a whole and thus, the unwanted air must be removed. Removal is carried out by vacuum degassers, which disentrain the air by exposing the CW flow to an underpressure. These have been trialled on two Type 45 destroyers, and their addition to the system highlights a trade-off with respect to the sustainability performance of the system. Namely, removing air using vacuum degassers: (a) reduces cavitation in the pumps, which in turn reduces energy losses and ensures the correct CW flow rate i.e. it improves system performance with respect to the production of waste and intended output; but (b) increases the CW system's electrical energy consumption i.e. it reduces system performance with respect to resource use. However, it is generally believed that gains in the former aspects outweigh reductions in the latter.

Table 3. Summary of sustainability interpretation of major CW system activities

D[a]	Activity	Renewable resources	Non-renewable resources	Intended resources	Intended outputs	Waste
A0	Absorb waste heat from users	CW flow & supply temp. (I[b])	CW users/CWS heat exchange mechs. (M[c])	----------------------	CW flow & return temp. (O[d])	----------------------
A0	Control & configure CWS	Electricity to CWS control sys. (I)	Human control interface (I)	----------------------	Informational → excluded	----------------------
		Humans (M)	Local control mechs. (I)			
			CWS control sys. (M)			
			Controllable CWP equip. (M)			
			Controllable CW circ. sys. equip. (M)			
A0	Accumulate & store cooling medium	Air (I)	H-tank equip. (M)	----------------------	Flow of water between H-tanks & CW circ. sys.	----------------------
		Water for storage in H-tanks (I)				

A0	Circulate cooling medium in CWS	CW flow & return temp. (I) Electricity to CW circ. sys. equip. (I)	CW circ. sys. equip. (M)	----------------------	CW flow & return temp. (O)	Air from vacuum degassers (O) Water losses from CW circ. sys. (O) Energy losses in CW circ. sys. (O)
A0	Chill cooling medium	CW flow & return temp. (I) Electricity to CWP equip. (I) Oil in compressors (I) SW flow & supply temp. (I) Refrig. in CWPs (I)	CWP equip. (M)	----------------------	CW flow & supply temp. (O)	Refrig. losses from CWP equip. (O) Energy losses in CWP equip. (O) SW flow & reject temp. (O)
A511	Compress flow of refrigerant from evaporator	Flow of refrig. in suction line (I) Electricity to compressor (I) Oil in CWP 1 compressor (I)	Compressor & oil circuit (M)	Oil re-injected to compressor	Flow of refrig. from compressor (O)	Energy losses in compressor (O)

[a] D = diagram number
[b] I = IDEF0 input
[c] M = IDEF0 mechanism
[d] O = IDEF0 output

4. Future work on system sustainability at BAE Systems

The study reported herein has focused on describing the behaviour of the CW system from a sustainability perspective, by: (i) modelling the CW system's behaviour; and (ii) interpreting this system model using the S-Cycle model. This work has opened up a number of avenues for future research on system sustainability at BAE Systems, briefly outlined in the following sections.

4.1 Quantifying and measuring the sustainability of the chilled water system

The current study has provided descriptive information on the behaviour of the CW system from a sustainability perspective, i.e. *what* intended output is to be sustained, *what* renewable and non-renewable resources are used to produce this output, *what* intended resources are produced for self-support, and *what* waste is produced alongside the intended output. However, to make truly well-informed decisions about the CW system's sustainability, information is needed on its *sustainability performance* – i.e. its behaviour in the above aspects must be quantified and evaluated.

A set of sustainability performance metrics for the CW system was originally intended to form an output of the current study. However, owing to time constraints and the need to model the system from scratch, this was not possible. Instead, it is planned that a Masters student from DMEM at the University of Strathclyde will deliver sustainability metrics for the system, using the CW system model and the sustainability interpretation as a basis for their development. It is anticipated that these metrics will be evaluated to provide quantitative information on the sustainability performance of the system. Defined sustainability metrics, along with their data gathering and calculation processes, would also provide the basis for a simulation model of the CW system. Such a model would allow the potential impact of system changes on sustainability performance to be investigated.

4.2 Applying the S-Cycle model from a through-life perspective

As discussed in Section 2.1, the CW system work focused on the life in service phase of the system life cycle. Within this phase, the scope of the work was further limited to the operation of the CW system. Its maintenance and repair were excluded. However, given the length of a ship's life in service (upwards of thirty years), it may be useful to understand the sustainability of the CW system (and other systems on a ship) from a through-life perspective. That is, considering the operation, maintenance and repair of the system throughout its life. Knowledge in this respect, combined with the use of simulation models (as touched upon above), could facilitate research on the potential impacts of alternative maintenance and repair practices on the sustainability performance of the CW system over its life. In turn, knowledge on these impacts could support decision making with respect to the introduction of new maintenance/repair technologies and processes.

4.3 Extending application of the S-Cycle model to other systems

The S-Cycle model is generic, meaning that it can be applied to any system at any level (see Figure 9). As such, it provides a consistent basis for modelling and analysing sustainability in a system of systems such as a ship. A natural progression from the CW system study is therefore to extend the application of the S-Cycle model to other systems. This could yield activity models (like the CW system model) for those systems, as well as sustainability performance metrics and simulation models. Additionally, modelling other systems could, over time, provide a holistic view of the systems on a ship and how they relate to one another (e.g. by highlighting the flows of resources, waste, and intended outputs between systems). In turn, this could facilitate research investigating how changes in the sustainability performance of one system impact upon the performance of other systems to which it is related and ultimately, the performance of the ship as a whole.

4.4 Relating sustainability to other abilities in a naval ships context

Finally, the sustainability interpretation of the CW system model has highlighted potential links between sustainability and other abilities in a naval ships context. For example, as discussed in Section 3.2.2, most of the items of physical equipment comprising the CW system were interpreted as non-renewable resources. This is due to the fact that if e.g. a CW plant or a pump is lost through damage or mechanical failure whilst the ship is at sea, it cannot be fully replaced. As such, it would seem that the *reliability* and *survivability* of equipment are important considerations with respect to CW system sustainability. Additionally, sustainability fundamentally depends upon the *availability* of resources. Furthermore, at a workshop focusing on evaluation of the CW system work at BAE Systems, participants also raised the concept of *supportability* as potentially related. Research on the relationships between these abilities (if any exist) could provide a basis for guidelines on how to bring about sustainability improvements through improvements in other domains. Guidelines of this nature could capitalise on the existing expertise of engineers and re-orient it towards the overarching goal of system sustainability.

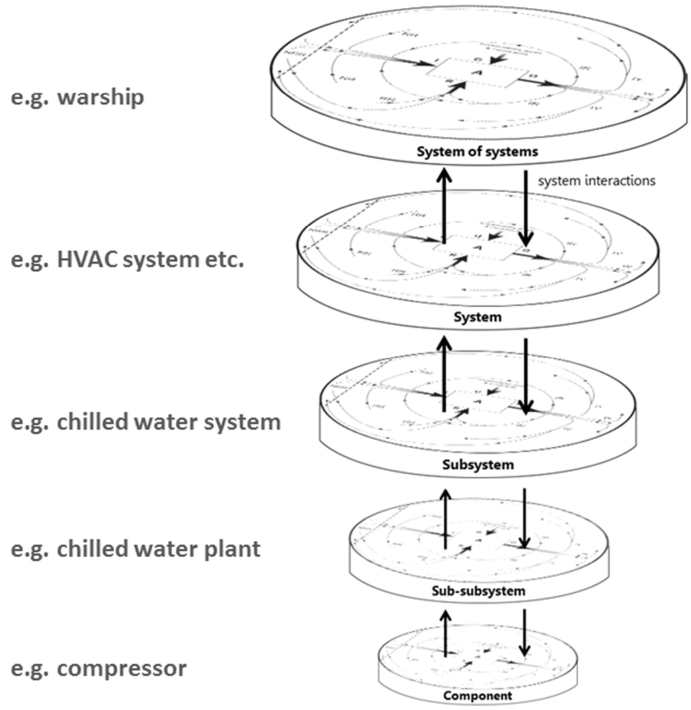


Figure 9. S-Cycle application levels

5. Conclusion

This report has presented the major outcomes of a study aiming to: (i) model the CW system for BAE Systems; and (ii) test and evaluate the S-Cycle model developed at the University of Strathclyde. The major outcomes of this study were: an activity model of the CW system; and a sustainability interpretation of this activity model, developed by applying the S-Cycle. As shown in Section 2, the activity model provides a general view on the behaviour of the CW system. It describes the major activities carried out to remove waste heat from equipment on board the ship, and their key relationships. The S-Cycle illustrates that the sustained production of intended output by a system depends fundamentally upon the availability of resources, and that waste is also produced alongside intended output. Accordingly, the sustainability interpretation of the CW system model (Section 3) highlights the renewable and non-renewable resources used by the system to produce a flow of chilled water for users, the resources produced by the system for its own use, and the waste produced alongside the intended output. The current work on CW system sustainability has in turn opened up a number of avenues for further research on system sustainability at BAE Systems, (Section 4), including: measuring the sustainability performance of the CW system, and simulating its behaviour to explore the impact of system changes; applying the S-Cycle model from a through-life perspective; extending application of the S-Cycle to other systems on a ship; and exploring the relationship (if any exists) between sustainability and other abilities in a naval ships context.

6. List of abbreviations

Abbreviation	Meaning
A	Activity
atm.	Atmosphere
circ.	Circulation
C_p	System variable representing the specific heat capacity of the cooling medium

CW	Chilled water
CW circ. sys.	Chilled water circulation system
CWP	Chilled water plant
CWS	Chilled water system
CWS control sys.	Chilled water system control system
CWSW	Describes items of equipment within a chilled water plant's chilled water sea water system
CWSW sys.	Chilled water sea water system
ΔT	System variable representing the difference between the chilled water supply and return temperature
DefStan	Defence Standard
demin.	Demineralised
DMEM	Design, Manufacture and Engineering Management, a department at the University of Strathclyde
equip.	Equipment
G	Activity goal
HCI	Human control interface
HP	High pressure
H-tanks	Header tanks, also known as expansion tanks and accumulators
I	Activity input
IDEF0	Integration Definition for Function Modelling, the language used to model the chilled water system
info	Information
IO	Intended output
IR	Intended resource
LP	Low pressure
LP air sys.	Low pressure air system
M	Mechanism
$\dot{m}$	Cooling medium flow rate
mechs.	Mechanisms
NBC shutdown	Nuclear, Biological and Chemical shutdown
NES	Naval Engineering Standard
no.	Number
NRR	Non-renewable resource
O	Output
o/b	Overboard
op. state	Operational state of the ship
P, T & F	Pressure, temperature and flow rate of cooling medium
PLC	Programmable logic centre
PMS	Platform management system
$\dot{Q}$	Heat transfer rate between equipment and the cooling medium
RAS	Replenishment at sea
refrig.	Refrigerant
RR	Renewable resource
S-Cycle	The Sustainability Cycle, a sustainability model used to interpret the chilled water system model
SOI	System of interest
SW	Sea water
sys.	System
temp.	Temperature
TEx valve	Thermostatic expansion valve
W	Waste

7. CW system function model

The IDEF0 diagrams comprising the CW system function model are presented on the following pages.

All diagrams in the model have a unique number, shown in the bottom left-hand corner of the diagram (illustrated in Figure 10 below). Throughout the model, any activity that has been decomposed in a sub-diagram is denoted with a number at its bottom right-hand corner. This number is the number of the diagram detailing the composition.

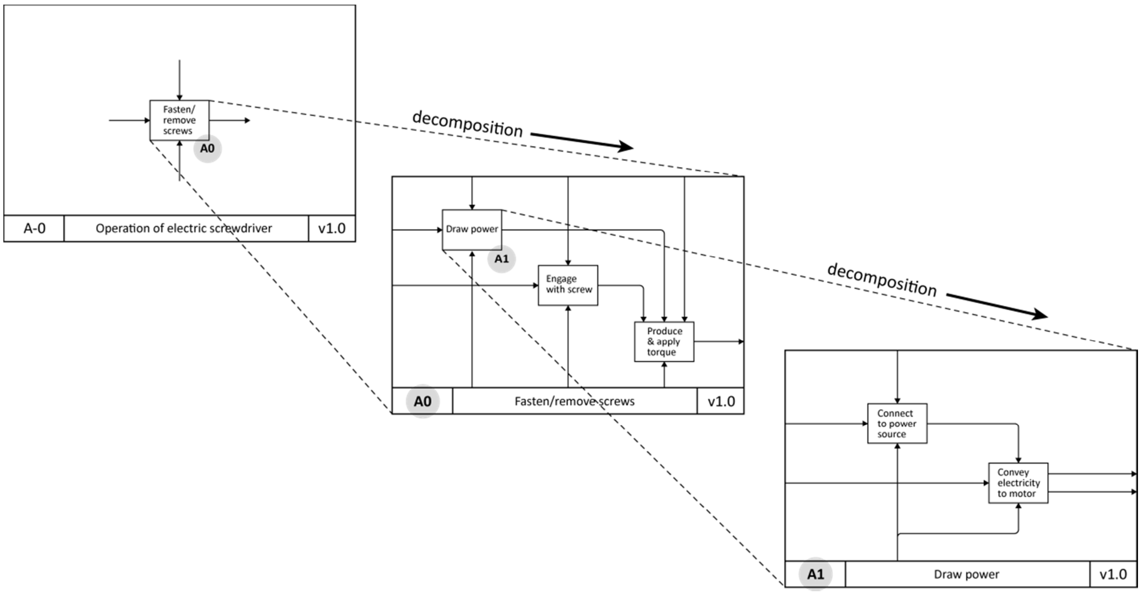
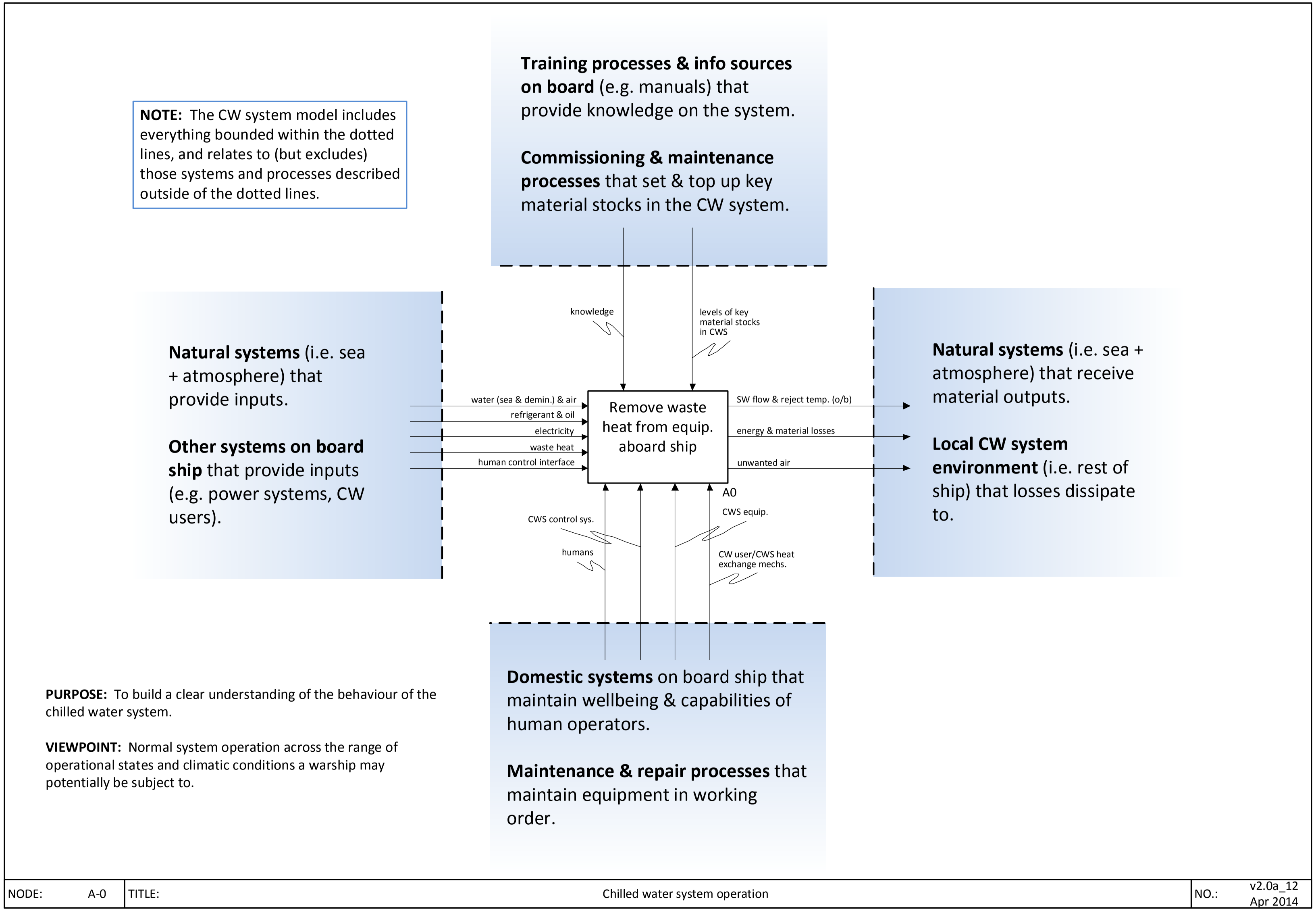
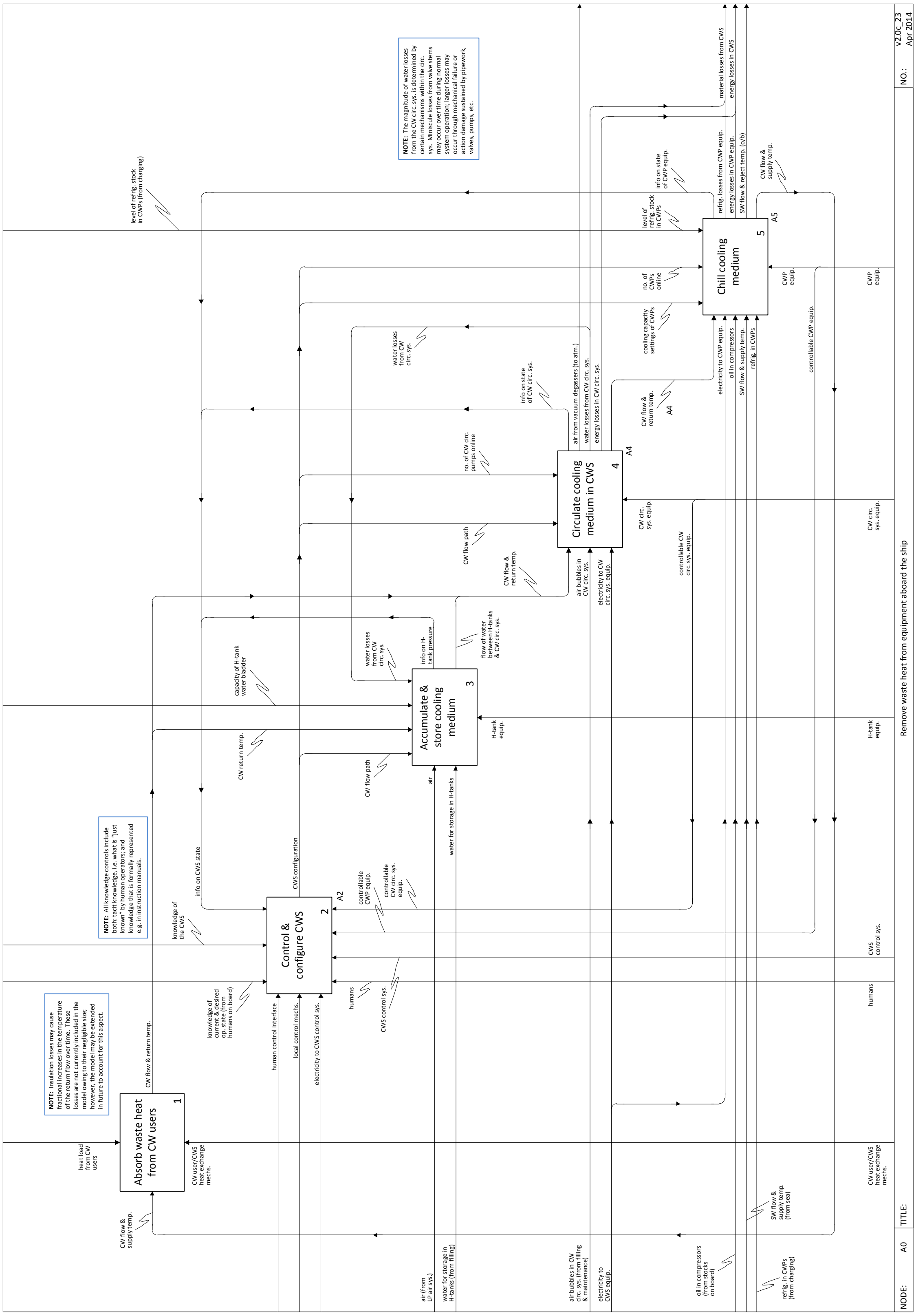
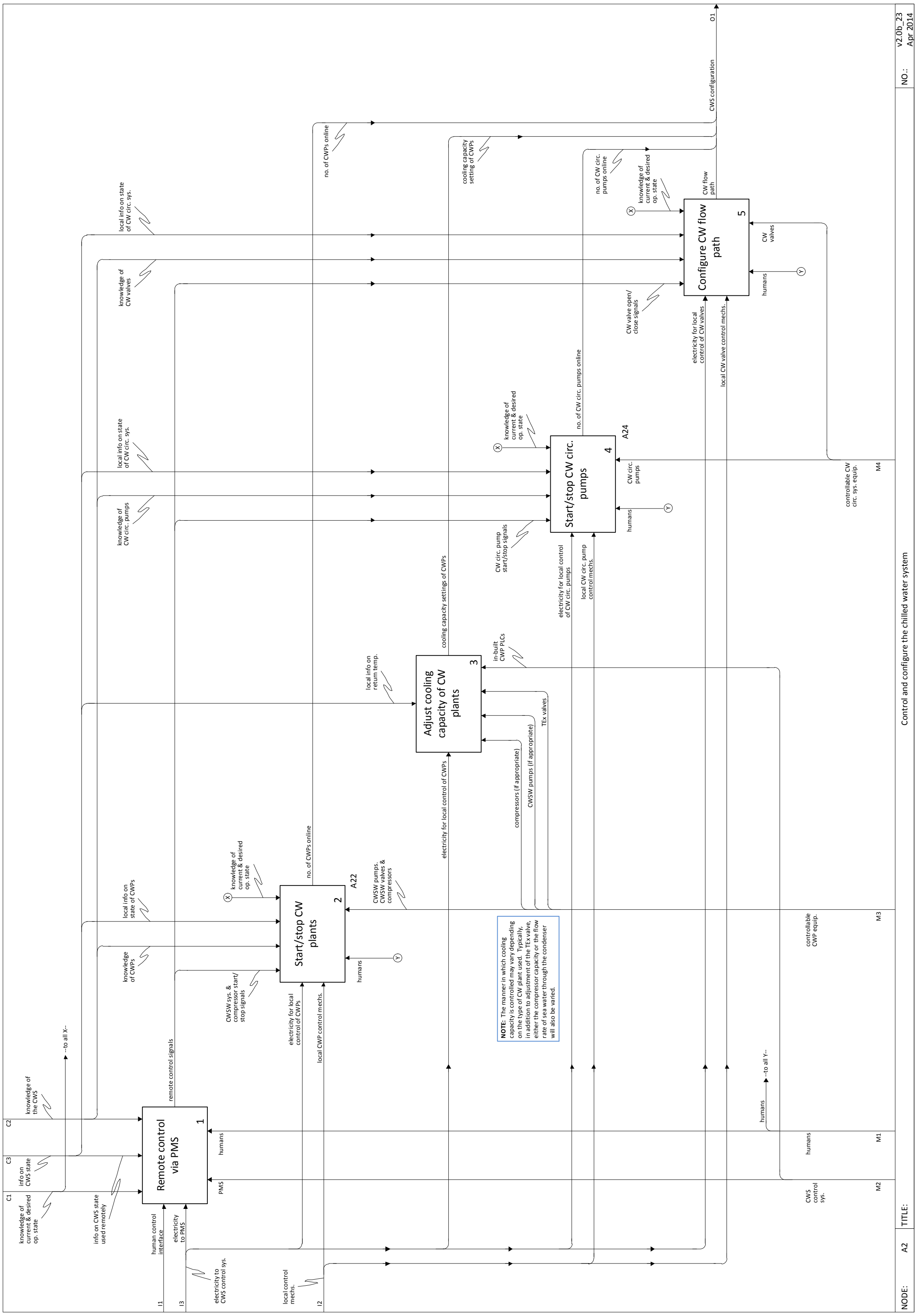
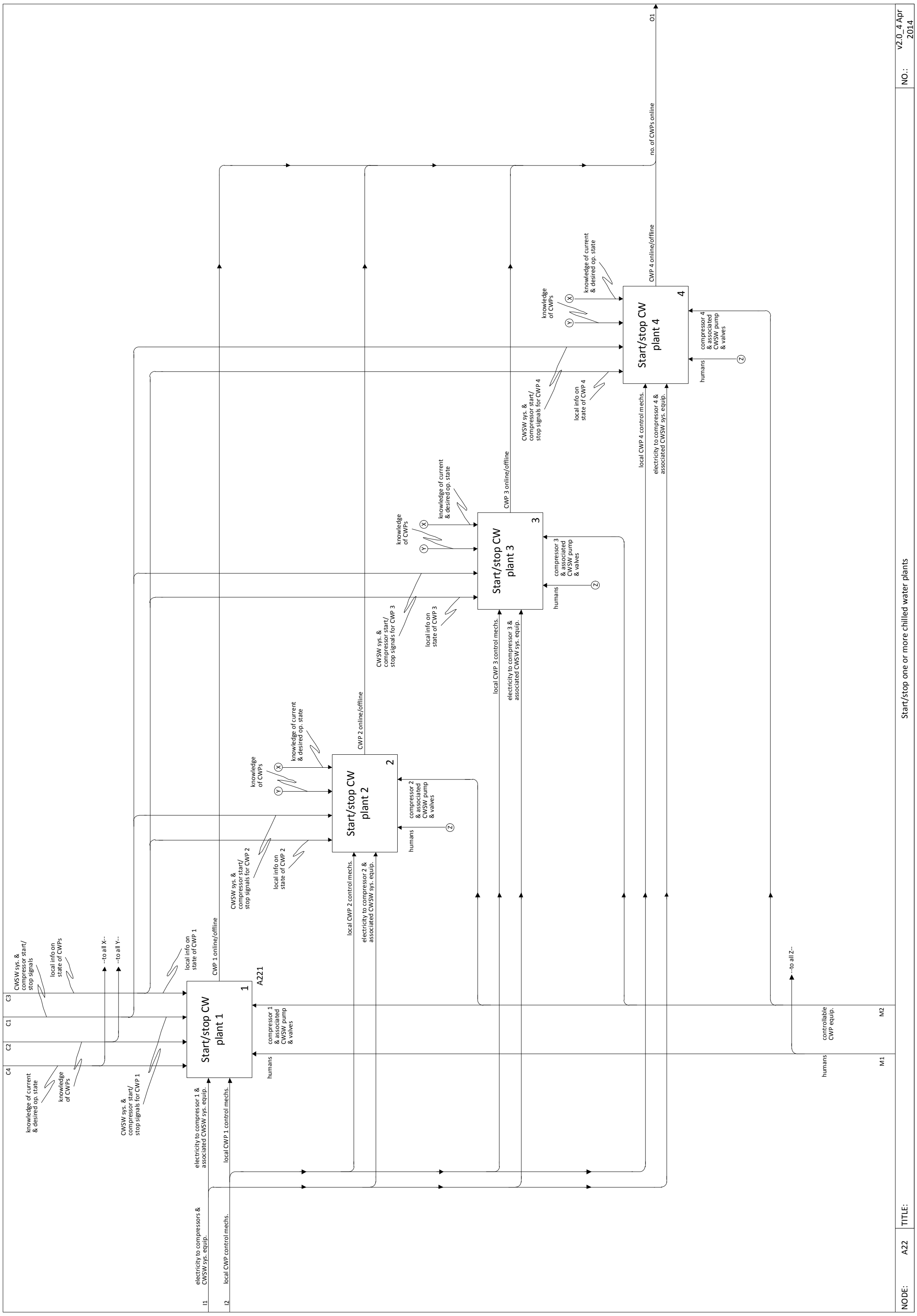


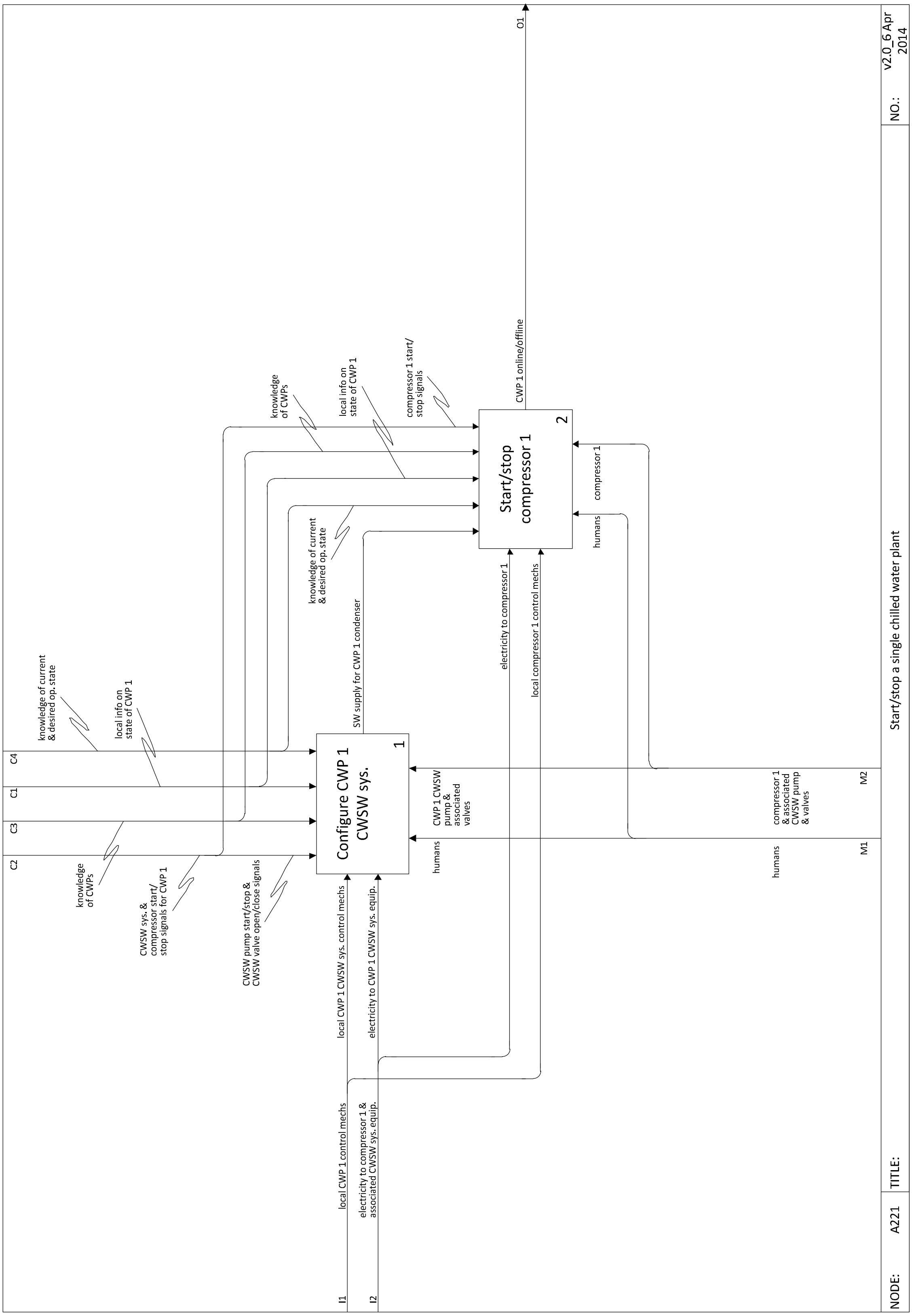
Figure 10. Tracing the decomposition of activities in an IDEF0 model


NOTE: The CW system model includes everything bounded within the dotted lines, and relates to (but excludes) those systems and processes described outside of the dotted lines.
Training processes & info sources on board (e.g. manuals) that provide knowledge on the system.
Commissioning & maintenance processes that set & top up key material stocks in the CW system.
Natural systems (i.e. sea + atmosphere) that provide inputs.
Other systems on board ship that provide inputs (e.g. power systems, CW users).
knowledge
levels of key material stocks in CWS
water (sea & demin.) & air
refrigerant & oil
electricity
waste heat
human control interface
Remove waste heat from equip. aboard ship
A0
SW flow & reject temp. (o/b)
energy & material losses
unwanted air
Natural systems (i.e. sea + atmosphere) that receive material outputs.
Local CW system environment (i.e. rest of ship) that losses dissipate to.
CWS control sys.
humans
CWS equip.
CW user/CWS heat exchange mechs.
Domestic systems on board ship that maintain wellbeing & capabilities of human operators.
Maintenance & repair processes that maintain equipment in working order.
PURPOSE: To build a clear understanding of the behaviour of the chilled water system.
VIEWPOINT: Normal system operation across the range of operational states and climatic conditions a warship may potentially be subject to.
NODE: A-0
TITLE: Chilled water system operation
NO.: v2.0a_12
Apr 2014

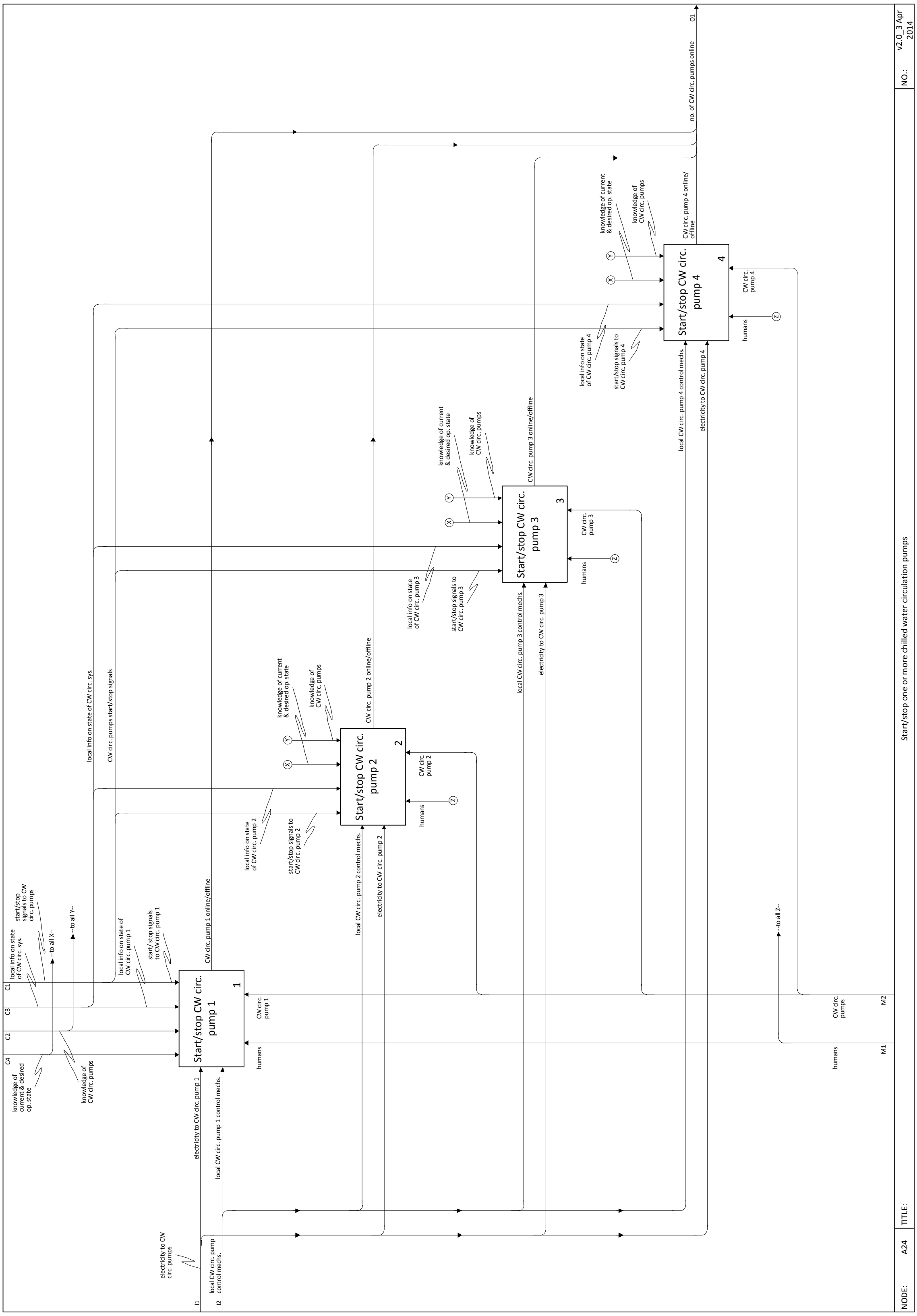

Absorb waste heat from CW users
Control & configure CWS
Accumulate & store cooling medium
Circulate cooling medium in CWS
Chill cooling medium
NODE: A0
TITLE: Remove waste heat from equipment aboard the ship
NO.: v2.0c_23 Apr 2014

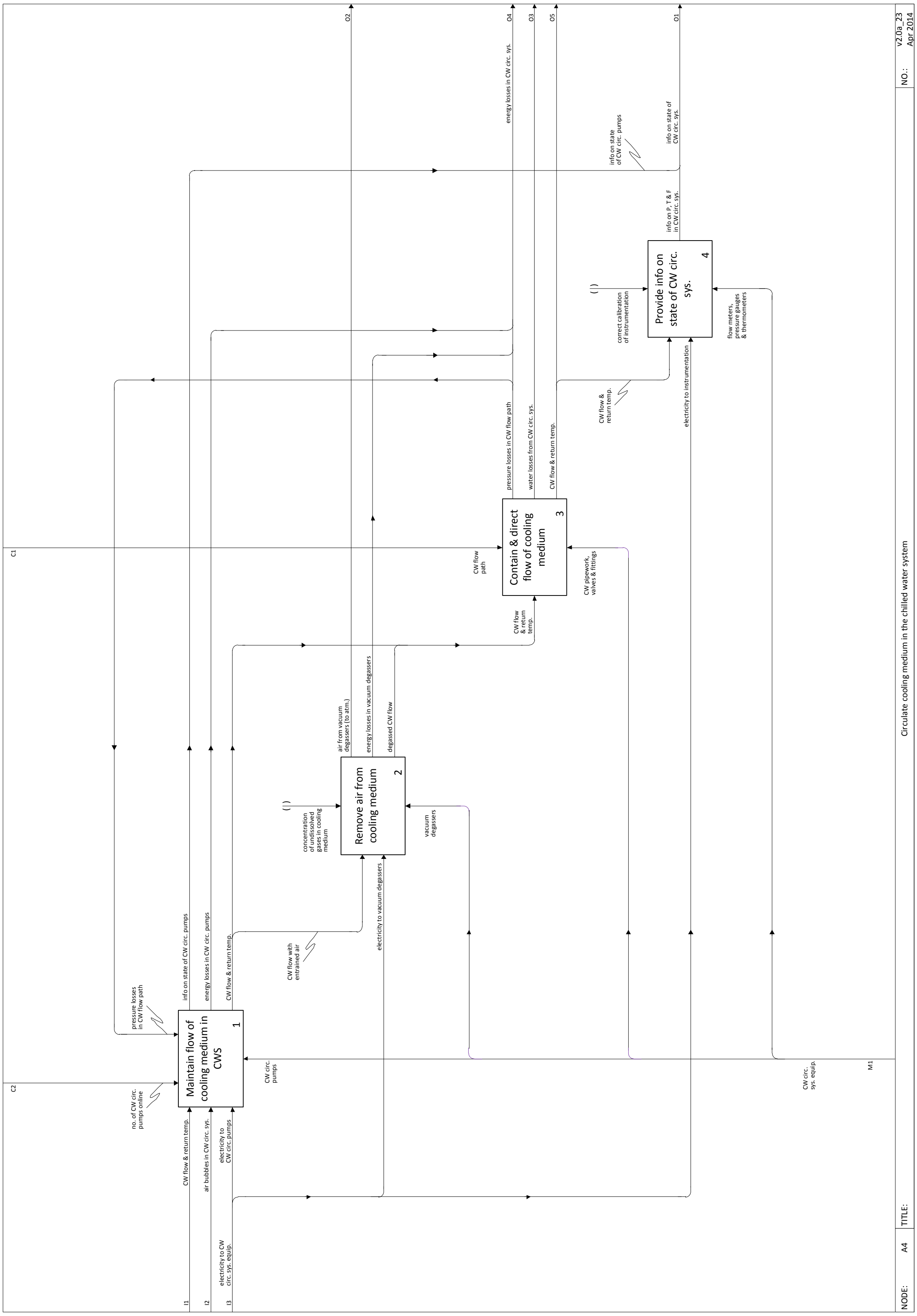

Remote control via PMS
1
Start/stop CW plants
2
A22
Adjust cooling capacity of CW plants
3
Start/stop CW circ. pumps
4
A24
Configure CW flow path
5
NOTE: The manner in which cooling capacity is controlled may vary depending on the type of CW plant used. Typically, in addition to adjustment of the TEx valve, either the compressor capacity or the flow rate of sea water through the condenser will also be varied.
CWS configuration
O1
NODE:
A2
TITLE:
Control and configure the chilled water system
NO.:
v2.0b_23 Apr 2014

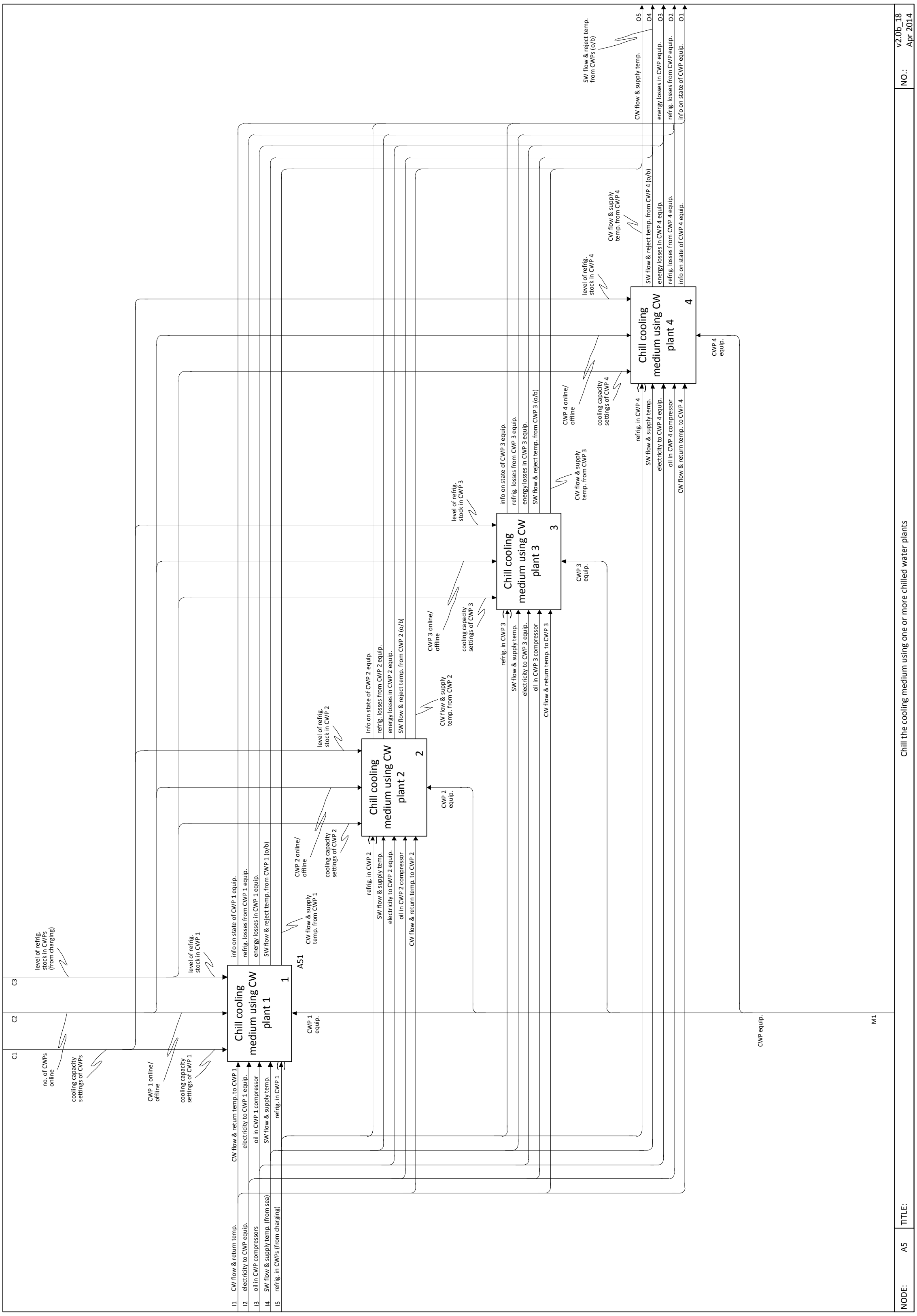

Start/stop CW plant 1
A221
Start/stop CW plant 2
Start/stop CW plant 3
Start/stop CW plant 4
CWP 1 online/offline
CWP 2 online/offline
CWP 3 online/offline
CWP 4 online/offline
no. of CWPs online
O1
knowledge of current & desired op. state
knowledge of CWPs
CWSW sys. & compressor start/ stop signals
local info on state of CWPs
CWSW sys. & compressor start/ stop signals for CWP 1
local info on state of CWP 1
electricity to compressors & CWSW sys. equip.
local CWP control mechs.
electricity to compressor 1 & associated CWSW sys. equip.
local CWP 1 control mechs.
compressor 1 & associated CWSW pump & valves
humans
controllable CWP equip.
--to all X--
--to all Y--
--to all Z--
C1
C2
C3
C4
I1
I2
M1
M2
NODE:
A22
TITLE:
Start/stop one or more chilled water plants
NO.:
v2.0_4 Apr 2014

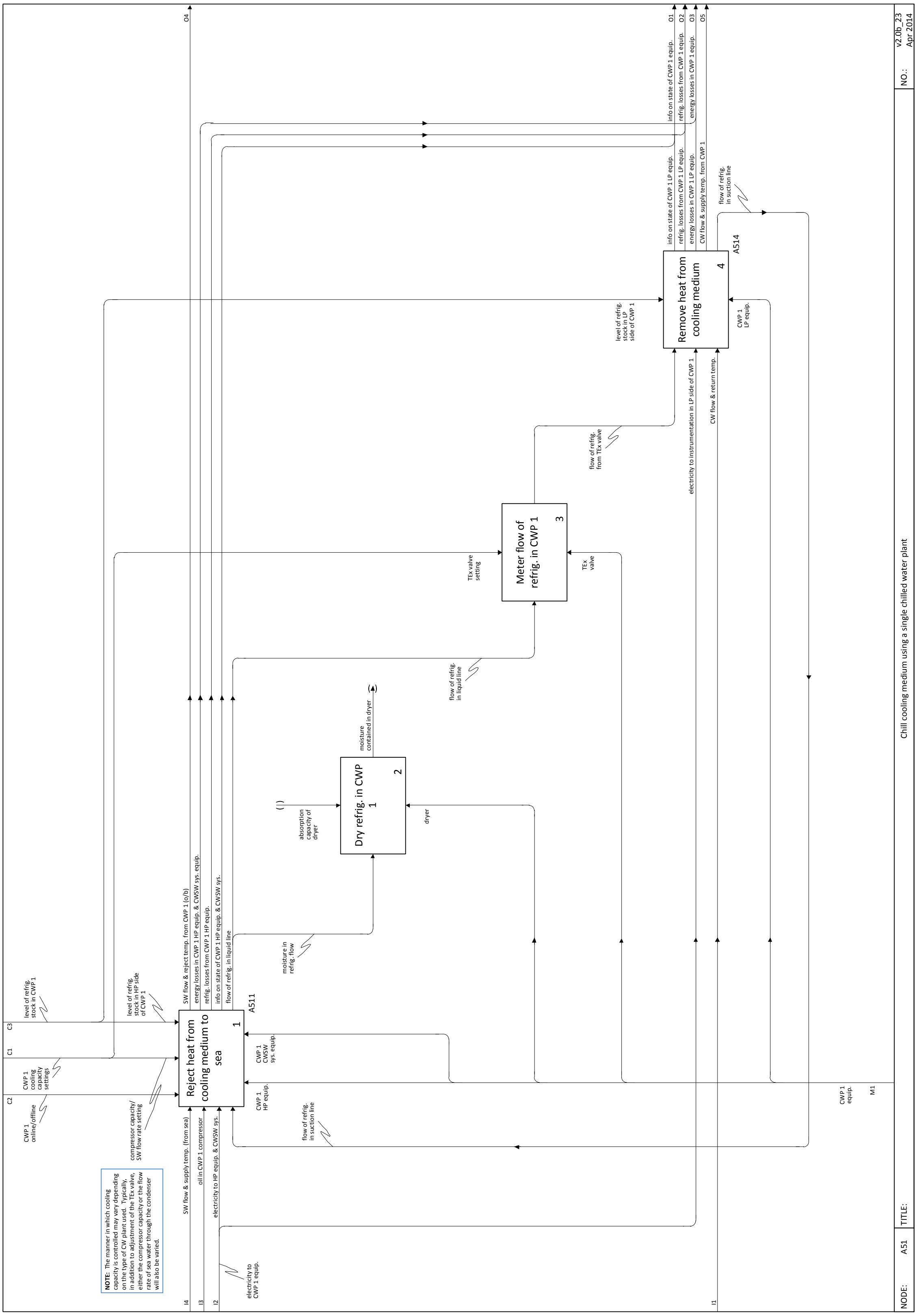


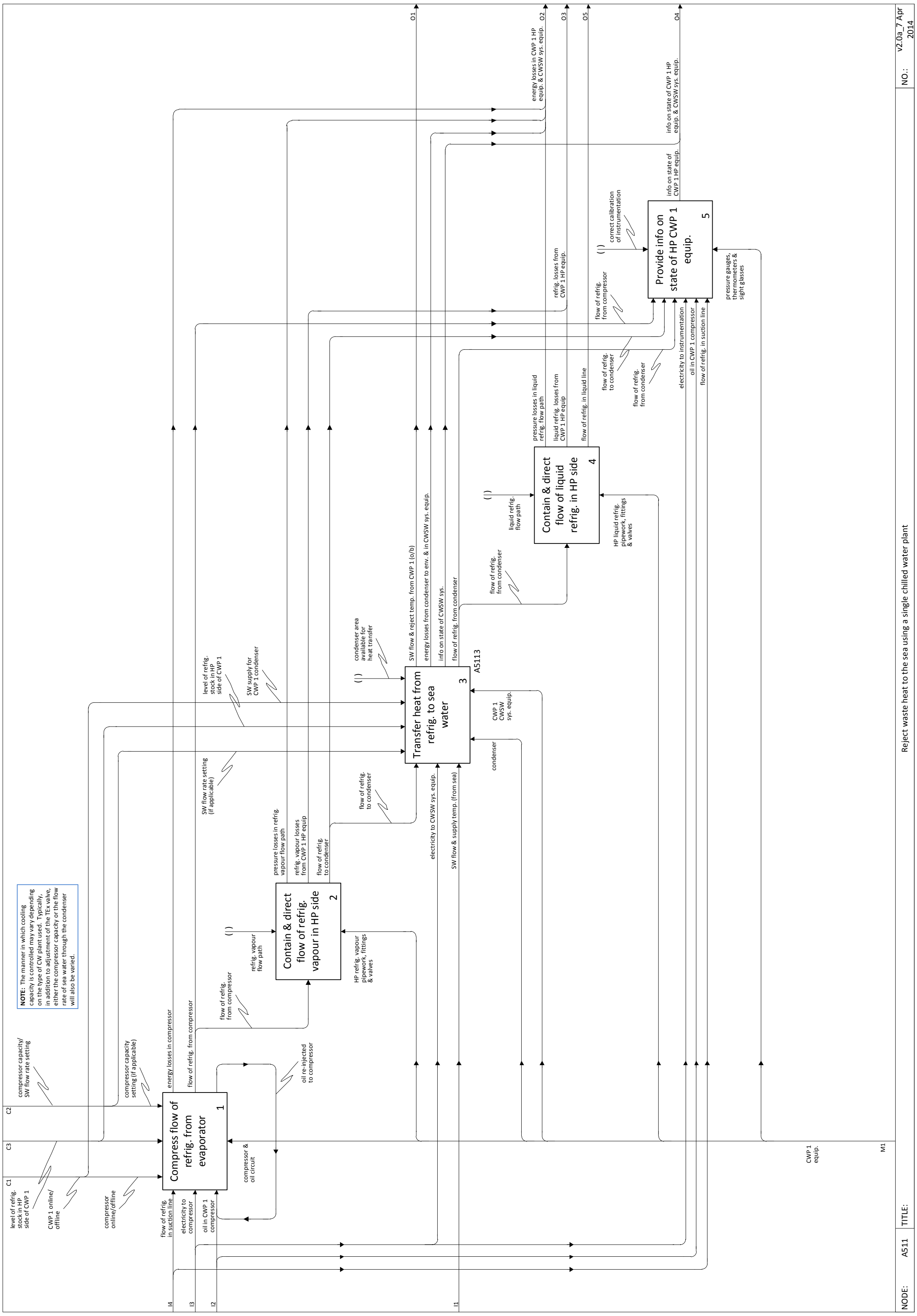
Configure CWP 1 CWSW sys.
1
Start/stop compressor 1
2
C1
C2
C3
C4
I1
I2
M1
M2
O1
knowledge of current & desired op. state
local info on state of CWP 1
knowledge of CWPs
CWSW sys. & compressor start/stop signals for CWP 1
CWSW pump start/stop & CWSW valve open/close signals
local CWP 1 CWSW sys. control mechs
electricity to CWP 1 CWSW sys. equip.
local CWP 1 control mechs
electricity to compressor 1 & associated CWSW sys. equip.
humans
CWP 1 CWSW pump & associated valves
compressor 1 & associated CWSW pump & valves
SW supply for CWP 1 condenser
knowledge of CWPs
local info on state of CWP 1
compressor 1 start/stop signals
knowledge of current & desired op. state
electricity to compressor 1
local compressor 1 control mechs
humans
compressor 1
CWP 1 online/offline
NODE:
A221
TITLE:
Start/stop a single chilled water plant
NO.:
v2.0_6 Apr 2014

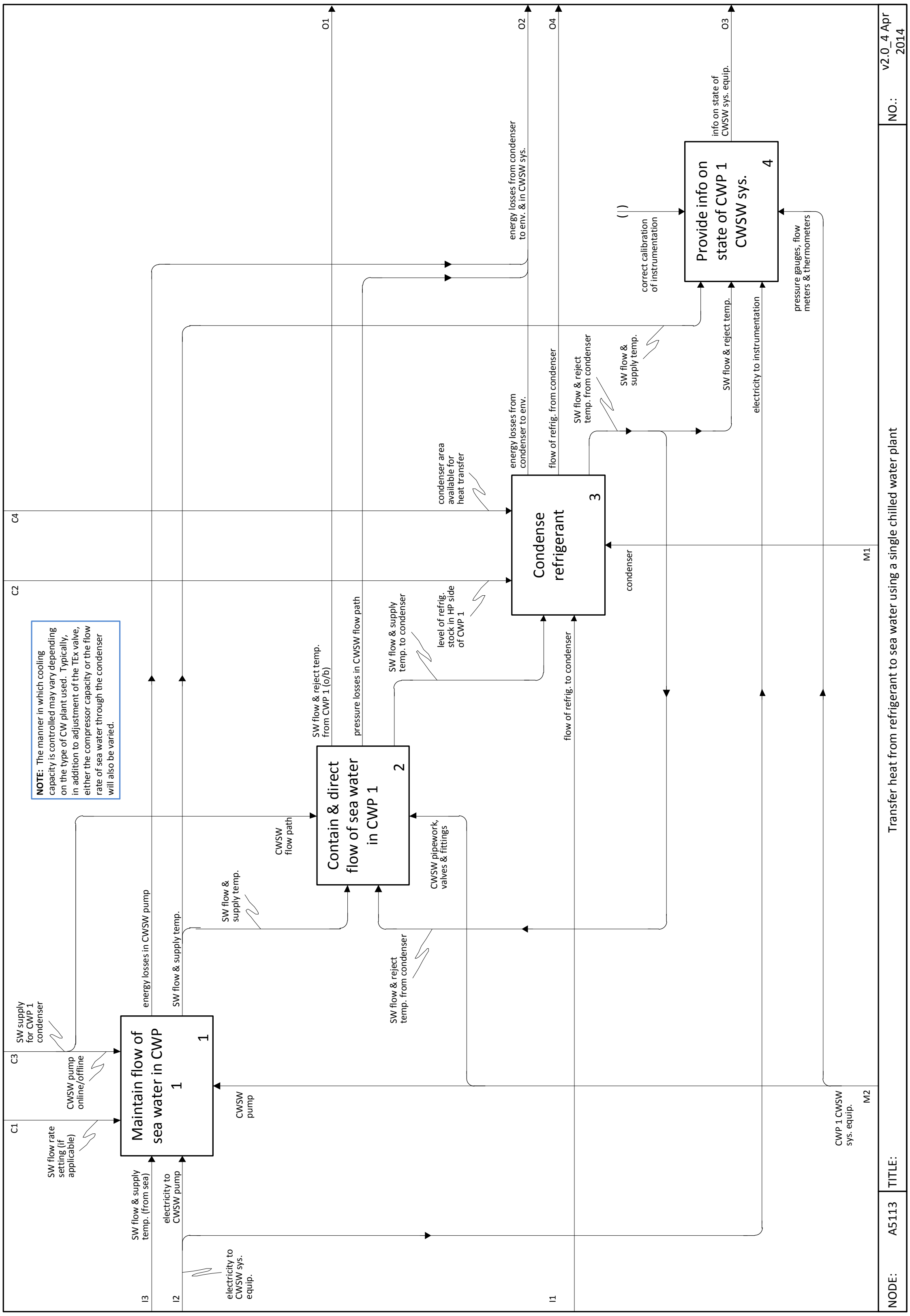

Start/stop CW circ. pump 1
Start/stop CW circ. pump 2
Start/stop CW circ. pump 3
Start/stop CW circ. pump 4
Start/stop one or more chilled water circulation pumps
NODE: A24
TITLE:
NO.: v2.0_3 Apr 2014
no. of CW circ. pumps online
humans
CW circ. pumps


Maintain flow of cooling medium in CWS
1
Remove air from cooling medium
2
Contain & direct flow of cooling medium
3
Provide info on state of CW circ. sys.
4
I1
I2
I3
C1
C2
O1
O2
O3
O4
O5
M1
CW flow & return temp.
air bubbles in CW circ. sys.
electricity to CW circ. sys. equip.
electricity to CW circ. pumps
no. of CW circ. pumps online
pressure losses in CW flow path
info on state of CW circ. pumps
energy losses in CW circ. pumps
CW circ. pumps
CW flow with entrained air
electricity to vacuum degassers
concentration of undissolved gases in cooling medium
vacuum degassers
air from vacuum degassers (to atm.)
energy losses in vacuum degassers
degassed CW flow
CW flow path
CW pipework, valves & fittings
water losses from CW circ. sys.
energy losses in CW circ. sys.
correct calibration of instrumentation
electricity to instrumentation
flow meters, pressure gauges & thermometers
info on P, T & F in CW circ. sys.
info on state of CW circ. sys.
CW circ. sys. equip.
NODE: A4
TITLE: Circulate cooling medium in the chilled water system
NO.: v2.0a_23 Apr 2014

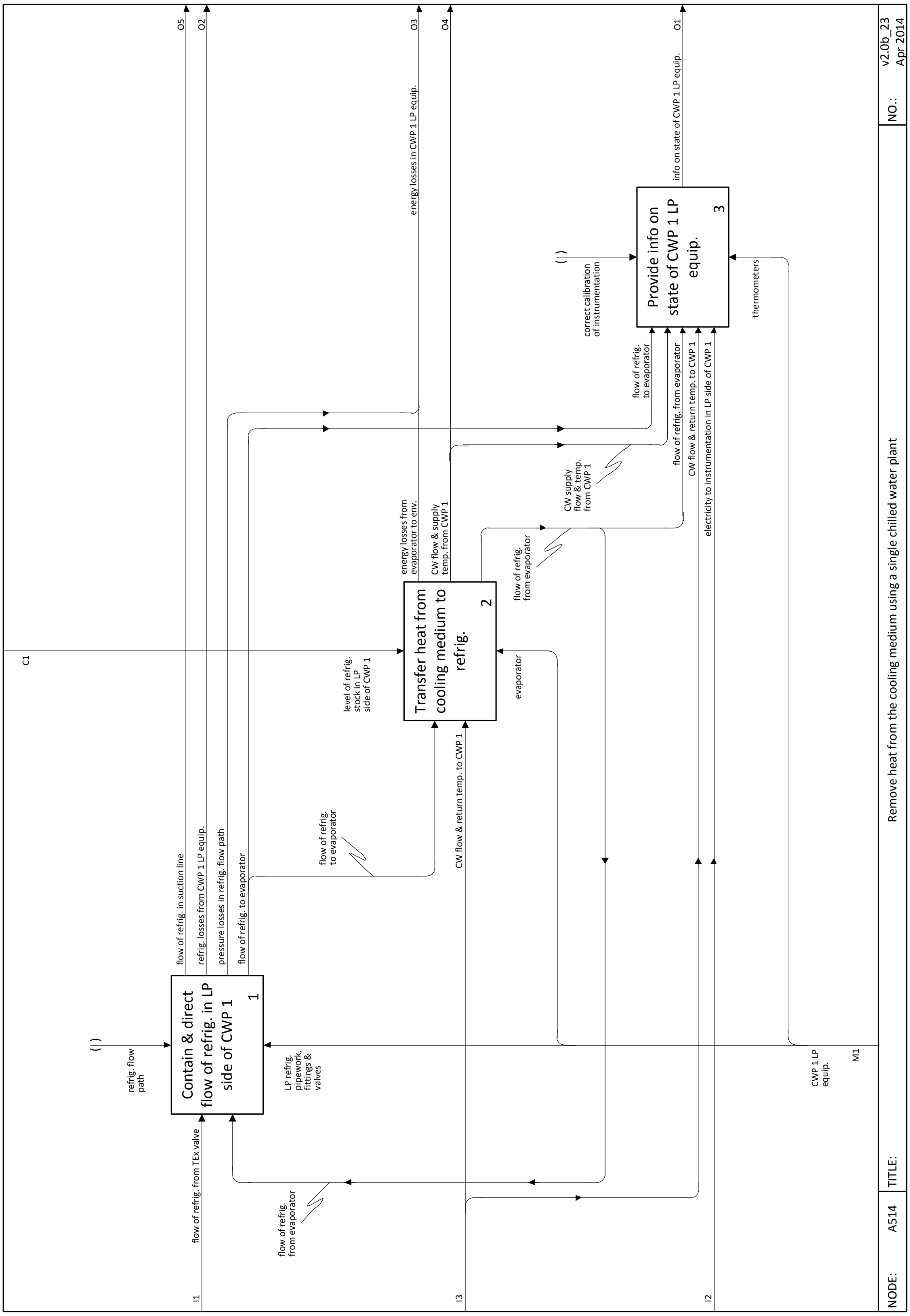

Chill cooling medium using CW plant 1
Chill cooling medium using CW plant 2
Chill cooling medium using CW plant 3
Chill cooling medium using CW plant 4
A51
NODE: A5
TITLE: Chill the cooling medium using one or more chilled water plants
NO.: v2.0b_18 Apr 2014
I1 CW flow & return temp.
I2 electricity to CWP equip.
I3 oil in CWP compressors
I4 SW flow & supply temp. (from sea)
I5 refrig. in CWPs (from charging)
O1 info on state of CWP equip.
O2 refrig. losses from CWP equip.
O3 energy losses in CWP equip.
O5 CW flow & supply temp.
M1 CWP equip.


Reject heat from cooling medium to sea
1
A511
Dry refrig. in CWP 1
2
Meter flow of refrig. in CWP 1
3
Remove heat from cooling medium
4
A514
CWP 1 online/offline
CWP 1 cooling capacity settings
level of refrig. stock in CWP 1
level of refrig. stock in HP side of CWP 1
compressor capacity/ SW flow rate setting
NOTE: The manner in which cooling capacity is controlled may vary depending on the type of CW plant used. Typically, in addition to adjustment of the TEx valve, either the compressor capacity or the flow rate of sea water through the condenser will also be varied.
SW flow & supply temp. (from sea)
oil in CWP 1 compressor
electricity to HP equip. & CWSW sys.
electricity to CWP 1 equip.
SW flow & reject temp. from CWP 1 (o/b)
energy losses in CWP 1 HP equip. & CWSW sys. equip.
refrig. losses from CWP 1 HP equip.
info on state of CWP 1 HP equip. & CWSW sys.
flow of refrig. in liquid line
CWP 1 HP equip.
CWP 1 CWSW sys. equip.
flow of refrig. in suction line
moisture in refrig. flow
absorption capacity of dryer
dryer
moisture contained in dryer
TEx valve setting
TEx valve
flow of refrig. from TEx valve
level of refrig. stock in LP side of CWP 1
electricity to instrumentation in LP side of CWP 1
CW flow & return temp.
CWP 1 LP equip.
info on state of CWP 1 LP equip.
refrig. losses from CWP 1 LP equip.
energy losses in CWP 1 LP equip.
CW flow & supply temp. from CWP 1
info on state of CWP 1 equip.
refrig. losses from CWP 1 equip.
energy losses in CWP 1 equip.
CWP 1 equip.
C1
C2
C3
I1
I2
I3
I4
O1
O2
O3
O4
O5
M1
NODE: A51
TITLE: Chill cooling medium using a single chilled water plant
NO.: v2.0b_23 Apr 2014


Compress flow of refrig. from evaporator
1
Contain & direct flow of refrig. vapour in HP side
2
Transfer heat from refrig. to sea water
3
A5113
Contain & direct flow of liquid refrig. in HP side
4
Provide info on state of HP CWP 1 equip.
5
NOTE: The manner in which cooling capacity is controlled may vary depending on the type of CW plant used. Typically, in addition to adjustment of the TEx valve, either the compressor capacity or the flow rate of sea water through the condenser will also be varied.
NODE: A511
TITLE: Reject waste heat to the sea using a single chilled water plant
NO.: v2.0a_7 Apr 2014



NODE:
A5113
TITLE:
Transfer heat from refrigerant to sea water using a single chilled water plant
NO.:
v2.0_4 Apr 2014
Maintain flow of sea water in CWP 1
1
Contain & direct flow of sea water in CWP 1
2
Condense refrigerant
3
Provide info on state of CWP 1 CWSW sys.
4
NOTE: The manner in which cooling capacity is controlled may vary depending on the type of CW plant used. Typically, in addition to adjustment of the TEx valve, either the compressor capacity or the flow rate of sea water through the condenser will also be varied.
C1
C2
C3
C4
I1
I2
I3
O1
O2
O3
O4
M1
M2
SW flow rate setting (if applicable)
CWSW pump online/offline
SW supply for CWP 1 condenser
SW flow & supply temp. (from sea)
electricity to CWSW pump
electricity to CWSW sys. equip.
CWSW pump
energy losses in CWSW pump
SW flow & supply temp.
CWSW flow path
CWSW pipework, valves & fittings
SW flow & reject temp. from condenser
SW flow & reject temp. from CWP 1 (o/b)
pressure losses in CWSW flow path
SW flow & supply temp. to condenser
level of refrig. stock in HP side of CWP 1
condenser area available for heat transfer
flow of refrig. to condenser
condenser
energy losses from condenser to env.
flow of refrig. from condenser
energy losses from condenser to env. & in CWSW sys.
SW flow & reject temp.
electricity to instrumentation
correct calibration of instrumentation
pressure gauges, flow meters & thermometers
info on state of CWSW sys. equip.
CWP 1 CWSW sys. equip.



Contain & direct flow of refrig. in LP side of CWP 1
1
Transfer heat from cooling medium to refrig.
2
Provide info on state of CWP 1 LP equip.
3
flow of refrig. in suction line
refrig. losses from CWP 1 LP equip.
pressure losses in refrig. flow path
flow of refrig. to evaporator
energy losses in CWP 1 LP equip.
energy losses from evaporator to env.
CW flow & supply temp. from CWP 1
level of refrig. stock in LP side of CWP 1
evaporator
flow of refrig. from evaporator
CW supply flow & temp. from CWP 1
flow of refrig. from evaporator
CW flow & return temp. to CWP 1
electricity to instrumentation in LP side of CWP 1
info on state of CWP 1 LP equip.
correct calibration of instrumentation
thermometers
refrig. flow path
LP refrig. pipework, fittings & valves
flow of refrig. from TEx valve
CWP 1 LP equip.
O5
O2
O3
O4
O1
C1
I1
I3
I2
M1
NODE:
A514
TITLE:
Remove heat from the cooling medium using a single chilled water plant
NO.:
v2.0b_23
Apr 2014

8. CW system IDEF0 diagrams interpreted using the S-Cycle model

The IDEF0 diagrams interpreted using the S-Cycle model are presented on the following pages. Renewable and non-renewable resources, intended resources, intended outputs, and waste are highlighted using a colour scheme outlined in Figure 11 below.

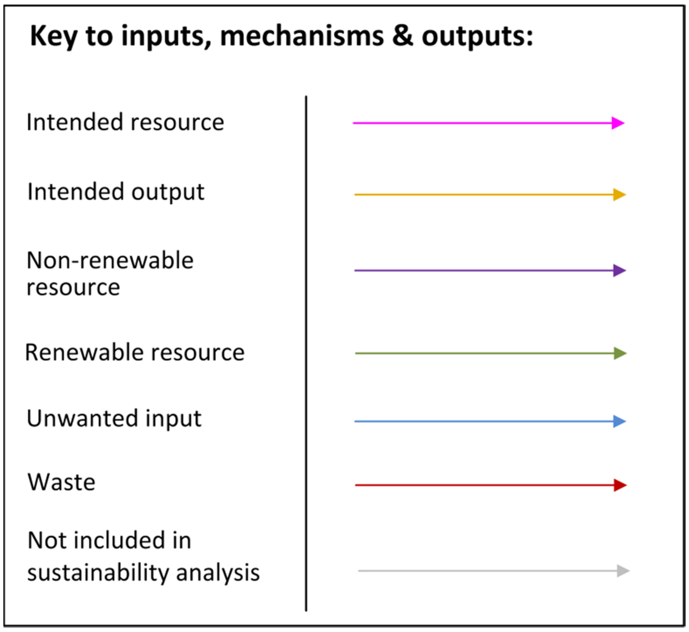
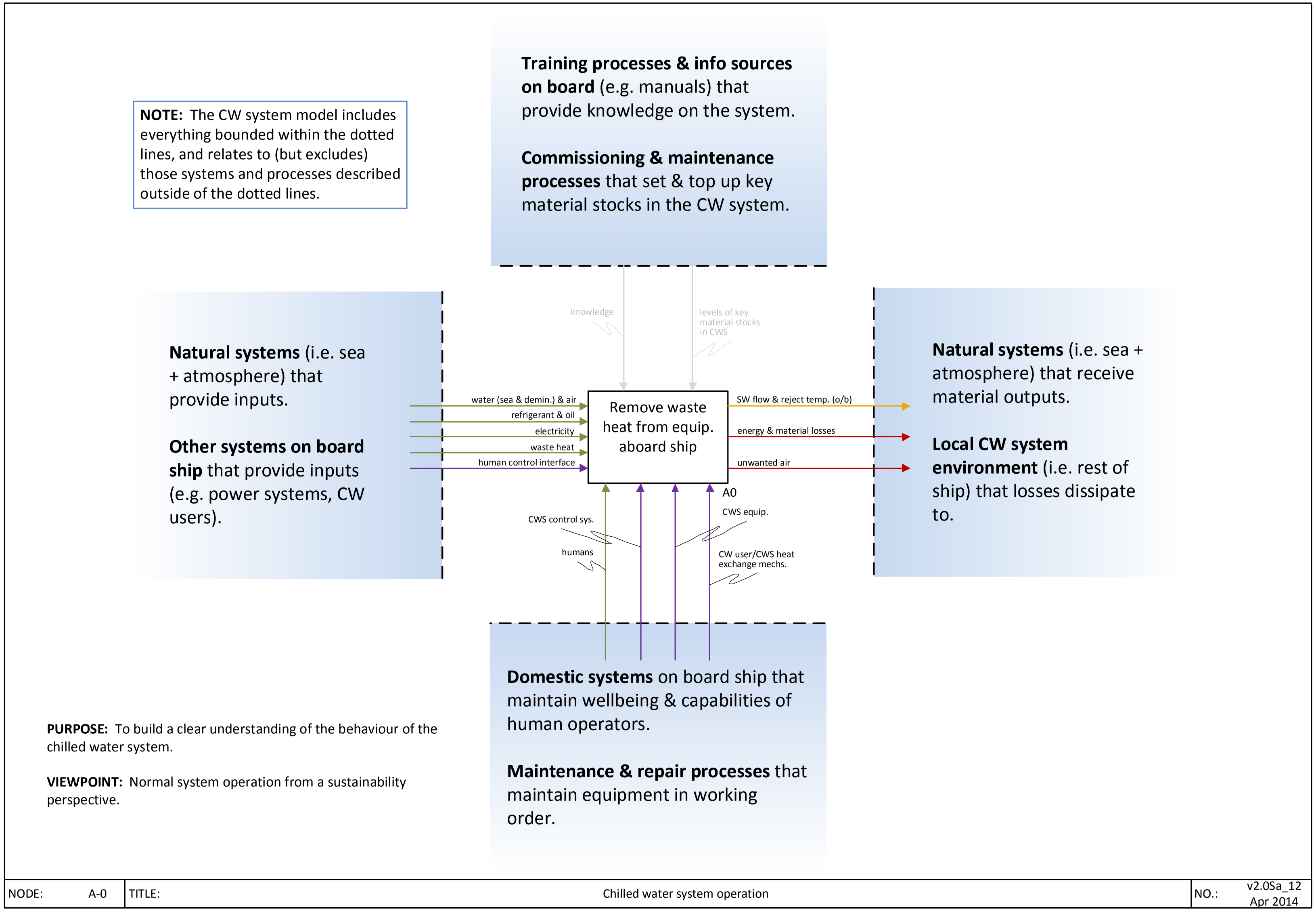
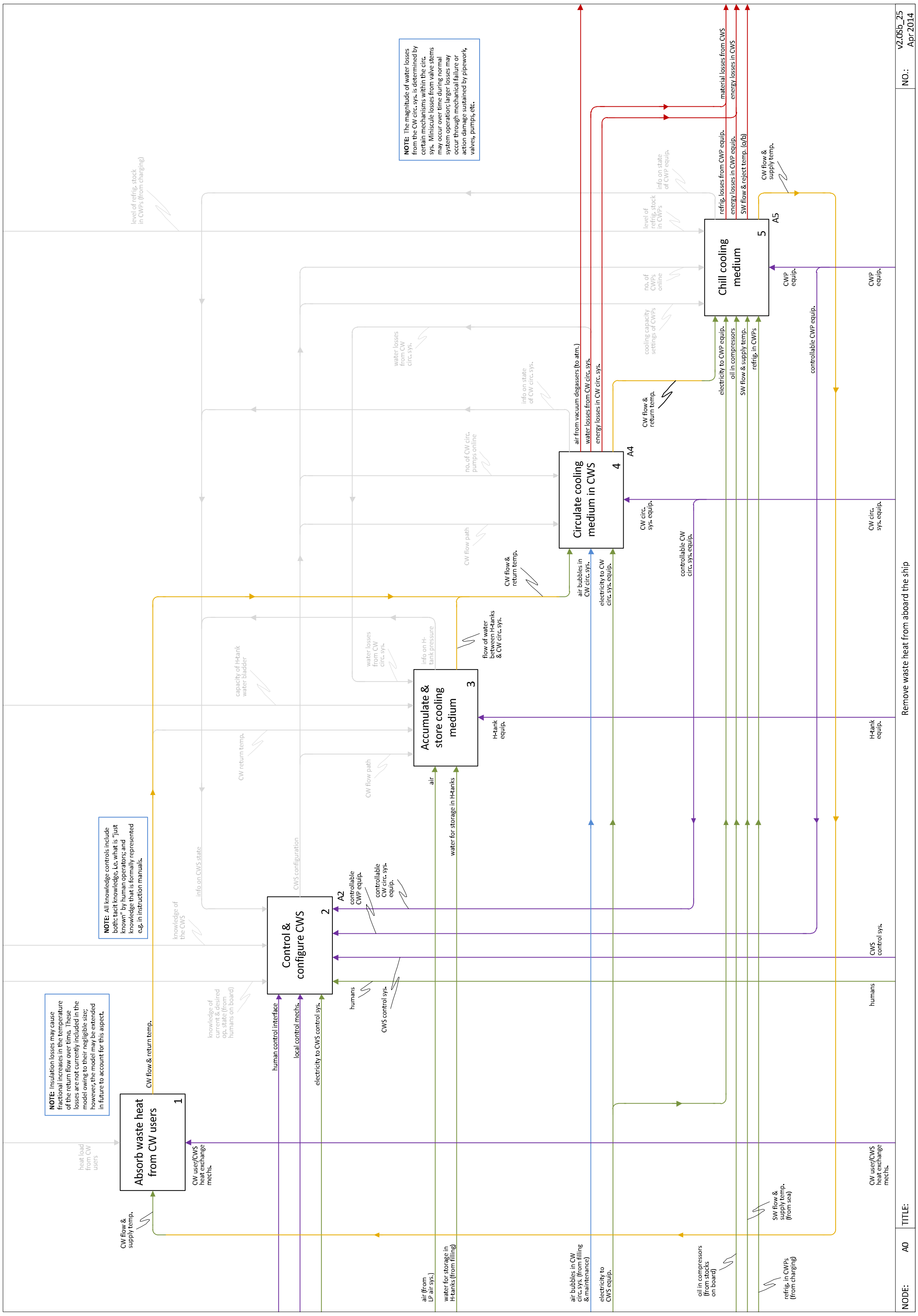
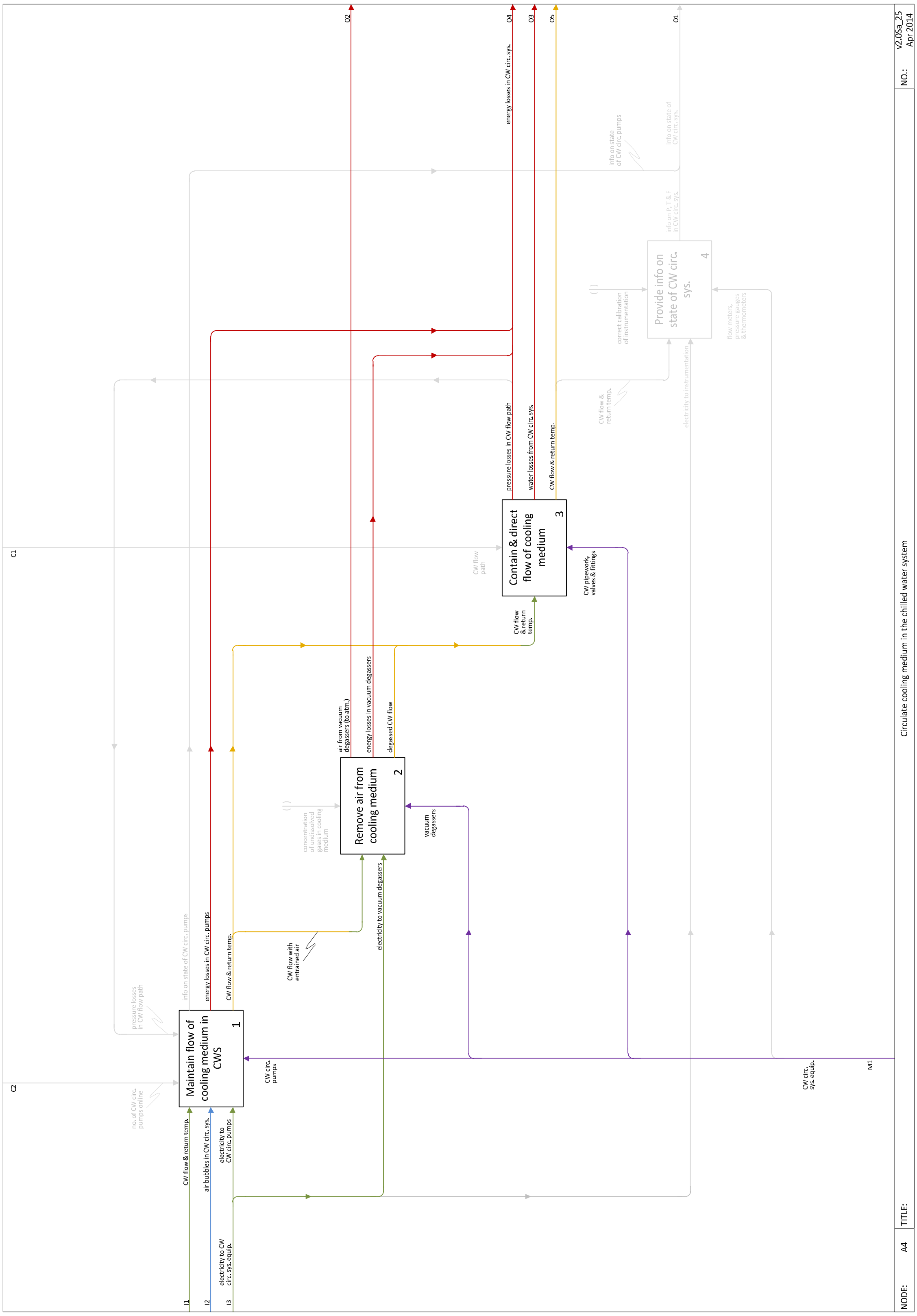
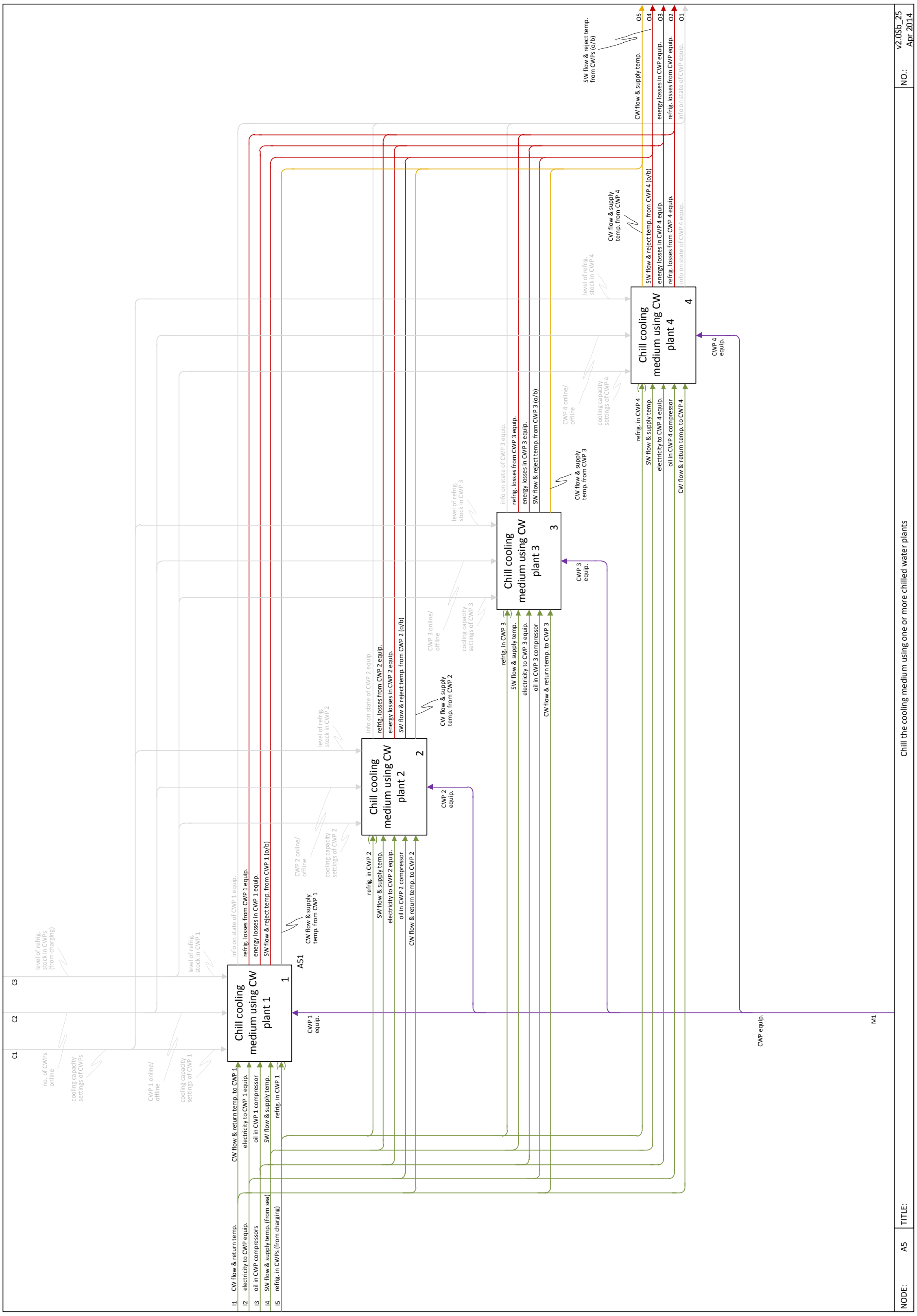


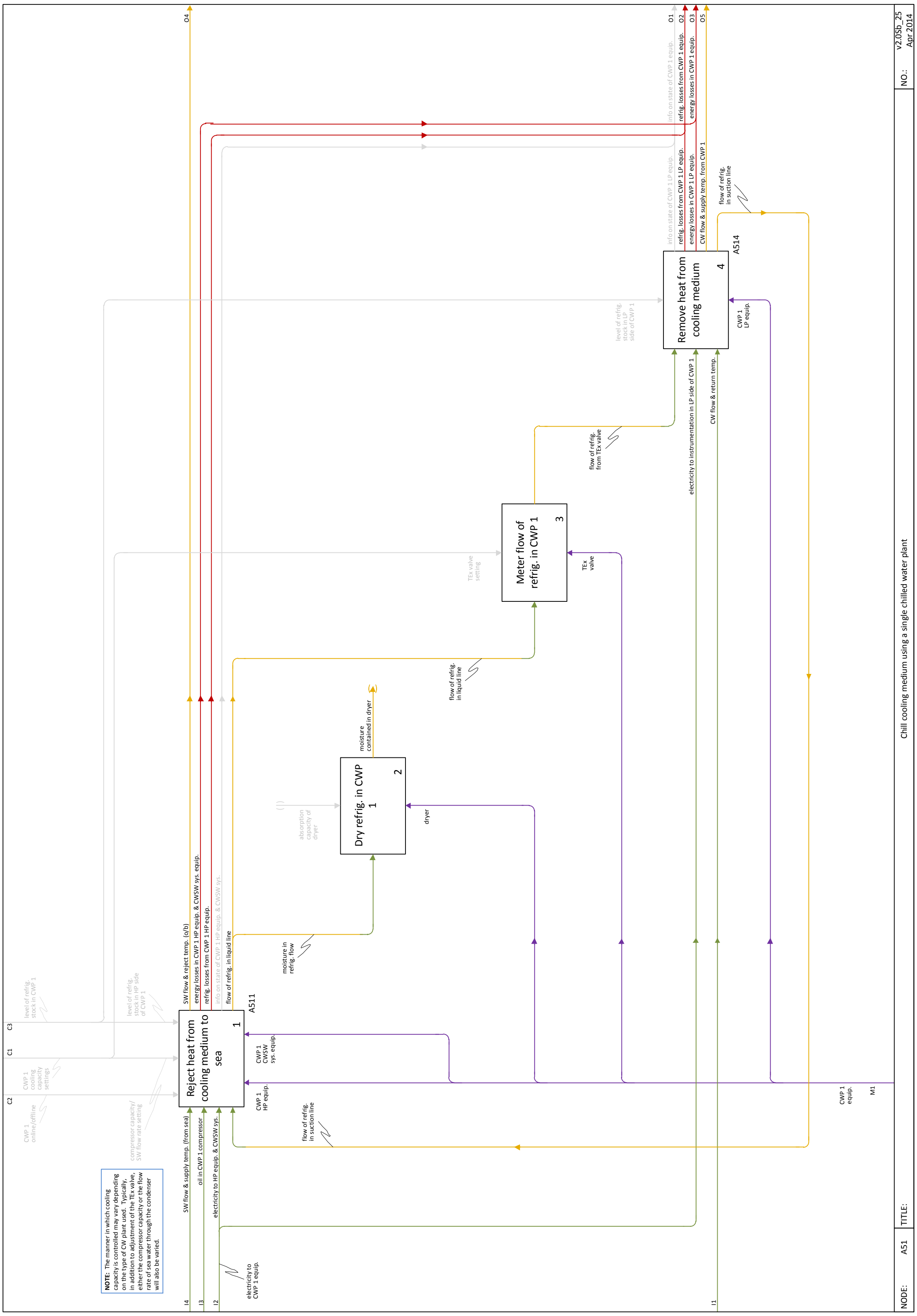
Figure 11. Key to S-Cycle colour coding of inputs, mechanisms, and outputs in interpreted IDEF0 diagrams

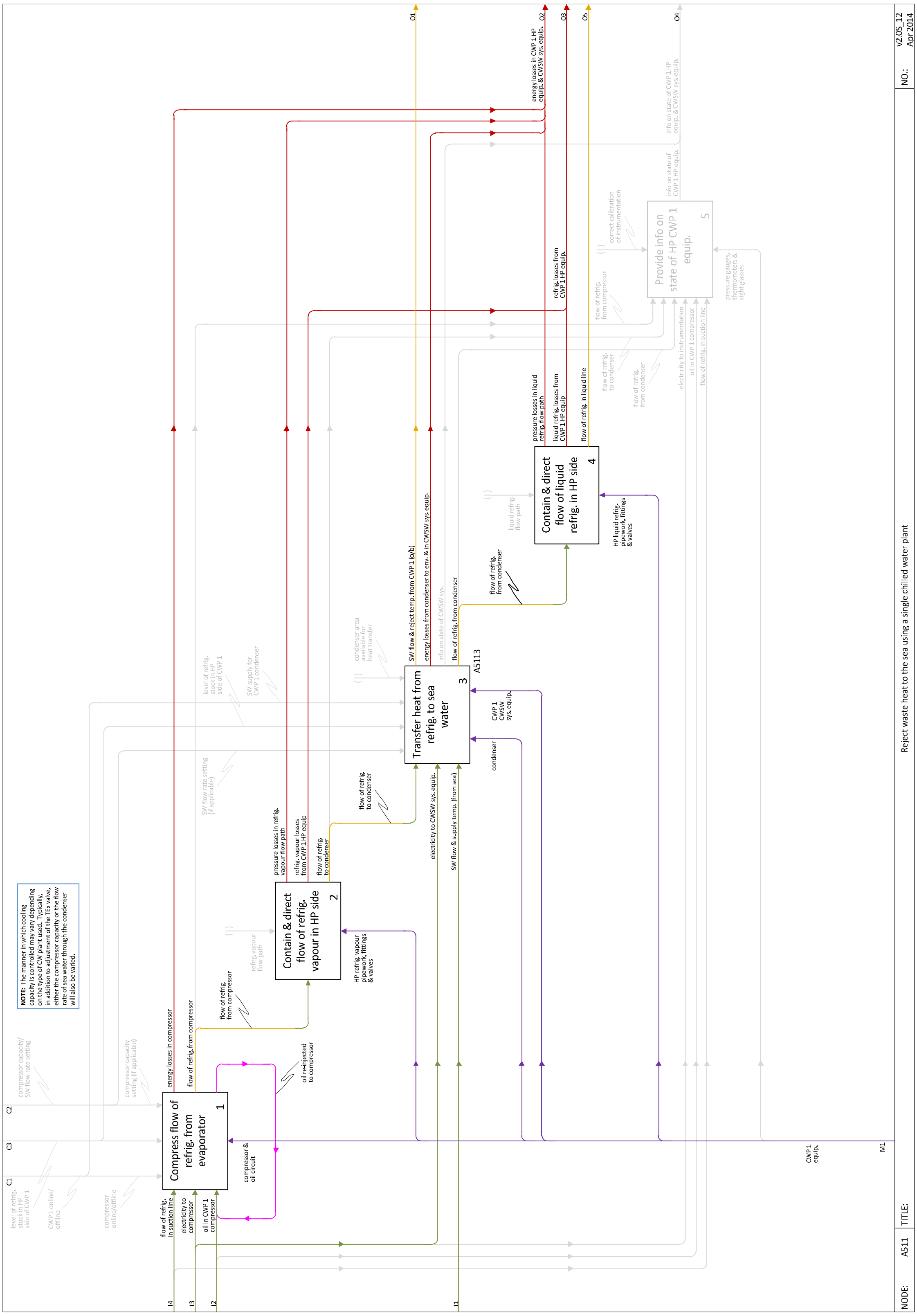

NOTE: The CW system model includes everything bounded within the dotted lines, and relates to (but excludes) those systems and processes described outside of the dotted lines.
Training processes & info sources on board (e.g. manuals) that provide knowledge on the system.
Commissioning & maintenance processes that set & top up key material stocks in the CW system.
knowledge
levels of key material stocks in CWS
Natural systems (i.e. sea + atmosphere) that provide inputs.
Other systems on board ship that provide inputs (e.g. power systems, CW users).
water (sea & demin.) & air
refrigerant & oil
electricity
waste heat
human control interface
Remove waste heat from equip. aboard ship
A0
SW flow & reject temp. (o/b)
energy & material losses
unwanted air
Natural systems (i.e. sea + atmosphere) that receive material outputs.
Local CW system environment (i.e. rest of ship) that losses dissipate to.
CWS control sys.
humans
CWS equip.
CW user/CWS heat exchange mechs.
Domestic systems on board ship that maintain wellbeing & capabilities of human operators.
Maintenance & repair processes that maintain equipment in working order.
PURPOSE: To build a clear understanding of the behaviour of the chilled water system.
VIEWPOINT: Normal system operation from a sustainability perspective.
NODE: A-0
TITLE: Chilled water system operation
NO.: v2.0Sa_12 Apr 2014


Absorb waste heat from CW users
1
Control & configure CWS
2
A2
Accumulate & store cooling medium
3
Circulate cooling medium in CWS
4
A4
Chill cooling medium
5
A5
Remove waste heat from aboard the ship
NODE:
A0
TITLE:
NO:
v2.06b_25
Apr 2014

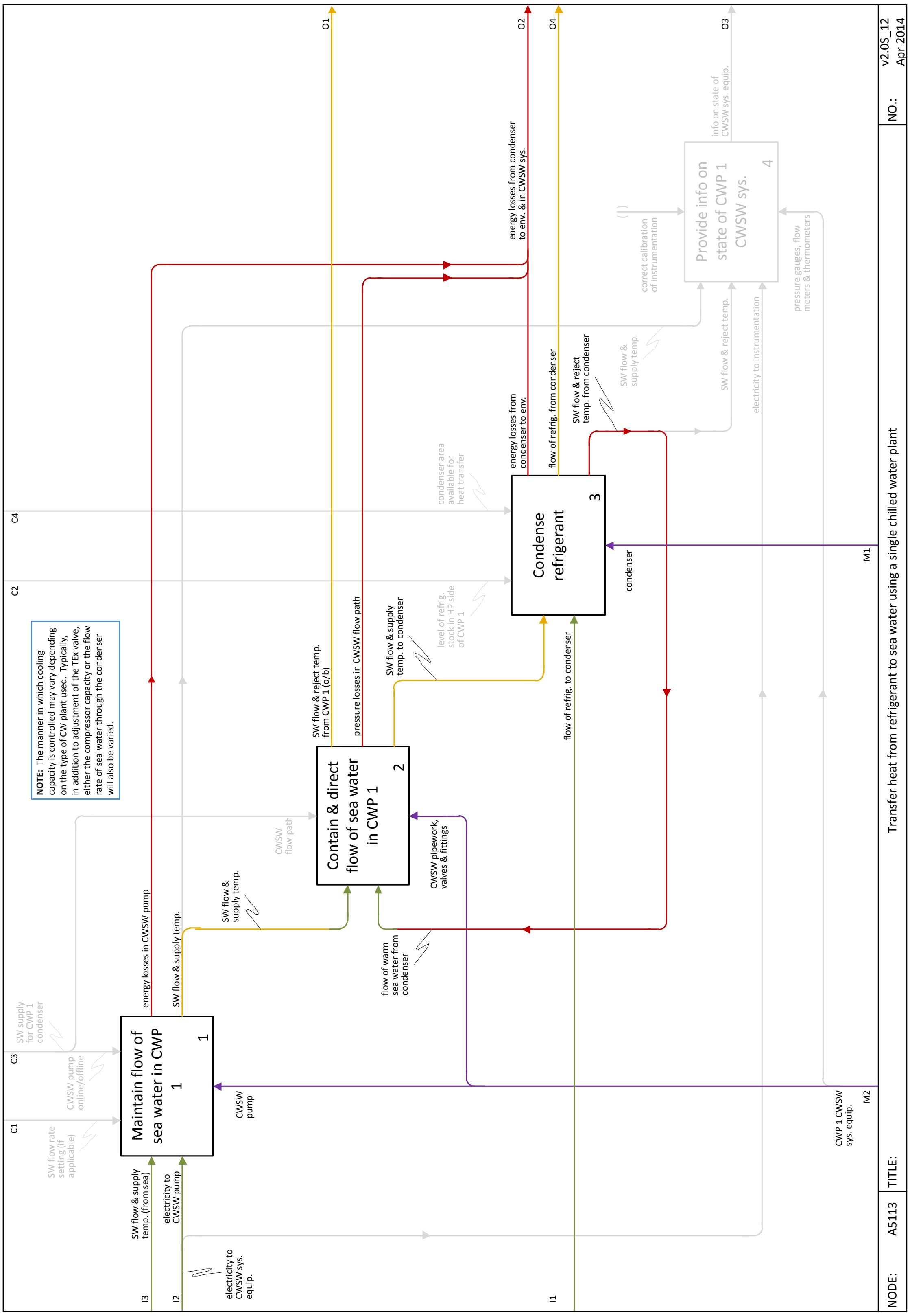

Maintain flow of cooling medium in CWS
1
Remove air from cooling medium
2
Contain & direct flow of cooling medium
3
Provide info on state of CW circ. sys.
4
CW flow & return temp.
air bubbles in CW circ. sys.
electricity to CW circ. pumps
electricity to CW circ. sys. equip.
energy losses in CW circ. pumps
CW flow with entrained air
electricity to vacuum degassers
vacuum degassers
air from vacuum degassers (to atm.)
energy losses in vacuum degassers
degassed CW flow
pressure losses in CW flow path
water losses from CW circ. sys.
energy losses in CW circ. sys.
CW pipework, valves & fittings
CW circ. pumps
CW circ. sys. equip.
I1
I2
I3
C1
C2
O1
O2
O3
O4
O5
M1
NODE:
A4
TITLE:
Circulate cooling medium in the chilled water system
NO.:
v2.05a_25
Apr 2014

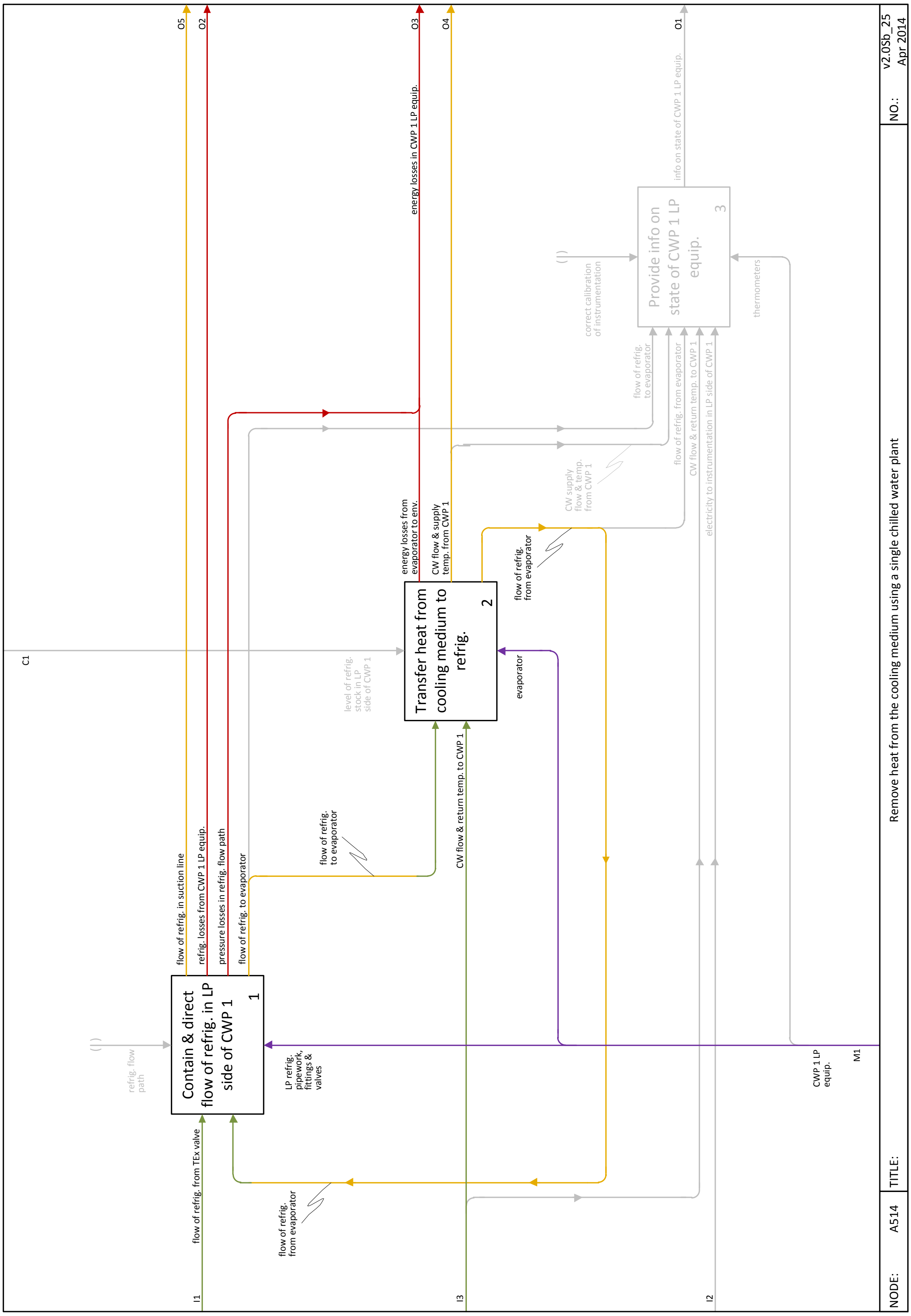

Chill cooling medium using CW plant 1
1
A51
Chill cooling medium using CW plant 2
2
Chill cooling medium using CW plant 3
3
Chill cooling medium using CW plant 4
4
I1 CW flow & return temp.
I2 electricity to CWP equip.
I3 oil in CWP compressors
I4 SW flow & supply temp. (from sea)
I5 refrig. in CWPs (from charging)
C1
C2
C3
M1
CWP equip.
O1
O2
O3
O4
O5
SW flow & reject temp. from CWPs (o/b)
CW flow & supply temp.
energy losses in CWP equip.
refrig. losses from CWP equip.
CW flow & supply temp. from CWP 1
CW flow & supply temp. from CWP 2
CW flow & supply temp. from CWP 3
CW flow & supply temp. from CWP 4
CWP 1 equip.
CWP 2 equip.
CWP 3 equip.
CWP 4 equip.
NODE:
A5
TITLE:
Chill the cooling medium using one or more chilled water plants
NO.:
v2.05b_25 Apr 2014


Reject heat from cooling medium to sea 1
A511
Dry refrig. in CWP 1 2
Meter flow of refrig. in CWP 1 3
Remove heat from cooling medium 4
A514
moisture contained in dryer
flow of refrig. in liquid line
flow of refrig. from TEx valve
flow of refrig. in suction line
moisture in refrig. flow
SW flow & reject temp. (o/b)
energy losses in CWP 1 HP equip. & CWSW sys. equip.
refrig. losses from CWP 1 HP equip.
flow of refrig. in liquid line
SW flow & supply temp. (from sea)
oil in CWP 1 compressor
electricity to HP equip. & CWSW sys.
electricity to CWP 1 equip.
electricity to instrumentation in LP side of CWP 1
CW flow & return temp.
refrig. losses from CWP 1 LP equip.
energy losses in CWP 1 LP equip.
CW flow & supply temp. from CWP 1
refrig. losses from CWP 1 equip.
energy losses in CWP 1 equip.
CWP 1 HP equip.
CWP 1 CWSW sys. equip.
dryer
TEx valve
CWP 1 LP equip.
CWP 1 equip.
M1
NOTE: The manner in which cooling capacity is controlled may vary depending on the type of CW plant used. Typically, in addition to adjustment of the TEx valve, either the compressor capacity or the flow rate of sea water through the condenser will also be varied.
NODE: A51
TITLE: Chill cooling medium using a single chilled water plant
NO.: v2.05b_25 Apr 2014



NOTE: The manner in which cooling capacity is controlled may vary depending on the type of CW plant used. Typically, in addition to adjustment of the TEx valve, either the compressor capacity or the flow rate of sea water through the condenser will also be varied.
Compress flow of refrig. from evaporator 1
Contain & direct flow of refrig. vapour in HP side 2
Transfer heat from refrig. to sea water 3
A5113
Contain & direct flow of liquid refrig. in HP side 4
Provide info on state of HP CWP 1 equip. 5
energy losses in compressor
flow of refrig. from compressor
SW flow & reject temp. from CWP 1 (o/b)
energy losses from condenser to env. & in CWSW sys. equip.
flow of refrig. from condenser
pressure losses in liquid refrig. flow path
liquid refrig. losses from CWP 1 HP equip.
flow of refrig. in liquid line
energy losses in CWP 1 HP equip. & CWSW sys. equip.
refrig. losses from CWP 1 HP equip.
flow of refrig. in suction line
electricity to compressor
oil in CWP 1 compressor
electricity to CWSW sys. equip.
SW flow & supply temp. (from sea)
CWP 1 equip.
NODE: A511
TITLE: Reject waste heat to the sea using a single chilled water plant
NO.: v2.05_12 Apr 2014


Maintain flow of sea water in CWP 1
1
Contain & direct flow of sea water in CWP 1
2
Condense refrigerant
3
Provide info on state of CWP 1 CWSW sys.
4
NOTE: The manner in which cooling capacity is controlled may vary depending on the type of CW plant used. Typically, in addition to adjustment of the TEx valve, either the compressor capacity or the flow rate of sea water through the condenser will also be varied.
SW flow & supply temp. (from sea)
electricity to CWSW pump
electricity to CWSW sys. equip.
SW flow rate setting (if applicable)
CWSW pump online/offline
SW supply for CWP 1 condenser
energy losses in CWSW pump
SW flow & supply temp.
CWSW pump
CWP 1 CWSW sys. equip.
CWSW flow path
CWSW pipework, valves & fittings
flow of warm sea water from condenser
SW flow & reject temp. from CWP 1 (o/b)
pressure losses in CWSW flow path
SW flow & supply temp. to condenser
level of refrig. stock in HP side of CWP 1
condenser area available for heat transfer
flow of refrig. to condenser
condenser
energy losses from condenser to env.
flow of refrig. from condenser
SW flow & reject temp. from condenser
SW flow & reject temp.
electricity to instrumentation
correct calibration of instrumentation
pressure gauges, flow meters & thermometers
info on state of CWSW sys. equip.
energy losses from condenser to env. & in CWSW sys.
I1
I2
I3
C1
C2
C3
C4
O1
O2
O3
O4
M1
M2
NODE:
A5113
TITLE:
Transfer heat from refrigerant to sea water using a single chilled water plant
NO.:
v2.0S_12
Apr 2014


Contain & direct flow of refrig. in LP side of CWP 1
1
Transfer heat from cooling medium to refrig.
2
Provide info on state of CWP 1 LP equip.
3
flow of refrig. in suction line
refrig. losses from CWP 1 LP equip.
pressure losses in refrig. flow path
flow of refrig. to evaporator
energy losses in CWP 1 LP equip.
energy losses from evaporator to env.
CW flow & supply temp. from CWP 1
CW flow & return temp. to CWP 1
flow of refrig. from evaporator
flow of refrig. from TEx valve
refrig. flow path
LP refrig. pipework, fittings & valves
evaporator
level of refrig. stock in LP side of CWP 1
CW supply flow & temp. from CWP 1
correct calibration of instrumentation
info on state of CWP 1 LP equip.
flow of refrig. from evaporator
CW flow & return temp. to CWP 1
electricity to instrumentation in LP side of CWP 1
thermometers
CWP 1 LP equip.
I1
I2
I3
C1
M1
O1
O2
O3
O4
O5
NODE:
A514
TITLE:
Remove heat from the cooling medium using a single chilled water plant
NO.:
v2.05b_25 Apr 2014

Appendix 5: Literature on the sustainability of society

In Chapter 3, three viewpoints on the sustainability concept were identified from the literature, along with associated perspectives (Figure 3-2, Section 3.3.1). That is: V1 – lexical definitions of sustainability; V2 – sustainability objectives, encapsulating what to sustain and for how long; and V3 – interpretations of the basic constitution of sustainability. In Table 3-1, it was shown how these viewpoints may be used to characterise different types of sustainability identifiable in the literature (a selection of which is presented in Figure 3-3). This appendix presents the literature sample analysed to identify the viewpoints and sustainability types (Appendix 5A), and an excerpt from the spreadsheet used to capture the analysis of this sample (Appendix 5B). A list of references for sources in the sample is included at the end of Appendix 5A.

Appendix 5A: Literature sample

The viewpoints and sustainability types presented and discussed in Chapter 3 (Section 3.3.1) were identified through an analysis of 60 sources from the literature on the sustainability of society. As stated in Chapter 3, the literature sample spanned nine sectors identified as major contributors to sustainability research, namely: agriculture, business, design, economics, fisheries, forestry, socio-economic development, sustainability science, and urban studies. The sam
ple is presented in Table A5-1 below, alongside examples of definitions/explanations considered from each source. Owing to space limitations, it is not possible to present the full range of definitions and explanations considered overall.

Table A5-1: Sample of literature on the sustainability of society

No.	Source	Sector	Example definition/explanation
1	Baumgartner and Quaas, 2010	Economics	"Sustainability is a normative notion about the way how humans should act towards nature, and how they are responsible towards one another and future generations."
2	Bell and Morse, 2008	Multiple	"Sustainable equates to a situation where [system] quality remains the same or increases. If quality declines, then the system can be regarded as unsustainable."
3	Bodini, 2012	Socio-economic development	"Sustainability is a complex feature that implies multiple dimensionality, but that also pertains to the system as a whole; it is an overall attribute that emerges from the internal processes that characterize human–environmental systems."
4	Brown and Ulgiati, 1997	Economics	"A definition of sustainability must include time. What is sustainable in one time period (during growth, for instance) may not be sustainable in the long run."
5	Brown et al., 1987	Multiple	"…the broadest sense of global sustainability includes the persistence of all components of the biosphere, even those with no apparent benefit to humanity."
6	Burger and Christen, 2011	Socio-economic development	"Sustainability is […] about responsibilities towards present and future human beings."
7	Chapman, 2011	Design	"In real terms, for a system to be classified as truly

			sustainable, it must possess the ability to be maintained indefinitely and must be capable of continuation ad infinitum."
8	Conway, 1985	Agriculture	"Sustainability can be defined as the ability of a system to maintain productivity in spite of a major disturbance such as is caused by intensive stress or a larger perturbation."
9	Costanza and Daly, 1992	Economics	"Strong sustainability is the maintaining intact of natural capital and man-made capital separately."
10	Costanza and Patten, 1995	Socio-economic development	"The basic idea of sustainability is quite straightforward: a sustainable system is one that survives or persists."
11	Daly, 1990	Economics	"Maintaining total capital intact might be referred to as weak sustainability," in that it is based on generous assumptions about substitutability of capital for natural resources in production."
12	Darnhofer et al., 2010	Agriculture	"For a farm to achieve sustainability, it must be able to take advantage of current opportunities, while managing the conditions that expand future possibilities. It must ensure adaptability and transformability."
13	Dawson et al., 2010	Socio-economic development	"...a sustainable SES [socio-ecological system] is one that, over the normal cycle of pressures and disturbance events, maintains its characteristic diversity of major functional groups, processes, services and utility thereby ensuring its capacity to endure."
14	Dempsey et al., 2011	Urban studies	"The sustainability of community is about the ability of society itself, or its manifestation as local community, to sustain and reproduce itself at an acceptable level of functioning."
15	Derissen et al., 2011	Economics	"...an ex-ante concept of sustainability makes an ex-ante assessment of the future consequences of today's actions with respect to some normative sustainability criterion which refers to the actual future state of the world and given today's information about the uncertain future consequences of today's action."
16	Dyllick and Hockerts, 2002	Business	"…corporate sustainability can accordingly be defined as meeting the needs of a firm's direct and indirect stakeholders (such as shareholders, employees, clients, pressure groups, communities etc), without compromising its ability to meet the needs of future stakeholders as well."
17	Ekins et al., 2003	Economics	"...it is logical to define environmental sustainability as the maintenance of important environmental functions and therefore, the maintenance of the capacity of the capital stock to provide those functions."
18	Eurostat, 2011	Socio-economic development	"'Sustainability' is a property of a system, whereby it is maintained in a particular state through time."
19	Figge and Hahn, 2005	Business	"Sustainable value thus expresses the excess value created by a company while preserving a constant level of capital use on the macro level."
20	Gagnon et al., 2012	Design	"...sustainable engineering projects maximise positive contributions to the well-being of individuals and simultaneously preserve the sound functioning of ecosystems and social systems."
21	Gaichas, 2008	Fisheries	"It is fairly easy to understand "sustainable yield" given these [quoted lexical] definitions. It is a yield or catch that can be endured (by a resource), that can be maintained (over time), and maintained at a certain level (over time)."
22	Gatto, 1995	Multiple	"Sustained abundance and genotypic diversity of individual species in ecosystems subject to human exploitation or, more generally, intervention (ecologist's definition)."
23	Goerner et al., 2009	Sustainability science	"...flow-network sustainability can reasonably be defined as the optimal balance of efficiency and resilience as determined by nature and measured by system structure."

24	Hahn and Figge, 2011	Business	"Sustainable development is a normative and paradigmatic but anthropocentric construct."
25	Hahn and Knoke, 2010	Forestry	"Identifying intra- and intergenerational fairness as primary objectives of both sustainable forestry and sustainable development…"
26	Hansen, 1996	Agriculture	"The system-describing concept interprets sustainability either as an ability to fulfil a diverse set of goals or as an ability to continue."
27	Hart and Milstein, 2003	Business	"A sustainable enterprise, therefore, is one that contributes to sustainable development by delivering simultaneously economic, social, and environmental benefits - the so-called triple bottom line."
28	Heal, 2012	Economics	"In analytical models, sustainability is generally defined […] in terms of the potential to maintain current living standards well into the future."
29	Holling, 2001	Socio-economic development	"Sustainability is the capacity to create, test, and maintain adaptive capability. Development is the process of creating, testing, and maintaining opportunity. The phrase that combines the two, "sustainable development", therefore refers to the goal of fostering adaptive capabilities while simultaneously creating opportunities."
30	Jamieson, 1998	Socio-economic development	"These ambiguities go back to the earliest English uses of 'sustain' and its cognates. One family of meanings is related to the idea of sustenance; a concern with needs is a natural extension of this notion. A second family of meanings centers on maintaining something in existence, and leads naturally to a focus on preservation."
31	Kajikawa, 2008	Sustainability science	"Sustainability literally means the ability to sustain, or a state that can be maintained at a certain level."
32	Larkin, 1977	Fisheries	"If there is such a thing as an MSY, then, it must be the yield that the residue of a population can continue to support when its less productive components have been reduced below their individual MSYs."
33	Lele and Norgaard, 1996	Socio-economic development	"Shorn of specific connotations and nuances, sustainability is simply the ability to maintain something undiminished over some time period."
34	Lo, 2010	Business	"Corporate sustainability is defined as the integration of financial benefit, environmental protection, and social responsibility into business operations and management."
35	Maclaren, 1996	Urban studies	"One way of distinguishing them, however, is to think of sustainability as describing a desirable state or set of conditions that persists over time."
36	Marcuse, 1998	Urban studies	"Sustainability as a goal in itself, if we are to take the term's ordinary meaning, is the preservation of the status quo."
37	McDonough and Braungart, 2002	Design	"But waste reduction and other palliatives aim for mere sustainability, which is, after all, a minimum condition for survival – hardly an inspiring prospect."
38	Neumayer, 2003	Economics	"…a definition most proponents of an economic concept of SD [sustainable development] would be likely to accept is the following: development is defined here to be *sustainable if it does not decrease the capacity to provide non-declining per capita utility for infinity*."
39	Norse et al., 2012	Fisheries	"Sustainability […] is living off the interest that capital generates (= the surplus production that a fish stock generates)."
40	Noss, 1993	Forestry	"A most important question we must ask with regard to sustainability is 'What do we wish to sustain and why?' This is essentially an issue of goal setting."
41	Odum, 1994	Economics	"Sustainability may not be the level "steady state" of the classic sigmoid growth curve but the process of adapting to oscillation."

42	Pearce et al., 2003	Forestry	"Sustainable timber management implies taking steps to ensure forests continue to produce timber in the longer-term, while maintaining the full complement of environmental services and non-timber products of the forest."
43	Pretty, 2008	Agriculture	"Sustainability in agricultural systems incorporates concepts of both resilience (the capacity of systems to buffer shocks and stresses) and persistence (the capacity of systems to continue over long periods), and addresses many wider economic, social and environmental outcomes."
44	Quental et al., 2010	Socio-economic development	"...sustainability considers that the scale of the human economy must not exceed environment's carrying capacity."
45	Rainey, 2006	Business	"The notion of "sustainability" usually implies that all human and business activities are carried out a rates equal to or less than the Earth's natural carrying capacity to renew the resources used and naturally mitigate the waste streams generated."
46	Rametsteiner et al., 2011	Socio-economic development	"...the concept of "sustainability" is per definition normative, reflected by the etymological roots of sustainability as a derivation from the Latin verb "sustenere" (= uphold)."
47	Shearman, 1990	Socio-economic development	"It [the term sustainability] has been consistently used, either explicitly or implicitly, to mean "a continuity through time" and that any resultant ambiguities are not with respect to the concept of sustainability itself, but rather with respect to the implications of sustainability when it is applied to any given context."
48	Solow, 1993	Economics	"If 'sustainability' is anything more than a slogan or expression of emotion, it must amount to an injunction to preserve productive capacity for the indefinite future."
49	Spangenberg, 2011	Sustainability science	"...sustainability is not a positive analytical concept, but a normative ethically justified utopia, describing a state of economy, society and environment considered optimal."
50	Standal and Utne, 2010	Fisheries	"The environmental dimension [of sustainability] means that the exploitation of the fisheries should be exercised with a long-term perspective in mind, so that future generations will be able to fulfill their needs for fish."
51	Tilman et al., 2002	Agriculture	"We define sustainable agriculture as practices that meet current and future societal needs for food and fibre, for ecosystem services, and for healthy lives, and that do so by maximizing the net benefit to society when all costs and benefits of the practices are considered."
52	United Nations Development Programme, 2011	Socio-economic development	"...we define "sustainable human development" as "the expansion of the substantive freedoms of people today while making reasonable efforts to avoid seriously compromising those of future generations.""
53	Voinov, 2007	Socio-economic development	"Sustainability in this case is a human intervention that is imposed on a system as part of human activity and is totally controlled and managed by humans in order to preserve the system in a state that is desired."
54	Vos, 2007	Socio-economic development	"Thin versions of sustainability seek to ensure that the overall value of natural and financial capital must be undiminished for future generations, even if the mix of the two is allowed to change. Thick versions of sustainability look for no overall diminution in the value of natural capital passed down to future generations."
55	Vucetich and Nelson, 2010	Socio-economic development	"If sustainability is defined as "meeting human needs in a socially just manner without depriving ecosystems of their health," most of the words in its definition are normative or value laden."
56	Wackernagel and Yount, 1998	Socio-economic development	"We therefore find it useful to define regional sustainability as "the continuous support of human quality of life within a

			region's ecological carrying capacity." By "support of human quality of life" we mean that people's subjectively perceived well-being [...] must be at least maintained (or possibly improved, in the case of the poor)."
57	Wahl and Baxter, 2008	Design	"Sustainability is an emergent property of appropriate interactions and relationships among active participants in the complex cultural, social, and ecological processes that constitute life in the twenty-first century."
58	Walter and Stutzel, 2009	Agriculture	"'Sustainable development' is the vision of a world free from some of mankind's very real pressing problems, present or anticipated."
59	WCED, 1987	Socio-economic development	"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."
60	Wiersum, 1995	Forestry	"...it has become increasingly clear that the values that determine an individual's or society's concept of sustainability depend upon its worldview."

References

Baumgärtner, S., Quaas, M., 2010. What is sustainability economics? Ecol. Econ. 69, 445–450.

Bell, S., Morse, S., 2008. Sustainability indicators: measuring the immeasurable?, 2nd ed. Earthscan, London.

Bodini, A., 2012. Building a systemic environmental monitoring and indicators for sustainability: What has the ecological network approach to offer? Ecol. Indic. 15, 140–148.

Brown, B.J., Hanson, M.E., Liverman, D.M., Merideth, R.W., 1987. Global sustainability: Toward definition. Environ. Manage. 11, 713–719.

Brown, M.., Ulgiati, S., 1997. Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation. Ecol. Eng. 9, 51–69.

Burger, P., Christen, M., 2011. Towards a capability approach of sustainability. J. Clean. Prod. 19, 787–795.

Chapman, J., 2011. Emotionally Durable Design, 3rd ed. Earthscan, London, Washington DC.

Conway, G.R., 1986. Agroecosystem analysis for research and development. Winrock International, Bangkok.

Costanza, R., Daly, H.E., 1992. Natural Capital and Sustainable Development. Conserv. Biol. 6, 37–46.

Costanza, R., Patten, B.C., 1995. Defining and predicting sustainability. Ecol. Econ. 15, 193–196.

Daly, H.E., 1990. Toward some operational principles of sustainable development. Ecol. Econ. 2, 1–6.

Darnhofer, I., Fairweather, J., Moller, H., 2010. Assessing a farm's sustainability: insights from resilience thinking. Int. J. Agric. Sustain. 8, 186–198.

Dawson, T.P., Rounsevell, M.D.A., Kluvánková-Oravská, T., Chobotová, V., Stirling, A., 2010. Dynamic properties of complex adaptive ecosystems: implications for the sustainability of service provision. Biodivers. Conserv. 19, 2843–2853.

Dempsey, N., Bramley, G., Power, S., Brown, C., 2011. The social dimension of sustainable development: Defining urban social sustainability. Sustain. Dev. 19, 289–300.

Derissen, S., Quaas, M.F., Baumgärtner, S., 2011. The relationship between resilience and sustainability of ecological-economic systems. Ecol. Econ. 70, 1121–1128.

Dyllick, T., Hockerts, K., 2002. Beyond the business case for corporate sustainability. Bus. Strateg. Environ. 11, 130–141.
Ekins, P., Simon, S., Deutsch, L., Folke, C., De Groot, R., 2003. A framework for the practical application of the concepts of critical natural capital and strong sustainability. Ecol. Econ. 44, 165–185.
Eurostat, 2011. Sustainable development in the European Union - 2011 monitoring report of the EU sustainable development strategy. Publications Office of the European Union, Luxembourg.
Figge, F., Hahn, T., 2005. The Cost of Sustainability Capital and the Creation of Sustainable Value by Companies. J. Ind. Ecol. 9, 47–58.
Gagnon, B., Leduc, R., Savard, L., 2012. From a conventional to a sustainable engineering design process: different shades of sustainability. J. Eng. Des. 23, 49–74.
Gaichas, S.K., 2008. A context for ecosystem-based fishery management: Developing concepts of ecosystems and sustainability. Mar. Policy 32, 393–401.
Gatto, M., 1995. Sustainability: Is it a well defined concept? Ecol. Appl. 5, 1181–1183.
Goerner, S.J., Lietaer, B., Ulanowicz, R.E., 2009. Quantifying economic sustainability: Implications for free-enterprise theory, policy and practice. Ecol. Econ. 69, 76–81.
Hahn, T., Figge, F., 2011. Beyond the Bounded Instrumentality in Current Corporate Sustainability Research: Toward an Inclusive Notion of Profitability. J. Bus. Ethics 104, 325–345.
Hahn, W.A., Knoke, T., 2010. Sustainable development and sustainable forestry: analogies, differences, and the role of flexibility. Eur. J. For. Res. 129, 787–801.
Hansen, J.W., 1996. Is agricultural sustainability a useful concept? Agric. Syst. 50, 117–143.
Hart, S.L., Milstein, M.B., 2003. Creating sustainable value. Acad. Manag. Exec. 17, 56–69.
Heal, G., 2012. Reflections - Defining and Measuring Sustainability. Rev. Environ. Econ. Policy 6, 147–163.
Holling, C.S., 2001. Understanding the Complexity of Economic, Ecological, and Social Systems. Ecosystems 4, 390–405.
Jamieson, D., 1998. Sustainability and beyond. Ecol. Econ. 24, 183–192.
Kajikawa, Y., 2008. Research core and framework of sustainability science. Sustain. Sci. 3, 215–239.
Larkin, P.A., 1977. An Epitaph for the Concept of Maximum Sustained Yield. Trans. Am. Fish. Soc. 106, 1–11.
Lele, S., Norgaard, R.B., 1996. Sustainability and the Scientist's Burden. Conserv. Biol. 10, 354–365.
Lo, S.-F., 2010. Performance evaluation for sustainable business: a profitability and marketability framework. Corp. Soc. Responsib. Environ. Manag. 17, 311–319.
Maclaren, V.W., 1996. Urban Sustainability Reporting. J. Am. Plan. Assoc. 62, 184–202.
Marcuse, P., 1998. Sustainability is not enough. Environ. Urban. 10, 103–112.
McDonough, W., Braungart, M., 2002. Design for the Triple Top Line: New Tools for Sustainable Commerce. Corp. Environ. Strateg. 9, 251–258.
Neumayer, E., 2003. Weak versus strong sustainability : exploring the limits of two opposing paradigms, 2nd ed. Edward Elgar, Cheltenham, UK; Northampton, MA.
Norse, E.A., Brooke, S., Cheung, W.W.L., Clark, M.R., Ekeland, I., Froese, R., Gjerde, K.M., Haedrich, R.L., Heppell, S.S., Morato, T., Morgan, L.E., Pauly, D., Sumaila, R., Watson, R., 2012. Sustainability of deep-sea fisheries. Mar. Policy 36, 307–320.
Noss, R.F., 1993. Sustainable Forestry or Sustainable Forests?, in: Aplet, G.H., Johnson, N., Olson, J.T., Sample, V.A. (Eds.), Defining Sustainable Forestry. Island Press, Washington D.C., pp. 17–43.

Odum, H.T., 1994. The emergy of natural capital, in: Jansson, A., Hammer, M., Folke, C., Costanza, R. (Eds.), Investing in Natural Capital - The Ecological Economics Approach to Sustainability. Island Press, Washington D.C., pp. 200–214.
Pearce, D., Putz, F.E., Vanclay, J.K., 2003. Sustainable forestry in the tropics: panacea or folly? For. Ecol. Manage. 172, 229–247.
Pretty, J., 2008. Agricultural sustainability: concepts, principles and evidence. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 363, 447–65.
Quental, N., Lourenço, J.M., da Silva, F.N., 2010. Sustainability: characteristics and scientific roots. Environ. Dev. Sustain. 13, 257–276.
Rainey, D.L., 2006. Sustainable business development : inventing the future through strategy, innovation, and leadership. Cambridge University Press, Cambridge; New York.
Rametsteiner, E., Pülzl, H., Alkan-Olsson, J., Frederiksen, P., 2011. Sustainability indicator development—Science or political negotiation? Ecol. Indic. 11, 61–70.
Shearman, R., 1990. The Meaning and Ethics of Sustainability. Environ. Manage. 14, 1–8.
Solow, R., 1993. An almost practical step toward sustainability. Resour. Policy 19, 162–172.
Spangenberg, J.H., 2011. Sustainability science: a review, an analysis and some empirical lessons. Environ. Conserv. 38, 275–287.
Standal, D., Utne, I.B., 2011. The hard choices of sustainability. Mar. Policy 35, 519–527.
Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418, 671–7.
United Nations Development Programme, 2011. Human Development Report 2011. Palgrave Macmillan, Basingstoke.
Voinov, A., 2007. Understanding and communicating sustainability: global versus regional perspectives. Environ. Dev. Sustain. 10, 487–501.
Vos, R.O., 2007. Defining sustainability: a conceptual orientation. J. Chem. Technol. Biotechnol. 82, 334–339.
Vucetich, J.A., Nelson, M.P., 2010. Sustainability: Virtuous or Vulgar? Bioscience 60, 539–544.
Wackernagel, M., Yount, D.J., 1998. The Ecological Footprint: an Indicator of Progress Toward Regional Sustainability. Environ. Monit. Assess. 51, 511–529.
Wahl, D.C., Baxter, S., 2008. The Designer's Role in Facilitating Sustainable Solutions. Des. Issues 24, 72–83.
Walter, C., Stützel, H., 2009. A new method for assessing the sustainability of land-use systems (I): Identifying the relevant issues. Ecol. Econ. 68, 1275–1287.
Wiersum, K.F., 1995. 200 Years of Sustainability in Forestry : Lessons from History. Environ. Manage. 19, 321–329.
World Commission on Environment and Development, 1987. Our common future. Oxford University Press, Oxford, New York.

Appendix 5B: Analysis of definitions and explanations

The three viewpoints on the sustainability concept recapitulated in the introduction to this appendix were identified through analysis of definitions and explanations of sustainability provided by authors in the literature sample presented in Appendix 5A. Firstly, a number of different sustainability types and entities to be sustained were found to be explicitly stated by authors. General interpretations of sustainability, including lexical definitions, interpretations of the constitution of sustainability, and entities to be sustained, were then inferred from key terms and characteristics identifiable in the definitions/explanations provided by authors. These inferences formed the basis of the three viewpoints, as well as Figure 3-2 and Figure 3-3, and Table 3-1. In order to convey the analysis process, an excerpt from the spreadsheet used to capture the analysis is presented below.

Source	Year	Research area	Definition of sustainability	Context (of the research)	Interpretation of sustainability	Stated type of sustainability	Target to be sustained	Key characteristics implied by interpretation/definition	Key terms in definition/interpretation	Inferred archetypal interpretation(s)	Inferred archetypal target(s)	Inferred archetypal class
Larkin 1977	1977	fishery	———————	Critique of MSY in fishing	"Briefly, the dogma was this: any species each year produces a harvestable surplus, and if you take that much, and no more, you can go on getting it forever and ever (Amen)."	maximum sustained yield	yield of fish	focus on harvest of biological populations; descriptive; value-dependent; anthropocentric; temporal; relative	forever; harvestable	ability to continue	yield	sustainability of yield
					"If there is such a thing as an MSY, then, it must be the yield that the residue of a population can continue to support when its less productive components have been reduced below their individual MSYs."				continue; support			
					"From my viewpoint of fish communities, the S in MSY, for any species, can't possibly mean more than 50 to 100 years. It certainly isn't forever and ever."				forever			
Conway 1985	1985	agriculture	———————	Agroecosystem analysis	"For the three ecological systems [...] the system behaviour can be disassembled into three system properties: productivity, stability and sustainability"	agricultural sustainability	———————	focus on ecological systems; holistic; descriptive	behaviour; properties; system	property/attribute of an entity	———————	sustainability of agriculture
			"Sustainability can be defined as the ability of a system to maintain productivity in spite of a major disturbance such as is caused by intesive stress or a larger perturbation."		———————		productivity of system	focus on productivity and resilience of an agricultural system; holistic; descriptive; relative	ability; maintain; productivity; disturbance; system	ability to maintain something	performance	
WCED 1987	1987	development	———————	Defining the concept of sustainable development	"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."	sustainable development	act of meeting human needs	ethical; normative; value-dependent; anthropocentric; temporal; spatial; absolute	ability; development; needs; present; future; generations	ability to continue	a process/activity/action	sustainability of development (N.B. This class is actually explicitly mentioned in OCF (p. 51)
					"In essence, sustainable development is a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development; and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations."		———————	ethical; normative; anthropocentric; spatial; temporal; absolute	development; process; change; enhance; potential; futue; needs; humans	process of change/improvement	———————	
					"No single blueprint of sustainability will be found, as economic and social systems and ecological conditions differ widely among countries."	sustainability	———————	multidimensional; anthropocentric	blueprint; economic; social; ecological	moral/social standard	———————	
					"But ultimate [ecological] limits there are, and sustainability requires that long before these are reached, the world must ensure equitable access to the constrained resource and reorient technological efforts to relieve the presume."		———————	normative; value-dependent; anthropocentric; spatial	sustainability requires; equitable; ensure; reorient		———————	
					"Sustainability requires views of human needs and well-being that incorporate such non-economic variables as education and health enjoyed for their own sake, clean air and water, and the protection of natural beauty."		———————	ethical; normative; value-dependent; anthropocentric	sustainability requires; human needs; well-being; for their own sake; beauty		———————	
					"Sustainability requires the enforcement of wider responsibilities for the impacts of decisions."		———————	ethical; normative; anthropocentric	sustainability requries; responsibilities; decisions		———————	

Appendix 6: Analysis of engineering design literature sample

In Chapter 4 (Section 4.2), key findings of a literature investigation focusing on sustainability-oriented engineering design were presented. That is, sustainability-oriented design in the context of technical artefacts. The investigation aimed to clarify the major design philosophies and methods/tools currently applied in this area, with the findings presented in full in Paper A, Appendix 1. As discussed in Section 4.2.1 of the thesis, a sample of 83 sources primarily drawn from the literature on engineering design was considered (presented in full in Table 1 in Paper A). From this sample, a number of sustainability-oriented design philosophies (S-philosophies) and a range of methods and tools were identified. Throughout Section 4.2, statistics on the prevalence of different types of S-philosophies and methods/tools in the literature sample were presented and discussed. These statistics are illustrated in the following figures in the thesis:

- Figure 4-6: Percentages of sources from the design literature sample discussing different S-philosophies (Section 4.2.2);
- Figure 4-7: Percentages of each type of design method/tool emerging from the literature sample (Section 4.2.3)
- Figure 4-9: Distribution of different types of methods/tools in the evaluation and analysis category (Section 4.2.3);
- Figure 4-10: Distribution of different types of performance evaluation methods/tools emerging from the literature sample (Section 4.2.3).

The purpose of this appendix is to present the full set of data used to compile the above statistics. That is, the complete range of design philosophies, methods, and tools identified from the sample, alongside the full list of sources discussing each one. Firstly, the complete range of S-philosophies identified, along with the full list of sources discussing each one, is presented in Section 1. The complete range of design methods and tools identified, along with the full list of sources discussing them, is then presented in Section 2. In Section 3, analysis conducted on a sub-set of the identified methods/tools, namely those focusing on evaluation and analysis, is discussed. Firstly, it is shown how the fraction of these methods/tools focusing on performance evaluation was determined. In turn, it is shown how the fractions of performance evaluation methods/tools focusing on the following aspects of performance were determined: (i) environmental performance; (ii) economic and social performance; and (iii) integrated environmental, economic, and/or social performance.

For the meaning of abbreviations employed throughout the appendix, please refer to the nomenclature section at the beginning of the thesis. All references may be found in the reference list included at the end of Paper A (Appendix 1).

1. Sustainability-oriented design philosophies

As discussed in Section 4.2.1 of the thesis, a design philosophy may be viewed as an overarching design concept, that expresses certain values and perspectives on design held by an individual (e.g. a lone designer) or a group of individuals (e.g. the design department of an organisation) (Evbuomwan, Sivaloganathan, and Jebb 1996; Hernandez 2010; Yoshikawa 1989). Typically, a design philosophy may be articulated in terms of broad aims and basic principles for design (Bhamra and Lofthouse 2007; Gould 2011; Hernandez 2010; Yoshikawa 1989). In essence, a design philosophy defines the designer's frame of reference for carrying out design activities. This interpretation formed the basis for identifying S-philosophies from the literature sample.

As discussed in Section 4.2.2 of the thesis, 15 S-philosophies were identified from the sample in total. Of these, five were observed to be discussed considerably more frequently than others, and were therefore identified as those S-philosophies emerging most prominently from the literature. These were: sustainable design; ecodesign; design for environment; design for sustainability; and whole system design. All 15 S-philosophies identified are presented in Table 4-2 in Section 4.2.2 of the thesis, alongside a selection of supporting sources. Table A6-1 below presents the full list of sources discussing each philosophy. This list was used as the basis for calculating the percentages presented in Figure 4-6 in Section 4.2.2 of the thesis. That is, the percentages of sources in the sample that were seen to discuss each of the identified S-philosophies. Note that in a limited number of cases, authors were observed to discuss more than one S-philosophy in a single source. As such, the percentages in Table A6-1 below do not sum to 100%.

Table A6-1: Full list of sources discussing each identified S-philosophy in the literature sample

S-philosophy	Sources	Total sources discussing S-philosophy	
		Number	% of total sources in sample
MAJOR SUSTAINABILITY-ORIENTED DESIGN PHILOSOPHIES			
Sustainable design	McDonough and Braungart 2002	33	39.8%
	Fiksel 2003		
	Karlsson and Luttropp 2006		
	Byggeth et al. 2007a		
	Waage 2007		
	Papandreou and Shang 2008		
	Stasinopoulos et al. 2009		
	Hossain et al. 2010		
	Urban et al. 2010		
	Vinodh and Rathod 2010		
	Azkarate et al. 2011		
	Bazmi and Zahedi 2011		
	Bhamra et al. 2011		
	Chapman 2011		
	Lu et al. 2011		
	Manesh and Tadi 2011		
	Yeo and Gabbai 2011		

	Zachrisson and Boks 2011		
	Chen et al. 2012		
	Chiu and Chu 2012		
	Gagnon et al. 2012		
	Gamage and Hyde 2012		
	Han et al. 2012		
	Hong et al. 2012		
	Luchs et al. 2012		
	Keitsch 2012a		
	Laitala et al. 2012		
	Lopes et al. 2012		
	Perez-Fortes et al. 2012		
	Rosen and Kishawy 2012		
	Skjerven 2012		
	Taras and Woinaroschy 2012		
	Urken et al. 2012		
Ecodesign	Bhamra et al. 1999	20	24.1%
	Huisman et al. 2000, 2003		
	McAloone 2001		
	Boks and Stevels 2003		
	Strasser and Wimmer 2003		
	Wimmer and Judmaier 2003		
	Bovea and Vidal 2004		
	McAloone and Andreasen 2004		
	Boks and Diehl 2005		
	Park et al. 2005		
	Wever et al. 2005		
	Karlsson and Luttropp 2006		
	Unger et al. 2008		
	Poole et al. 2009		
	Collado-Ruiz and Ostad-Ahmad-Ghorabi 2010		
	Ramani et al. 2010		
	Ostad-Ahmad-Ghorabi and Collado-Ruiz 2011		
	Aschehoug et al. 2012		
	Bovea and Perez-Belis 2012		
Design for environment	Lindahl 1999	16	19.3%
	Poole et al. 1999		
	Lenau and Bey 2001		
	Lindahl 2001		
	Ernzer and Wimmer 2002		
	Bhander et al. 2003		
	McAloone and Andreasen 2004		
	Lindahl et al. 2005		
	Lindahl 2006		
	Boks and Stevels 2007		
	Lindahl et al. 2007		
	Choi et al. 2008		
	Ramani et al. 2010		
	Trotta 2010		
	Wigum et al. 2011		
	Rosen and Kishawy 2012		
Design for sustainability	Rodriguez and Boks 2005	10	12.0%
	Bhamra and Lofthouse 2007		
	Wahl and Baxter 2008		
	Clark et al. 2009		

	Alfaris et al. 2010		
	Oram 2010		
	Spangenberg et al. 2010		
	Mayyas et al. 2012a		
	Mayyas et al. 2012b		
	Rosen and Kishawy 2012		
Whole system design	Fiksel 2003	6	7.2%
	Coley and Lemon 2009		
	Stasinopoulos et al. 2009		
	Charnley et al. 2011		
	Blizzard and Klotz 2012		
	Gagnon et al. 2012		
OTHER SUSTAINABILITY-ORIENTED DESIGN PHILOSOPHIES		12	14.5%
Discursive design	Edeholt 2012	1	
Ecological engineering	Gagnon et al. 2012	1	
Emotionally durable design	Chapman 2011	1	
Empathic design	Niinimäki and Koskinen, 2011	1	
Environmentally conscious design	Poole et al. 1999	1	
Evolutionary systems design	Laszlo et al. 2009	1	
Industrial ecology	Wang and Côté, 2011	2	
	Urban et al. 2010		
Life cycle design	Ernzer and Bey 2003	2	
	McAloone and Andreasen 2004		
Restorative design	Gu and Frazer 2009	1	
Scale-linking design	Wahl 2012	1	

2. Methods and tools supporting sustainability-oriented design

In Section 4.2.1 of the thesis, the concepts of a design method and a design tool were defined. A design method may be viewed as an identifiable way of working that supports a designer in meeting design goals or finding a solution to a problem (Cross 2008; Lindahl 2006). The notion of a design tool is closely related to that of a design method, and may be viewed as a physical or intangible means that supports a designer in meeting design goals or finding a solution to a problem (Lindahl 2006). A design tool is typically used to support the application of a design method (Cross, 2008), though not always. These interpretations formed the basis for identifying design methods and tools from the literature sample.

As discussed in Section 4.2.3 of the thesis, 170 distinct design methods and tools were identified from the sample. That is, methods and tools positioned by authors as useful or effective in sustainability-oriented engineering design. In turn, these were categorised according to the kinds of design activities they are intended to support, i.e.: creating; decision making; evaluation and analysis; modelling and simulation; and optimisation. An overview of the methods/tools identified is presented in Table 4-3, alongside a selection of supporting sources. The complete range of methods/tools identified in each category is presented in Table A6-2 below, alongside the full list of supporting sources.

As noted above, a tool may be used to support the application of a particular design method (Cross, 2008). As such, it was assumed during the investigation that a method and a tool that are seen to be used in direct conjunction will always belong to the same category from the list provided above. Therefore, in cases where a tool was found to be clearly associated with a method, only the method was recorded and included in the list presented in Table A6-2. In cases where a tool was seen to be discussed in isolation from any particular method, then the tool was recorded and included in the list. Tools are suffixed with (T) in Table A6-2, in order to distinguish them from methods. Additionally, certain methods/tools presented in Table 4-3 represent generalisations of groups of specific methods/tools discussed by authors in the sample. Namely, the following may all be decomposed into specific examples discussed and/or applied by different authors:

- benchmarking methods;
- checklists;
- concept generation methods/tools;
- design for/to X methods;
- design guidelines;
- design principles;
- economic and social performance evaluation methods/tools;
- environmental performance evaluation methods/tools;
- failure mode and effects analysis (FMEA) and FMEA-based methods/tools;
- formal optimisation methods;
- impact assessment methods/tools;
- integrated environmental, economic, and/or social performance evaluation methods/tools;
- multi criteria decision analysis methods/tools;
- quality function deployment (QFD) and QFD-based methods/tools;
- Theory of Inventive Problem Solving (TRIZ) and TRIZ-based methods/tools; and
- user-centred design methods.

The specific methods/tools comprising each of the general groups above are made explicit in Table A6-2 below.

The list of methods/tools presented in Table A6-2 was used as the basis for calculating the percentages illustrated in Figure 4-7 in Section 4.2.3 of the thesis. That is, the percentages of each type of design method/tool emerging from the literature sample. Additionally, the methods/tools for evaluation and analysis in Table A6-2 provided the basis for further analysis with respect to methods/tools for performance evaluation of technical artefacts, discussed in Section 3.

Table A6-2: Complete range of design methods and tools identified from the sample, along with the full list of supporting sources

ID	Method/tool description	Sources	No.	% of total M/T
CREATING			**18**	**10.6%**
Concept generation:			9	5.3%
1	Brainstorming	Gagnon et al., 2012; Stasinopoulos et al., 2009		
2	Brainwriting	Gagnon et al., 2012		
3	Flowmaker	Bhamra and Lofthouse, 2007		
4	Forced relationships	Gagnon et al., 2012; Bhamra and Lofthouse, 2007		
5	Information/Inspiration (T)	Karlsson and Luttropp, 2006; Bhamra and Lofthouse, 2007		
6	Random words	Bhamra and Lofthouse, 2007		
7	SCAMPER	Gagnon et al., 2012		
8	Synectics			
9	What if?	Bhamra and Lofthouse, 2007		
Theory of Inventive Problem Solving (TRIZ) and TRIZ-based methods/tools:			3	1.8%
10	Bio-TRIZ	Gamage and Hyde, 2012		
11	TRIZ	Strasser and Wimmer, 2003; Trotta, 2010		
12	TRIZ laws of evolution (T)	Chiu and Chu, 2012		
Non-generalisable methods for creating:			6	3.5%
13	Backcasting	Ernzer and Bey 2003; Bhamra and Lofthouse, 2007; Byggeth et al., 2007a,b; Gagnon et al., 2012		
14	Design spiral	Gamage and Hyde, 2012		
15	Layered games	Bhamra and Lofthouse, 2007		
16	Mood boards			
17	Real People (T)			
18	Templates for Sustainable Development (T)	Byggeth et al., 2007a,b		
DECISION MAKING			**41**	**24.1%**
Checklists:			5	2.9%
19	AT&T checklist	Bovea and Pérez-Belis, 2012		
20	Checklist method	Park et al., 2005		
21	Checklists generally	Lindahl, 1999; Lindahl, 2001		
22	Eco-Design Checklist Method	Bovea and Pérez-Belis, 2012		
23	Fast Five	Bhamra and Lofthouse, 2007; Bovea and Pérez-Belis, 2012		
Design for/to X:			14	8.2%
24	Design for disassembly	Karlsson and Luttropp, 2006		
25	Design for disassembly and recycling	Byggeth et al., 2007b		
26	Design for durability	Mayyas et al., 2012a		
27	Design for end-of-life	Huisman et al., 2000		
28	Design for energy efficiency	Mayyas et al., 2012a		
29	Design for Manufacture and Assembly	Ramani et al., 2010		
30	Design for manufacturing	Mayyas et al., 2012a		
31	Design for recyclability	Huisman et al., 2000; Mayyas et al., 2012a		
32	Design for recycling	Bhander et al., 2003; Wigum et al., 2011		
33	Design for remanufacture	Bhander et al., 2003; Chiu and Chu, 2012		

34	Design for re-use	Bhander et al., 2003		
35	Design for waste treatment			
36	Design to minimize material usage	Mayyas et al., 2012a		
37	Design for Sustainable Behaviour	Bhamra et al., 2011; Laitala et al., 2011; Zachrisson and Boks, 2011		
Design guidelines:			7	4.1%
38	Guidelines generally	Lindahl, 1999; Lindahl, 2001		
39	Environmental reporting guidelines	Mayyas et al., 2012a		
40	Guideline-based reference information system for sustainable design (T)	Chiu and Chu, 2012		
41	Kodak Guidelines	Bovea and Pérez-Belis, 2012		
42	Material selection guidelines	Mayyas et al., 2012a		
43	Six Rules of Thumb	Bhamra and Lofthouse, 2007		
44	Ten Golden Rules	Karlsson and Luttropp, 2006; Bovea and Pérez-Belis, 2012		
Design principles:			3	1.8%
45	Factor 10 Engineering (10xE) principles	Blizzard and Klotz, 2012		
46	Generic DfE principles	Boks and Stevels, 2007		
47	SCALES principles	Chiu and Chu, 2012; Spangenberg et al., 2010		
Multi criteria decision analysis:			8	4.7%
48	Analytic hierarchy process	Choi et al., 2008; Gagnon et al., 2012		
49	Douglas hierarchical decision procedure	Hossain et al., 2010		
50	ELECTRE	Gagnon et al., 2012		
51	Hopfield network (T)	Chiu and Chu, 2012		
52	Multi criteria decision analysis	Azkarate et al., 2011		
53	PROMETHEE	Gagnon et al., 2012		
54	Simple multi attribute rating technique			
55	TOPSIS[f]			
Non-generalisable methods/tools for decision making:			4	2.4%
56	A framework for ethical decision-making in design - the "culturally negotiated ethical triangle" (T)	Oram, 2010		
57	Fractal triangle (T)	McDonough and Braungart, 2002		
58	Typological analysis	Gamage and Hyde, 2012		
59	User-centred design methods	Wigum et al., 2011		
EVALUATION AND ANALYSIS			**87**	**51.2%**
Benchmarking:			4	2.4%
60	Benchmarking generally	Huisman et al., 2000; Stasinopoulos et al., 2009		
61	EcoBenchmarking method	Boks and Diehl, 2005		
62	Environmental Benchmarking Method	Boks and Stevels, 2003		
63	Multiple Environmental Benchmarking Data Analysis			
Economic and social performance evaluation:			7	4.1%
64	Contingent valuation	Bovea and Vidal, 2004		
65	Cost-benefit analysis	Gagnon et al., 2012		
66	Inequality and equity analysis	Gagnon et al., 2012		
67	Life cycle costing	Bovea and Vidal, 2004; Azkarate et al., 2011; Lu et al., 2011; Bovea and Pérez-Belis, 2012; Gagnon et al. 2012; Mayyas et al., 2012b		
68	Life cycle quality evaluation	Lu et al., 2011		

69	Social life cycle assessment	Gagnon et al., 2012		
70	Quality Engineering for Early Stage of Environmentally Conscious Design	Bovea and Pérez-Belis, 2012		
Environmental performance evaluation:			39	22.9%
71	Assistant environmental assessment tool (T)	Wimmer and Judmaier, 2003		
72	Cumulated Energy Demand	Unger et al. 2008; Ostad-Ahmad-Ghorabi and Collado-Ruiz 2011		
73	Design abacus	Bhamra and Lofthouse, 2007		
74	DfE matrix (T)	Bovea and Pérez-Belis, 2012		
75	Eco effectiveness	Wang and Côté 2011		
76	Eco efficiency	McAloone and Andreasen, 2004; Unger et al., 2008; Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010; Hong et al., 2012		
77	Ecodesign web	Bhamra and Lofthouse, 2007		
78	Eco-Indicator 95	Huisman et al., 2000; Lenau and Bey, 2001; Huisman et al., 2003		
79	Eco-Indicator 99	Huisman et al., 2003; Bhamra and Lofthouse, 2007		
80	Ecological footprinting	Unger et al., 2008; Gagnon et al., 2012		
81	Ecological indicators (T)	Stasinopoulos et al., 2009		
82	Emergy analysis	Gagnon et al., 2012		
83	Energy analysis	Hossain et al., 2010		
84	Environmental Priority Strategies	Lenau and Bey, 2001; Huisman et al., 2003		
85	Environmental product declaration	Mayyas et al., 2012a		
86	Environmental Product Life Cycle matrix (T)	Bovea and Pérez-Belis, 2012		
87	Environmental valuation	Gagnon et al., 2012		
88	Environmentally Responsible Product Assessment	Chiu and Chu, 2012		
89	Environmentally Responsible Product/Process Assessment Matrix (T)	Bovea and Pérez-Belis, 2012		
90	Exergy analysis	Hossain et al., 2010; Urban et al. 2010; Gagnon et al., 2012		
91	Footprinting	Bovea and Pérez-Belis, 2012		
92	Life cycle assessment	Lindahl 1999; Lenau and Bey 2001; Lindahl 2001; McAloone 2001; Bhander et al. 2003; Boks and Stevels 2003; Ernzer and Bey 2003; Fiksel 2003; Bovea and Vidal 2004; Karlsson and Luttropp 2006; Bhamra and Lofthouse 2007; Papandreou and Shang 2008; Unger et al. 2008; Hossain et al. 2010; Trotta 2010; Vinodh and Rathod 2010; Azkarate et al. 2011; Ostad-Ahmad-Ghorabi and Collado-		

		Ruiz 2011; Bovea and Perez-Belis 2012; Chiu and Chu 2012; Hong et al. 2012; Laitala et al. 2012; Mayyas et al. 2012b; Rosen and Kishawy 2012		
93	Life cycle check	McAloone, 2001		
94	Life Cycle Planning	Bovea and Pérez-Belis, 2012		
95	Material Flow Analysis	Unger et al., 2008		
96	Material Intensity per Unit of Service			
97	Material Recycling Efficiency calculations	Huisman et al., 2000; Huisman et al., 2003		
98	Materials, Energy & Toxicity matrix (T)	Bovea and Pérez-Belis, 2012; Chiu and Chu, 2012		
99	Oil Point Method	Lenau and Bey, 2001; Ernzer and Bey 2003; Bovea and Pérez-Belis, 2012; Chiu and Chu, 2012		
100	Okala method	Chiu and Chu, 2012		
101	Product life thinking	McAloone, 2001		
102	RAILS	Bovea and Pérez-Belis, 2012		
103	Recyclability assessment	Huisman et al., 2000		
104	Simplified life cycle assessment	Lu et al., 2011; Chiu and Chu, 2012		
105	Strategic environmental assessment	Gagnon et al. 2012		
106	Strategic Life Cycle Management	Byggeth et al., 2007b		
107	Strategic wheel (T)	Unger et al., 2008		
108	Streamlined life cycle assessment	Unger et al., 2008; Bovea and Pérez-Belis, 2012		
109	Toxicity assessment	Huisman et al., 2000		
Failure mode and effects analysis (FMEA) and FMEA-based methods/tools:			4	2.4%
110	Eco-FMEA	Bovea and Pérez-Belis, 2012		
111	Environmental Effect Analysis	Lindahl, 2001		
112	Environmental FMEA	Bovea and Pérez-Belis, 2012		
113	Failure Mode and Effect Analysis	Byggeth et al., 2007a,b		
Impact assessment:			5	2.9%
114	Economic impact analysis	Gagnon et al., 2012		
115	Environmental Impact and Factor Analysis	Bovea and Pérez-Belis, 2012		
116	Environmental impact assessment	Gagnon et al., 2012		
117	Integrated impact assessment			
118	Social impact assessment			
Integrated environmental, economic, and/or social performance evaluation:			6	3.5%
119	Eco Value Analysis	Bovea and Pérez-Belis, 2012		
120	Integrated tools (T)	Ramani et al., 2010		
121	Life Cycle Environmental Cost Analysis	Bovea and Pérez-Belis, 2012		
122	Life Cycle Sustainability Assessment	Chiu and Chu, 2012		
123	Requirements matrix (T)	Bovea and Pérez-Belis, 2012		
124	Two-stage network data envelopment analysis	Chen et al., 2012		
Quality function deployment (QFD) and QFD-based methods/tools:			7	4.1%
125	Environmental Objective Deployment	Bovea and Pérez-Belis, 2012		
126	Environmental QFD			
127	Environmentally Conscious QFD	Vinodh and Rathod, 2010; Bovea and Pérez-Belis, 2012;		
128	Green QFD	Bovea and Pérez-Belis, 2012		
129	Life cycle QFD			

130	QFD for Environment			
131	Quality Function Deployment	Strasser and Wimmer, 2003; Ramani et al., 2010; Aschehoug et al., 2012; Bovea and Pérez-Belis, 2012		
User-centred design:			8	4.7%
132	Ethnographic fieldwork	Bhamra et al., 2011		
133	Participant observation	Bhamra and Lofthouse, 2007		
134	Product-in-use	Bhamra and Lofthouse, 2007; Bhamra et al., 2011		
135	Questionnaire	Bhamra et al., 2011		
136	Scenario-of-use	Bhamra and Lofthouse, 2007		
137	Semi-structured interview	Bhamra et al., 2011		
138	User diaries			
139	User trials	Bhamra and Lofthouse, 2007		
Non-generalisable methods/tools for evaluation and analysis:			7	4.1
140	ABCD analysis	Byggeth et al., 2007a,b; Unger et al., 2008		
141	Functional analysis	Stasinopoulos et al., 2009		
142	Hierarchical design decomposition	Alfaris et al., 2010		
143	Morphological analysis	Chiu and Chu, 2012; Gagnon et al., 2012		
144	Nature studies analysis	Gamage and Hyde, 2012		
145	Scenario analysis	Huisman et al., 2000		
146	System analysis	Stasinopoulos et al., 2009		
MODELLING, SIMULATION, AND OPTIMISATION			**24**	**14.1%**
Formal optimisation methods:			9	5.3%
147	Interactive multi objective optimisation	Taras and Woinaroschy, 2012		
148	Interval mathematical programming	Han et al., 2012		
149	Lexicographic method	Gagnon et al., 2012		
150	Maximin method			
151	Multi objective optimisation	Papandreou and Shang, 2008; Bazmi and Zahedi, 2011; Han et al., 2012; Pérez-Fortes et al., 2012		
152	Optimisation under uncertainty	Bazmi and Zahedi, 2011		
153	Stochastic mathematical programming	Han et al., 2012		
154	Structural optimisation	Yeo and Gabbai, 2011		
155	Weighted sum	Gagnon et al., 2012		
Models and modelling:			8	4.7%
156	CAD software (T)	Byggeth et al., 2007a,b		
157	Causal loop diagrams	Byggeth et al., 2007b		
158	Computer models	Stasinopoulos et al., 2009		
159	Mathematical models			
160	Multi domain formulation	Alfaris et al., 2010		
161	Physical models	Stasinopoulos et al., 2009		
162	Screening Life Cycle Modelling	Chiu and Chu, 2012		
163	Systems Modeling within Sustainability Constraints	Byggeth et al., 2007b		
Simulation:			4	2.4%
164	Life cycle simulation	Chiu and Chu, 2012		
165	Multi disciplinary simulation	Byggeth et al., 2007b		
166	Process simulation	Hossain et al., 2010		
167	Virtual reality (T)	Byggeth et al., 2007a,b		
Non-generalisable methods/tools for optimisation:			3	1.8%
168	Life cycle optimisation	Mayyas et al., 2012b		
169	PILOT (T)	Strasser and Wimmer, 2003; Wimmer and Judmaier, 2003;		

		Bovea and Pérez-Belis, 2012	
170	System optimisation	Stasinopoulos et al., 2009	

4. Methods and tools for sustainability performance evaluation

As discussed in Section 4.2.2 of the thesis, a key characteristic shared by all of the major S-philosophies identified from the sample is a focus on improving the environmental, economic, and/or social impacts of technical artefacts (in varying degrees, depending on the aims of each philosophy). In turn, knowledge on the environmental, economic, and/or social performance of artefacts may be viewed as a key element of knowledge employed in sustainability-oriented engineering design. Accordingly, the methods/tools for evaluation and analysis identified from the sample may be broken down into those for evaluating: economic and/or social performance; environmental performance; and integrated environmental, economic, and social performance, as well as other evaluation and analysis methods. This breakdown is illustrated in Figure 4-9 in the thesis.

In Table A6-3 below, the full list of methods/tools for evaluation and analysis is presented. As shown in Table A6-1 in Section 1 above, a total of 87 methods and tools were identified in this category. In Table A6-3, the methods/tools are organised from the perspective of performance evaluation methods/tools. This list was used as the basis for calculating the percentage of performance evaluation methods/tools identified from the sample. As shown, in Table A6-3 the performance evaluation methods/tools are categorised according to their focus on: environmental performance; economic and social performance; or integrated environmental, economic, and/or social performance. In turn, the list of methods/tools in Table A6-3 was also used as the basis for calculating the percentages presented in Figure 4-10 in the thesis. That is, the distribution of different types of performance evaluation methods/tools emerging from the literature sample.

Table A6-3: Breakdown of identified methods/tools for evaluation and analysis, from the perspective of performance evaluation methods

ID	Method/tool description	Sources	No.	% of total PE M/T	% of total EA M/T	% of total M/T
PERFORMANCE EVALUATION			**52**	**-----------**	**59.7%**	**30.6%**
Economic and social performance:			7	13.5%	8.0%	4.1%
1	Contingent valuation	Bovea and Vidal, 2004				
2	Cost-benefit analysis	Gagnon et al., 2012				
3	Inequality and equity analysis	Gagnon et al., 2012				
4	Life cycle costing	Bovea and Vidal, 2004; Azkarate et al., 2011; Lu et al., 2011; Bovea and Pérez-Belis, 2012; Gagnon et al. 2012; Mayyas et al., 2012b				
5	Life cycle quality evaluation	Lu et al., 2011				
6	Social life cycle assessment	Gagnon et al., 2012				
7	Quality Engineering for Early Stage of Environmentally	Bovea and Pérez-Belis, 2012				

	Conscious Design					
Environmental performance:			39	75.%	44.8%	22.9%
8	Assistant environmental assessment tool (T)	Wimmer and Judmaier, 2003				
9	Cumulated Energy Demand	Unger et al. 2008; Ostad-Ahmad-Ghorabi and Collado-Ruiz 2011				
10	Design abacus	Bhamra and Lofthouse, 2007				
11	DfE matrix (T)	Bovea and Pérez-Belis, 2012				
12	Eco effectiveness	Wang and Côté 2011				
13	Eco efficiency	McAloone and Andreasen, 2004; Unger et al., 2008; Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010; Hong et al., 2012				
14	Ecodesign web	Bhamra and Lofthouse, 2007				
15	Eco-Indicator 95	Huisman et al., 2000; Lenau and Bey, 2001; Huisman et al., 2003				
16	Eco-Indicator 99	Huisman et al., 2003; Bhamra and Lofthouse, 2007				
17	Ecological footprinting	Unger et al., 2008; Gagnon et al., 2012				
18	Ecological indicators (T)	Stasinopoulos et al., 2009				
19	Emergy analysis	Gagnon et al., 2012				
20	Energy analysis	Hossain et al., 2010				
21	Environmental Priority Strategies	Lenau and Bey, 2001; Huisman et al., 2003				
22	Environmental product declaration	Mayyas et al., 2012a				
23	Environmental Product Life Cycle matrix (T)	Bovea and Pérez-Belis, 2012				
24	Environmental valuation	Gagnon et al., 2012				
25	Environmentally Responsible Product Assessment	Chiu and Chu, 2012				
26	Environmentally Responsible Product/Process Assessment Matrix (T)	Bovea and Pérez-Belis, 2012				
27	Exergy analysis	Hossain et al., 2010; Urban et al. 2010; Gagnon et al., 2012				
28	Footprinting	Bovea and Pérez-Belis, 2012				
29	Life cycle assessment	Lindahl 1999; Lenau and Bey 2001; Lindahl 2001; McAloone 2001; Bhander et al. 2003; Boks and Stevels 2003; Ernzer and Bey 2003; Fiksel 2003; Bovea and Vidal 2004; Karlsson and Luttropp 2006; Bhamra and Lofthouse				

		2007; Papandreou and Shang 2008; Unger et al. 2008; Hossain et al. 2010; Trotta 2010; Vinodh and Rathod 2010; Azkarate et al. 2011; Ostad-Ahmad-Ghorabi and Collado-Ruiz 2011; Bovea and Perez-Belis 2012; Chiu and Chu 2012; Hong et al. 2012; Laitala et al. 2012; Mayyas et al. 2012b; Rosen and Kishawy 2012				
30	Life cycle check	McAloone, 2001				
31	Life Cycle Planning	Bovea and Pérez-Belis, 2012				
32	Material Flow Analysis	Unger et al., 2008				
33	Material Intensity per Unit of Service					
34	Material Recycling Efficiency calculations	Huisman et al., 2000; Huisman et al., 2003				
35	Materials, Energy & Toxicity matrix (T)	Bovea and Pérez-Belis, 2012; Chiu and Chu, 2012				
36	Oil Point Method	Lenau and Bey, 2001; Ernzer and Bey 2003; Bovea and Pérez-Belis, 2012; Chiu and Chu, 2012				
37	Okala method	Chiu and Chu, 2012				
38	Product life thinking	McAloone, 2001				
39	RAILS	Bovea and Pérez-Belis, 2012				
40	Recyclability assessment	Huisman et al., 2000				
41	Simplified life cycle assessment	Lu et al., 2011; Chiu and Chu, 2012				
42	Strategic environmental assessment	Gagnon et al. 2012				
43	Strategic Life Cycle Management	Byggeth et al., 2007b				
44	Strategic wheel (T)	Unger et al., 2008				
45	Streamlined life cycle assessment	Unger et al., 2008; Bovea and Pérez-Belis, 2012				
46	Toxicity assessment	Huisman et al., 2000				
Integrated environmental, economic, and/or social performance evaluation:			6	11.5%	6.9%	3.5%
47	Eco Value Analysis	Bovea and Pérez-Belis, 2012				
48	Integrated tools (T)	Ramani et al., 2010				
49	Life Cycle Environmental Cost Analysis	Bovea and Pérez-Belis, 2012				
50	Life Cycle Sustainability Assessment	Chiu and Chu, 2012				
51	Requirements matrix (T)	Bovea and Pérez-Belis, 2012				

52	Two-stage network data envelopment analysis	Chen et al., 2012				
OTHER METHODS/TOOLS FOR EVALUATION AND ANALYSIS			**35**	**-----------**	**40.2%**	**20.6%**
Benchmarking:			4	-----------	4.6%	2.4%
53	Benchmarking generally	Huisman et al., 2000; Stasinopoulos et al., 2009				
54	EcoBenchmarking method	Boks and Diehl, 2005				
55	Environmental Benchmarking Method	Boks and Stevels, 2003				
56	Multiple Environmental Benchmarking Data Analysis					
Failure mode and effects analysis (FMEA) and FMEA-based methods:			4	-----------	4.6%	2.4%
57	Eco-FMEA	Bovea and Pérez-Belis, 2012				
58	Environmental Effect Analysis	Lindahl, 2001				
59	Environmental FMEA	Bovea and Pérez-Belis, 2012				
60	Failure Mode and Effect Analysis	Byggeth et al., 2007a,b				
Impact assessment:			5	-----------	5.7%	2.9%
61	Economic impact analysis	Gagnon et al., 2012				
62	Environmental Impact and Factor Analysis	Bovea and Pérez-Belis, 2012				
63	Environmental impact assessment	Gagnon et al., 2012				
64	Integrated impact assessment					
65	Social impact assessment					
Quality function deployment (QFD) and QFD-based methods:			7	-----------	8.0%	4.1%
66	Environmental Objective Deployment	Bovea and Pérez-Belis, 2012				
67	Environmental QFD					
68	Environmentally Conscious QFD	Vinodh and Rathod, 2010; Bovea and Pérez-Belis, 2012;				
69	Green QFD	Bovea and Pérez-Belis, 2012				
70	Life cycle QFD					
71	QFD for Environment					
72	Quality Function Deployment	Strasser and Wimmer, 2003; Ramani et al., 2010; Aschehoug et al., 2012; Bovea and Pérez-Belis, 2012				
User-centred design:			8	-----------	9.2%	4.7%
73	Ethnographic fieldwork	Bhamra et al., 2011				
74	Participant observation	Bhamra and Lofthouse, 2007				
75	Product-in-use	Bhamra and Lofthouse, 2007; Bhamra et al., 2011				
76	Questionnaire	Bhamra et al., 2011				
77	Scenario-of-use	Bhamra and Lofthouse, 2007				
78	Semi-structured interview	Bhamra et al., 2011				
79	User diaries					
80	User trials	Bhamra and Lofthouse, 2007				

Non-generalisable methods/tools for evaluation and analysis:			7	-----------	8.0%	4.1%
81	ABCD analysis	Byggeth et al., 2007a,b; Unger et al., 2008				
82	Functional analysis	Stasinopoulos et al., 2009				
83	Hierarchical design decomposition	Alfaris et al., 2010				
84	Morphological analysis	Chiu and Chu, 2012; Gagnon et al., 2012				
85	Nature studies analysis	Gamage and Hyde, 2012				
86	Scenario analysis	Huisman et al., 2000				
87	System analysis	Stasinopoulos et al., 2009				

Appendix 7: Analytical study of performance indicators

As discussed in Chapter 7 (Section 7.3), an analytical study of 324 performance indicators applied to evaluate the sustainability performance of technical systems was conducted as part of the evaluation of the S-Cycle model. The study led to development of the S-Cycle Performance Matrix (Figure 8-9, Section 8.2.3.2, Chapter 8). This appendix presents the full list of indicators analysed (Appendix 7A), and an excerpt from the spreadsheet used to capture the analysis (Appendix 7B). All references may be found in the reference list included at the end of Paper B (Appendix 2).

Appendix 7A: Indicator sample

The full list of 324 indicators analysed is presented in Table A7-1 below. The indicators were identified from the literature sample that formed the basis of the review on sustainability performance evaluation of technical systems (Section 4.3, Chapter 4) – this is presented in Table 6 of Paper B (Appendix 2). 390 indicators were initially identified from this literature sample; however, 66 of these were excluded from the final analysis sample for reasons elaborated in Section 5.2 of Paper B:

- information on the indicator provided in the source was not sufficient to classify it;
- the indicator focused purely on technical aspects rather than aspects contributing to sustainability performance;
- the indicator focused on a system's contribution to sustainable development or socio-economic development generally; or
- the indicator was not a measure of system performance.

Table A7-1: Sample of indicators analysed during evaluation of the S-Cycle model

Source	Technical system	Evaluation method	No.	Indicators
Abdel-Salam and Simonson, 2014	Air conditioning system	*Ad hoc*	1 2 3 4 5 6	Primary energy consumption CO2 emissions CO emissions NOx emissions SOx emissions PM emissions
Adams and McManus, 2014	Combined heat & power plant	Life cycle assessment	7 8 9 10 11 12 13 14 15	Climate change (human health) Climate change (ecosystems) Human toxicity Particulate matter formation Terrestrial ecotoxicity Metal depletion Fossil depletion Energy payback period Energy gain ratio
Agarski et al., 2012	Five different models of car	Multi criteria assessment	16 17 18 19 20 21	Fuel consumption CO2 emissions CO emissions HC emissions NOx emissions Particulate emissions

			22	Noise level
			23	Engine power
Antony et al., 2014	Biomimetic ceiling structure	Life cycle assessment	24	Global warming potential
			25	Cumulative energy demand
			26	Land use
			27	Photochemical ozone creating potential
			28	Acidification potential
			29	Eutrophication potential
Asif and Muneer, 2014	Three different kinds of window	*Ad hoc*	30	Annual heat loss
			31	Life cycle heat loss
			32	Annual CO2 emission – electricity
			33	Annual CO2 emission - gas
			34	Life cycle CO2 emission - electricity
			35	Life cycle CO2 emission - gas
Aydin et al., 2013	Turboprop engine	Exergy analysis	36	Exergy efficiency
			37	Waste exergy ratio
			38	Recoverable exergy ratio
			39	Exergy destruction factor
			40	Environmental effect factor
			41	Exergetic sustainability index
Balta et al., 2010	Four different building heating systems	Exergy & energy analysis	42	Metric based on a relation between exergy efficiency & the exergetic sustainability index
			43	Energetic renewability ratio
			44	Exergetic renewability ratio
Bianchi et al., 2014	Three different combined heat & power plants	*Ad hoc*, plus Avoided Heat Generator (AHG) method	45	Electric power size
			46	Electric efficiency
			47	Thermal efficiency
			48	Primary Energy Saving index
			49	NOx concentration
			50	NOx emissions (output-based)
			51	NOx emissions (AHG method)
			52	Pollutant Savings Index (NOx)
Buonocore et al., 2012	Combined heat & power plant	Material flow accounting	53	Abiotic material intensity per MJ of electricity generated
			54	Abiotic material intensity per MJ of heat generated
			55	Water demand per MJ of electricity generated
			56	Water demand per MJ of heat generated
			57	Global to local ratio of abiotic material
			58	Global to local ratio of water demand
			59	Total abiotic material requirement
			60	Total water demand
		Embodied energy analysis	61	Oil equivalent intensity per MJ of electricity
			62	Oil equivalent intensity per MJ of heat
			63	Embodied energy per MJ of electricity
			64	Embodied energy per MJ of heat
			65	Energy return on investment (EROI) of products
			66	EROI of electricity
			67	EROI of heat
			68	Total embodied energy applied
			69	Total oil equivalent applied
		Emergy accounting	70	Emergy from local renewable resources

			71	Emergy from local non-renewable resources
			72	Emergy from imported resources
			73	Total emergy
			74	Transformity of electricity
			75	Transformity of heat
			76	Renewable fraction
			77	Environmental Loading Ratio
			78	Emergy Yield Ratio
			79	Emergy Sustainability Index
		Life cycle assessment	80	Carbon footprint (overall)
			81	Carbon footprint per unit of electricity
			82	Carbon footprint per unit of heat
			83	Human toxicity (overall)
			84	Human toxicity per unit of electricity
			85	Human toxicity per unit of heat
			86	Photochemical oxidation (overall)
			87	Photochemical oxidation per unit of electricity
			88	Photochemical oxidation per unit of heat
			89	Acidification (overall)
			90	Acidification per unit of electricity
			91	Acidification per unit of heat
			92	Eutrophication (overall)
			93	Eutrophication per unit of electricity
			94	Eutrophication per unit of heat
Caliskan et al., 2011a	Four different building air cooling systems	Exergy analysis	95	Exergetic sustainability index
Caliskan et al., 2011b	Solar ground-based heat pump	Energy analysis	96	Energy input rate
			97	Energy storage rate
			98	Total heat loss rate
			99	Collector heat loss rate
			100	Other heat loss rate
			101	Energy efficiency
		Exergy analysis	102	Exergy input rate
			103	Total exergy loss rate
			104	Exergy rate of collector loss
			105	Exergy rate of other losses
			106	Exergy storage rate
			107	Exergy efficiency
			108	Exergetic sustainability index
Caliskan et al., 2012	Three different building air cooling systems	Energy analysis	109	Wet bulb effectiveness
			110	Cooling capacity
			111	Coefficient of Performance
			112	Energy consumption per day
		Exergy analysis	113	Exergy input rate
			114	Exergy input rate of dry air
			115	Exergy input rate of water
			116	Exergy output rate
			117	Exergy loss rate
			118	Exergy destruction rate
			119	Exergy efficiency
			120	Sustainability assessment
		Ad hoc	121	CO2 emissions
Cellura et al., 2013	Biomass boiler and combined heat & power plant	Life cycle assessment	122	Cumulative Energy Demand
			123	Climate change
			124	Ozone depletion
			125	Human toxicity
			126	Photochemical ozone formation

			127 128 129 130 131 132	Acidification Terrestrial eutrophication Freshwater eutrophication Marine eutrophication Land use Water resource depletion
Chandrasekaran and Guha, 2013	Turbofan engine	*Ad hoc*	133 134 135 136 137 138 139 140 141	Net thrust Specific fuel consumption Inlet mass flow Thermal efficiency Overall efficiency Emission index of NOx Emission index of carbon monoxide Emission index of carbon dioxide Emission index of hydrocarbons
Chicco and Mancarella, 2008	Poly-generation system (heat, power & cooling)	*Ad hoc*	142 143	Poly-generation Primary Energy Saving Poly-generation CO2 Emission Reduction
Coelho et al. 2012	Ten different waste-to-energy plants	*Ad hoc*	144 145 146 147 148 149 150 151 152 153 154 155 156 157 158 159	Water consumption by treated waste Liquid effluents generated by treated waste Water vapour consumption by treated waste CO2 emissions by treated waste Greenhouse gas emissions by treated waste Other gases emitted by treated waste Dust emissions by treated waste Area required by treated waste Soil used by treated waste Waste or sub products generated by treated waste Chemicals and additives consumption by treated waste Other materials consumed by treated waste Electricity consumption by treated waste Fossil fuel consumption by treated waste Thermal energy generation by treated waste Electricity generation by treated waste
Denholm et al., 2005	Baseload wind energy system	*Ad hoc*	160 161 162 163 164 165	Peak power ratio Fuel consumption rate Primary energy efficiency GHG emission rate SO2 emission rate NOx emission rate
Evans et al., 2009	Various renewable energy conversion systems	*Ad hoc*	166 167 168 169	Greenhouse gas emissions Efficiency of energy generation Land use Water consumption
Hondo, 2005	Various energy conversion systems	*Ad hoc*	170	Life cycle GHG emission factor
Kim et al., 2014	Solar photovoltaic systems	Life cycle assessment	171 172 173	Global warming potential Fossil fuel consumption Energy payback time
Li et al., 2012	Azeotropic	Energy analysis	174	Decanter heat loss

	distillation column		175 176 177 178	Minimum separation work Lost work Thermodynamic efficiency CO2 emissions
		Exergy analysis	179	Total exergy input
Liu, 2014	Various renewable energy systems	*Ad hoc*	180 181 182 183 184	CO2 emissions NOx emissions SO2 emissions Renewable fraction Energy efficiency
Maxim, 2013	Fourteen different energy conversion systems	Weighted sum multi-attributes	185 186 187	Efficiency Capacity factor Land use
Moss et al., 2014	Two different anaerobic digestions systems	Emergy analysis	188 189 190 191 192 193	Proportion renewable Emergy yield ratio Environmental loading ratio Emergy sustainability index Emergy efficiency index Adjusted yield ratio
Ofori-Boateng and Lee, 2014	Conceptual biorefinery	Exergetic Life Cycle Assessment	194 195 196 197 198	Total exergy input Total exergy output Total exergy destroyed Exergy efficiency Thermodynamic sustainability index
		Life cycle assessment	199 200 201 202 203 204 205 206	Acidification potential Aquatic ecotoxicity potential Eutrophication potential Global warming potential Human toxicity potential Ozone layer depletion potential Photochemical oxidant potential Terrestric ecotoxicity potential
Onat and Bayar, 2010	Energy conversion systems in general	*Ad hoc*	207 208 209 210	Carbon dioxide emissions Efficiency Fresh water consumption Land use
Pacca et al., 2007	Roof-mounted solar photovoltaic system	Life cycle assessment	211 212 213	Net energy ratio Energy payback time CO2 emissions
Rahman et al., 2014	Various compression ignition engines	*Ad hoc*	214 215 216 217 218 218 219	Brake specific fuel consumption Thermal efficiency Exhaust gas temperature Nitrogen oxides (emission parameter) Hydrocarbons (emission parameter) Particulate matter (emission parameter) Carbon monoxide (emission parameter)
Raugei et al., 2005	Molten carbonate fuel cell, and three gas turbines	Material flow analysis	220 221 222 223	Material intensity, abiotic factor Material intensity, water factor Material intensity, air factor Material intensity, biotic factor
		Energy analysis	224 225 226	LCA electric energy efficiency LCA total energy efficiency CO2 release
		Emergy accounting	227 228	Transformity of electricity without services Transformity of electricity with services
		Exergy analysis	229	Electric exergy efficiency

			230 231	Total exergy efficiency Exergy loss, operating phase
Rosato et al., 2013	Various combined heat & power plants	*Ad hoc*	232 233	Primary Energy Saving Carbon dioxide equivalent emissions
Rosato et al., 2014a	Building-integrated cogeneration system	*Ad hoc*	234 235 236 237 238 239 240 241 242 243 244 245	Electric energy produced by the MCHP unit Thermal energy produced by the MCHP unit and transferred to the water within the tank Primary energy consumed by the MCHP unit Electric efficiency of MCHP unit Thermal efficiency of MCHP unit Thermal energy produced by the boiler Primary energy consumed by boiler Electric energy bought from the grid Primary energy consumed to produce the electric energy bought from the grid Total primary energy consumed by whole proposed system Primary Energy Ratio Primary Energy Saving
Rosato et al., 2014b	Building-integrated cogeneration system	*Ad hoc*	246	Carbon dioxide equivalent emissions
Rotella et al., 2010	Hard machining system	*Ad hoc*	247 248 249 250 251 252	Cutting force Thrust force Mechanical power Wear rate White layer thickness Material removal rate
Russell-Smith et al., 2014	Mixed-use university campus building	Life cycle assessment	253 254 255 256	Global warming potential Primary energy consumption Potable water consumption Ozone depletion potential
Shah et al., 2008	Three different residential heating & cooling systems	Life cycle assessment	257 258 259 260	Respiratory inorganics Aquatic ecotoxicity Global warming Non-renewable energy
Shahabi et al., 2014	Seawater reverse osmosis desalination plant	Life cycle assessment	261	Life cycle GHG emissions
Singh et al., 2014	Biodiesel-fuelled compression combustion engine	*Ad hoc*	262 263 264 265 266 267	Indicated specific fuel consumption Indicated thermal efficiency CO2 emissions Hydrocarbon emissions NO emissions Smoke opacity
Sogut et al., 2012	Coal preparation unit	Energy analysis	268 269	CO2 emissions Energy efficiency
		Exergy analysis	270	Exergy efficiency
Thiers and Peuportier, 2012	Two different high energy performance buildings	Life cycle assessment	271 272 273 274 275 276	Cumulative Energy Demand Water consumption Abiotic depletion potential Non-radioactive waste creation Radioactive waste creation Global warming potential at 100 years

			277	Acidification potential
			278	Eutrophication potential
			279	Photochemical oxidant formation potential
			280	Odour
Uddin and Kumar, 2014	A horizontal and a vertical axis wind turbine	Life cycle assessment	281	CO_2 emissions
			282	CH_4 emissions
			283	CO emissions
			284	NO_x emissions
			285	SO_x emissions
			286	Chemical oxygen demand
			287	Dissolved organic carbon
			288	PO_4 emissions
			289	SO_4 emissions
			290	Global warming potential
			291	Electricity generation
			292	Life cycle embodied energy
			293	Energy intensity
			294	CO_2 emission intensity
			295	Energy payback time
Ulgiati et al., 2011	Various co-generation electricity conversion systems	Material flow accounting	296	Abiotic material intensity
			297	Water intensity
			298	Air intensity
		Energy analysis	299	GER of electricity
			300	Oil equivalent of electricity
			301	Electric energy efficiency
			302	Cogeneration energy efficiency
		Exergy analysis	303	Cogeneration exergy efficiency
		Emergy accounting	304	Transformity, without services
			305	Emergy Yield Ratio
			306	Environmental Loading Ratio
		Life cycle assessment	307	Global warming potential
			308	Acidification
Waheed et al., 2014	Crude oil distillation unit	Energy analysis	309	Fuel rate
			310	Energy supplied
			311	Energy loss in combustion chamber
			312	Energy loss in heat exchanger
			313	Energy loss in stack
			314	Total energy loss
			315	Furnace energy efficiency
			316	CO_2 emissions rate
			317	Specific CO_2 emissions
			318	Exergy supplied
			319	Exergy loss in combustion chamber
			320	Exergy loss in heat exchanger
			321	Exergy loss in stack
			322	Total exergy loss
			323	Furnace exergy efficiency
			324	Exergy change in process streams

Appendix 7B: Indicator analysis

The indicators presented in Table A7-1 were analysed with respect to the generic goals, SPI archetypes, and associated metrics and measures proposed in the S-Cycle Performance Matrix (as discussed in Section 7.3, Chapter 7). This analysis sought to determine:

- whether the indicators in the sample could be classified with respect to the proposed goals, SPI archetypes and metrics in the matrix (Figure 7-11), thus providing support for the latter; and
- whether there are any indicators in the sample that are not described in the performance matrix, which may be suggestive of additional SPI archetypes and metrics, and generic goals.

Using a spreadsheet, each indicator was classified with respect to the aspects of system behaviour measured, and the component of performance measured (i.e. efficiency or effectiveness). Inferences were then made regarding which generic goal, SPI archetype, and metric each indicator relates to, if any. An excerpt from the spreadsheet used is presented overleaf in order to convey the analysis process.

Author/date	Evaluation method(s)	Indicators	Units	Formula/definition	Aspect(s) of TS behaviour measured [5] [6] [7] [10] [11] [12] [13] [14] [15] [16]													Elements of performance measured		Fundamental SPI?	SPI formula	Goals [4]	
					C	AR	PR	A-RR	P-RR	A-NRR	P-NRR	A-IR	P-IR	IO	W	T/B	SD	Efficiency [8]	Effectiveness [9]			Explicitly stated (if any)	Inferred (if possible)
Buonocore et al. 2012	Material flow accounting	Abiotic material intensity per MJ of electricity generated	g/MJ_electricity	Not specifically stated, but all indicators in this paper are essentially evaluated by creating input/output inventories, and then multiplying the physical/ energetic flows by various conversion factors from different evaluation methods (like standard LCA, but they use a combination of local/global and upstream/downstream indicators)	—	—	✓	—	—	—	—	—	—	✓	—	—	—	✓	—	Resource intensity	i	—	Renewability not specified; however, could be: (a) minimise use of NRR; and/or (b) minimise use rate of RR
		Abiotic material intensity per MJ of heat generated	g/MJ_heat		—	—	✓	—	—	—	—	—	—	✓	—	—	—	✓	—	Resource intensity	i	—	Renewability not specified; however, could be: (a) minimise use of NRR; and/or (b) minimise use rate of RR
		Water demand per MJ of electricity generated	g/MJ_electricity		—	—	—	—	✓	—	—	—	—	✓	—	—	—	✓	—	RR intensity	i	—	Minimise use rate of RR
		Water demand per MJ of heat generated	g/MJ_heat		—	—	—	—	✓	—	—	—	—	✓	—	—	—	✓	—	RR intensity	i	—	Minimise use rate of RR
		Global to local ratio of abiotic material	—		—	—	✓	—	—	—	—	—	—	—	—	—	—	—	✓	Relates to resource consumption at different scales - not currently classifiable	N/A	—	Renewability not specified; however, could be: (a) minimise use of NRR; and/or (b) minimise use rate of RR
		Global to local ratio of water demand	—		—	—	—	—	✓	—	—	—	—	—	—	—	—	—	✓	Relates to resource consumption at different scales - not currently classifiable	N/A	—	Minimise use rate of RR
		Total abiotic material requirement	g/yr		—	—	✓	—	—	—	—	—	—	—	—	—	—	—	✓	Resource consumption rate	i	—	Renewability not specified; however, could be: (a) minimise use of NRR; and/or (b) minimise use rate of RR
		Total water demand	g/yr		—	—	—	—	✓	—	—	—	—	—	—	—	—	—	✓	RR consumption rate	i	—	Minimise use rate of RR
	Embodied energy analysis	Oil equivalent intensity per MJ of electricity	g_oil/MJ_electricity		—	—	—	—	—	—	✓	—	—	✓	—	—	—	✓	—	NRR intensity	ii	—	Minimise use of NRR
		Oil equivalent intensity per MJ of heat	g_oil/MJ_heat		—	—	—	—	—	—	✓	—	—	✓	—	—	—	✓	—	NRR intensity	ii	—	Minimise use of NRR
		Embodied energy per MJ of electricity	MJ/MJ_electricity		—	—	—	—	—	—	✓	—	—	✓	—	—	—	✓	—	NRR intensity	i	—	Minimise use of NRR
		Embodied energy per MJ of heat	MJ/MJ_heat		—	—	—	—	—	—	✓	—	—	✓	—	—	—	✓	—	NRR intensity	i	—	Minimise use of NRR
		EROI of products	—	Ratio of the energy content of the output to the amount of fossil energy invested in the input to the process	—	—	—	—	—	—	✓	—	—	✓	—	—	—	✓	—	NRR intensity	i	—	Minimise use of NRR
		EROI of electricity	—	Ratio of the energy content of the output to the amount of fossil energy invested in the input to the process	—	—	—	—	—	—	✓	—	—	✓	—	—	—	✓	—	NRR productivity	i	—	Minimise use of NRR
		EROI of heat	—	Ratio of the energy content of the output to the amount of fossil energy invested in the input to the process	—	—	—	—	—	—	✓	—	—	✓	—	—	—	✓	—	NRR productivity	i	—	Minimise use of NRR
		Total embodied energy applied	MJ/yr	Not stated	—	—	—	—	—	—	✓	—	—	—	—	—	—	—	✓	NRR consumption rate	i	—	Minimise use of NRR
		Total oil equivalent applied	g_oil/yr	Not stated, but inferred as sum of oil equivalents for all system inputs per year	—	—	—	—	—	—	✓	—	—	—	—	—	—	—	✓	NRR consumption rate	ii	—	Minimise use of NRR

Appendix 8: The S-Cycle guideline and documentation

Appendix 8A: The S-Cycle guideline

As discussed in Chapter 7 (Section 7.1), the S-Cycle guideline was applied by all three researchers during the case studies (CS1 – CS3). The guideline is presented in full in this appendix, and has been reformatted owing to space limitations. The guideline is currently undergoing revision on the basis of the evaluation findings. As such, the ideas and concepts discussed are in a state of evolution.

A guide to using the S-Cycle model v1.6

Laura Hay, Alex Duffy

PART 1: Overview

1.1 Introduction

"Sustainability" is increasingly adopted as an overarching goal for a multitude of human activities, from agriculture and forestry, to design, production, and the process of socio-economic development. In general terms, sustainability may be defined as the ability to maintain or continue something over time [1]. Thus, in its most basic form, it is a rather abstract concept. In order to move from this abstract definition to a more concrete vision of sustainability that can actually be achieved, humans must decide upon what it is that they want, or more fundamentally, need, to maintain. With respect to the latter, it is generally understood that the Earth system provides the basis for all human activity, from economic production and consumption down to the basic processes of life. However, the growing scale of this activity is argued to be compromising vital aspects of the system that supports it [2]. In turn, human efforts to achieve sustainability ultimately seek to maintain the operation of human activities, by maintaining those aspects of the Earth system that they depend upon (e.g. natural resource stocks, and waste processing capacity) [1, 3].

From the above, it may be seen that human efforts to achieve sustainability are ultimately motivated by a social need to ensure the continuation of human activity within the Earth system. However, in any specific attempt to achieve sustainability, decisions must be made regarding precisely what activities and what aspects of the system should be maintained in order to meet this broad need. Decisions of this nature are unavoidably value laden [4]: humans generally choose to maintain the things that they value, and dispose of those that they do not [5]. In turn, a particular issue arises: different people, with their myriad experiences, worldviews, opinions, and so on, tend to value different things [6]. As a result, they also tend to hold different ideas on what sustainability is and how to achieve it. This facet of sustainability can make it difficult to discuss the concept in a coherent manner, even within a single organisation or department.

Co-ordinating efforts to achieve sustainability may represent a considerable challenge when those involved do not speak the same "sustainability language." To improve the effectiveness of such efforts, it is necessary to unite a range of decision makers with different perspectives in a common understanding of sustainability. Along these lines, this guide details a general process for achieving sustainability, centring on the use of a generic model of sustainability, known as the S-Cycle model. This model may be applied to any system at any level in any context and thus, provides a common and consistent basis for discussions on and action towards sustainability.

The remainder of this guide is organised as follows. In Section 1.2, the major activities involved in efforts to achieve sustainability are briefly outlined, before the S-Cycle model is presented in

Section 1.3. In Part 2, the process that should be followed when using the S-Cycle model to achieve sustainability is detailed, along with suggested documentation to be completed at each stage. In Part 3, a glossary of key terms employed throughout the guide is provided. Finally, references are listed in Part 4. Electronic copies of suggested documentation, and a copy of the S-Cycle model for use during the process are provided along with this guide.

1.2 Achieving sustainability

As discussed in Section 1.1, sustainability can be defined as the ability to maintain something over time. Generally speaking, sustainability may be viewed as a property of a system [1, 7, 8, 9], i.e. a "discernible manifestation of the components of a system" [10]. In turn, it may be said that a system exhibits behaviour *for* sustainability. That is, behaviour that maintains a target entity, chosen by humans. A system that has attained sustainability may be described as "sustainable." Decisions on targets to be maintained are made on the basis of what humans value (as discussed in Section 1.1). As such, given that different people tend to value different things, a range of different targets may be adopted even within a single context. For example, different targets are discussed in the literature on sustainability in design, including: the function of a system [11]; the Earth system's natural resource base and waste processing capacity [12]; the relationship between a product and a user [5]; and the value of a product for a user [5].

To achieve sustainability, having chosen a target to be maintained in the context of a particular system of interest, decision makers must influence the behaviour of the system by defining and implementing sustainability goals [8, 13, 14]. Generally speaking, a goal "refers to a future situation, that is perceived by the goal originator to be more desirable than the current situation" [15]. Essentially, a goal serves to direct behaviour towards a desired future state. Sustainability goals direct the behaviour of a system towards maintaining a chosen target [16]. As such, a system may be considered to be sustainable if it fulfils its sustainability goals. In order to determine what actions need to be taken to ensure that the system's behaviour fulfils these goals, it is necessary to assess and analyse the system's performance against the goals [15]. As such, in addition to sustainability goals, decision makers must also define corresponding sustainability performance metrics for the system, which may be evaluated through performance assessment. All of these activities are outlined in greater detail in Part 2 of this guide.

In order to effectively define sustainability goals, performance metrics, and actions, an understanding of the system's behaviour from the perspective of sustainability is required. In this guide, the S-Cycle model (a generic model of sustainability, as discussed in Section 1.1) is presented as a means to study system behaviour from this perspective, and thus to arrive at such an understanding. The model is outlined in the following section.

1.3 The S-Cycle model

As discussed in Section 1.1, different people tend to value different things. As a result, they also tend to hold different ideas on what sustainability is and how to achieve it. This may be the case even in a single organisation, or in an individual department within an organisation. In the absence of any common "sustainability language," it may be challenging to co-ordinate efforts to achieve sustainability. To ensure the effectiveness of such efforts, it is necessary to unite a range of people with different perspectives in a common understanding of sustainability. Along these lines, the S-Cycle model (shown in Figure 1) is a generic model of sustainability that may be applied to any system in any context.

Figure 1: The S-Cycle model (see Figure 6-5, Section 6.5.1, Chapter 6 of thesis)

At the highest level, the S-Cycle model may be applied to the Earth system as a whole (as shown in Figure 1). However, in practice, it may be applied to any system at any level within the Earth system, as illustrated in Figure 2 below. Essentially, S-Cycle provides a common and consistent basis for discussions on sustainability, and the analysis of system behaviour from the perspective of sustainability. Thus, it can facilitate the development of a shared understanding of sustainability during efforts to achieve it in a particular context.

Figure 2: Application levels of the S-Cycle model (see Figure 9, Section 4.4 of Paper D, Appendix 4)

As shown in Figure 1, the concept of an activity is used to represent the behaviour of a system in the S-Cycle model. An activity is a goal-directed physical or cognitive action, where active resources use passive resources to produce an output that should satisfy the goal of the activity [17]. Fundamentally, an activity depends upon resources for its continued operation [18]. Active resources are resources that use other resources in activities [17]. For instance, both human beings and intelligent software may be viewed as active resources in a variety of activities, including design and business activities. Conversely, passive resources are resources that are used by active resources in activities [17]. For instance, materials, energy, and information may be viewed as passive resources in a range of activities, again including design and business activities.

As discussed in Section 1.2, it may be said that a system exhibits behaviour *for* sustainability. That is, behaviour that maintains a target entity chosen by humans. In turn, there are four specific kinds of system behaviour that contribute to behaviour for sustainability: (i) the use of passive and active resources; (ii) the production of yield; (iii) the production of passive and active resources; and (iv) the production of waste [1]. When defining goals, metrics, and actions for the achievement of sustainability in the context of a particular system of interest, it is primarily these four aspects of behaviour that should be considered. Each of these aspects is represented within the S-Cycle model (Figure 1), and is briefly discussed below.

Use of passive and active resources:

The Earth system is typically viewed as containing various stocks of resources [19, 20, 21], that may be classed as either natural (e.g. forests, oceans, land, oil reserves, etc.) or artificial (e.g. economic capital stocks, industrial plant, information/knowledge databases, etc.). Further, these stocks may be classified as either renewable or non-renewable in nature [22, 23, 24]. That is, resource stocks that either regenerate over time (e.g. forests and oceans), or do not regenerate significantly along anthropological timescales (e.g. oil reserves), respectively. An activity in the Earth system (and in turn, its sub-systems) may use components from these stocks as passive and active resources, to meet a need for resources as indicated by the goal of the activity.

Production of yield:

An activity may produce entities that are intended to be yielded to the wider system. These entities may either contribute to resource stocks in the system, or they may be used directly as passive and/or active resources in other activities within the system [20, 22, 23, 25]. They are represented in the S-Cycle model (Figure 1) as *intended yield.* For example, a design activity may produce outputs such as products, services, and systems as yield to be used by humans in a range of different activities.

Production of passive and active resources:

An activity may also produce entities intended to be used as passive and/or active resources in the activity itself [19, 20]. These are represented in the S-Cycle model (Figure 1) as *intended resources*. For example, a production activity may produce electricity that can be reused in the activity itself as an energy source (i.e. passive resource). Note that certain parts of the intended resource stream may conventionally be considered to constitute waste, but are instead to be utilised in the activity as a resource [26, 27, 28]. For example, heat energy may from certain perspectives be viewed as waste in relation to a number of production activities. However, in order to reduce the environmental impact of these activities, this heat energy may be used in the activities as an energy source (i.e. passive resource) to drive production.

Production of waste:

In addition to intended resources and yield, an activity may produce entities that can be considered to constitute *waste* in relation to the activity [22, 26, 28, 29, 30], as shown in the S-Cycle model in Figure 1. That is, the fraction of the activity's output that is intended neither as yield nor resources and as such, has no utility in relation to the activity. For example, production activities may produce greenhouse gases due to the use of fossil fuels as passive resources, which have no utility in relation to the activity itself and are not intended for use by other activities on Earth. However, the terms "resource" and "waste" are defined here in relation to the activity under study. As such, entities that may be classed as waste in relation to one activity may in fact represent resources to a different activity. For example, heat energy may be considered as waste in relation to certain production activities, but a passive resource in the activity of heating a building.

A generic process for achieving sustainability, using the S-Cycle model as a tool for studying and understanding system behaviour from the perspective of sustainability, is detailed in Part 2 of this guide. An electronic copy of the S-Cycle model that may be printed out for use during the process is provided along with this guide.

PART 2: Using the S-Cycle model

As discussed in Part 1, this guide details a general process for achieving sustainability, centring on the use of the generic S-Cycle model. In the following sections, the specific stages in this process (shown in Figure 3, along with the outputs from each stage) are detailed. The overarching aim of each stage is specified, and an overview of the activities involved is provided. In turn, the specific steps involved in each stage are outlined, and suggested documentation to be filled out during these steps is presented.

Figure 3: The S-Cycle process (see Figure 7-3, Section 7.1.1, Chapter 7 of thesis)

STEP 1: MOTIVATING AND UNDERSTANDING SUSTAINABILITY

1. Aim

To secure the engagement of relevant decision makers with the S-Cycle model, and to develop a common understanding of sustainability and the sustainability challenges for a particular system of interest.

2. Overview

From the perspective of a particular individual or group of people, sustainability is but one potential goal among numerous others. For instance, an organisation may be more urgently concerned with its profitability and contributions to economic growth than the achievement of sustainability. In short, sustainability may not always immediately feature among the aspirations of a particular group of decision makers. Thus, before the S-Cycle model can even be applied, it may be necessary to motivate efforts to achieve sustainability through discussion among relevant decision makers in the context in question. However, as shown in Part 1, different people may have different ideas on sustainability, which can in turn hamper discussions of this nature. As such, during Stage 1, the S-Cycle model is used as a common basis for explaining sustainability to decision makers, which in turn fosters the development of a shared understanding of sustainability. In Part 1, it was also shown that sustainability can be viewed as a property of a system. Accordingly, the S-Cycle model is oriented towards the achievement of sustainability in systems. Therefore, before the model can be applied in a particular context, it is necessary to focus the attention of decision makers on a specific system of interest (SOI).

3. Steps

1. *Explain sustainability to decision makers using the S-Cycle model.*

   During this step, the S-Cycle model should be used as a tool to explain the concept of sustainability to relevant decision makers during introductory meetings. The meaning of sustainability (i.e. the ability to maintain something over time) should be discussed. In turn, the four kinds of system behaviour that contribute to behaviour for sustainability (i.e. the use of passive and active resources, and the production of intended resources, intended yield, and waste) should be illustrated using the S-Cycle model.

   When explaining sustainability, it may be beneficial to highlight how the four aspects of behaviour represented within the S-Cycle model could specifically translate to the decision makers' context. Such an approach facilitates engagement with the model, and the development of a clear understanding of sustainability among all relevant decision makers.

2. *Identify a system of interest (SOI).*

   To apply the S-Cycle model in a specific context, it is necessary to identify a SOI through discussion with relevant decision makers. That is, a system falling under the remit of the decision makers involved, that is determined to have significant challenges from the perspective of sustainability. The S-Cycle model is completely generic, and thus may be applied to any system at any level. Therefore, the SOI may be any kind of system with any purpose. For example, it may be desired to apply S-Cycle to an organisational system such as a manufacturing system or a supply chain, or a designed system such as a vehicle, a consumer product, or a building.

3. *Explore the sustainability challenges for the SOI.*

   Sustainability challenges may differ considerably depending upon the nature of the SOI. However, on a fundamental level, they will centre on the need to maintain some aspect of the system (e.g. an attribute, function, or capability) or the system as a whole over time. To understand the sustainability challenges for a particular system, it is necessary to discuss the system and its operation in the context of the S-Cycle model, i.e. considering the use of passive and active resources, and the production of intended resources, intended yield, and waste.

   When discussing what the sustainability challenges may be for a particular system, it is important to consider sustainability and the S-Cycle model in the context of the decision makers' aspirations. For instance, an engineering firm may not be immediately concerned with environmental sustainability, i.e. maintaining the Earth system's natural resource base by reducing the negative environmental impacts of human activity. However, the firm may, for example, wish to reduce costs over the life of a particular system by maximising the amount of time that the system is available for service as opposed to down for maintenance. In other words, to meet certain economic aspirations, the organisation may wish to maintain the operation of this system over time, i.e. achieve operational sustainability. In turn, this may contribute to the sustainability of human activity as a whole by reducing any negative environmental impacts that arise from carrying out maintenance on the system throughout its life.

   A particular SOI may have a raft of associated challenges. For the purposes of clarity, and to ensure that all relevant decision makers clearly understand the task at hand, the specific challenges to be addressed through application of the S-Cycle model should be agreed upon during this step.

4. Outcomes

- Relevant decision makers should understand sustainability from the same perspective, i.e. the perspective of the S-Cycle model, and how it may fit with their particular context and aspirations.
- A SOI for application of the S-Cycle model during Stage 2 should have been identified and agreed upon by relevant decision makers.
- The major sustainability challenges for the chosen SOI should be understood, and the specific challenges to be addressed through application of the S-Cycle model should be agreed upon by relevant decision makers.

5. Documentation

- Ensure that minutes are kept for each meeting, i.e. a formal record of what was said by whom, and the major outcomes of the meeting.
- The *S-Cycle Project Specification* may be filled out to provide a basic outline of the chosen SOI and the sustainability challenges to be addressed. An electronic copy of this document is provided along with this guide.

STEP 2: UNDERSTANDING THE SYSTEM OF INTEREST

1. Aim

To analyse the behaviour of the SOI, and define goals to direct this behaviour towards sustainability.

2. Overview

To achieve sustainability, a system's behaviour should fulfil sustainability goals as discussed in Part 1 (Section 1.2). As such, after identifying a specific SOI and understanding its sustainability challenges in Stage 1, the next step towards sustainability involves defining sustainability goals for the SOI. In general terms, a goal serves to direct behaviour towards a desired future state. Sustainability goals direct the behaviour of a system towards maintaining a chosen target. Thus, in order to define sustainability goals for the SOI, it is necessary to first develop an understanding of its behaviour. To this end, during Stage 2 the S-Cycle model is used as a tool to support the analysis of the SOI's behaviour from the perspective of sustainability. To ensure that the S-Cycle model is applied in an objective and consistent manner by decision makers, it is first necessary to define the scope of the analysis.

3. Steps

1. *Define the scope of analysis for the S-Cycle model.*

   As discussed in Part 1 (Section 1.3), the S-Cycle model may be applied to any system at any level. Thus, having applied the model to a system at one level in a particular context, it may be desired to apply it to another system at a different level in future efforts. To ensure that: (i) the S-Cycle model is applied in an objective and consistent manner by decision makers, and (ii) the relationship between the behaviour of the SOI and that of other systems studied in future can be understood, it is necessary to define the scope of the analysis. This scope may be defined with respect to two aspects of the SOI: (i) the *extent* of the SOI, i.e. where the boundary delimiting the system from its environment lies; and (ii) the *level* of the SOI, i.e. the system's position within the system hierarchy, as shown in Figure 4 below.

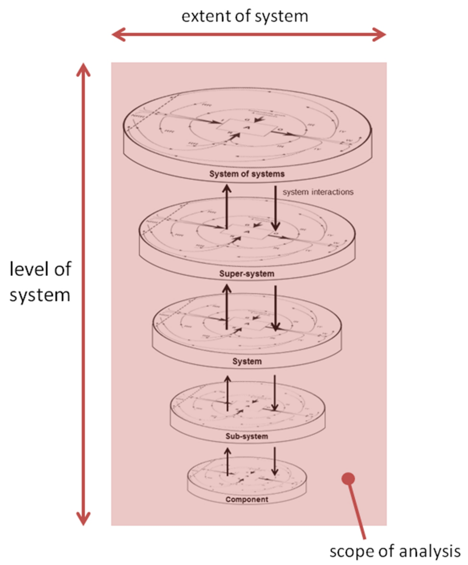


Figure 4: The scope of analysis for the S-Cycle model

2. *Identify the inputs and outputs in the SOI.*

   To understand the behaviour of the SOI from the perspective of sustainability, it is necessary to determine the relevant inputs and outputs of its internal activities within the defined scope of analysis. In line with the S-Cycle model, the following inputs and outputs should be identified for activities within the SOI: (i) inputs of renewable and non-renewable passive and active resources; (ii) outputs of intended resources; (iii) outputs of intended yield; and (iv) outputs of waste. Any inputs and outputs of this nature that exist at the system boundary should also be identified. These inputs and outputs should be recorded in a form that is appropriate for use as a basis for defining the SOI's sustainability goals in Step 4.

3. *Identify the conventional goals of the SOI.*

   From the perspective of a particular group of decision makers, sustainability is but one potential goal among numerous others (as discussed in Stage 1). As such, in any attempt to achieve sustainability, the SOI will be subject to two sets of goals: (i) sustainability goals, i.e. those that direct behaviour towards maintaining a chosen target; and (ii) conventional goals, i.e. those that do not pertain to sustainability. For instance, the SOI may be subject to design goals in aspects such as function and technical performance, and business goals in aspects such as cost and value. These two sets of goals – that is, sustainability goals and conventional goals – may conflict with one another. In other words, there may be trade-offs between the two sets of goals. For example, consider a technical system such as a ship. For sustainability, we may define a goal to minimise the ship's energy consumption. However, from a design perspective, we may define a goal to maximise the ship's operating range with respect to speed. Achieving this design goal will likely require increased energy consumption, leading to a trade-off between this goal and the aforementioned sustainability goal. To ensure that the SOI is both sustainable and viable from other perspectives, trade-offs between sustainability goals and conventional system goals must be managed.

   To effectively manage the trade-offs described above, it is necessary to first identify the conventional goals of the SOI within the defined scope of analysis. For instance, if the SOI is a technical system such as a ship, then the conventional goals of the ship should be identified here. Similarly, if the SOI is a whole organisation, then the conventional goals of the organisation should be identified here. These goals may be identified through discussion with relevant decision makers.

4. *Define a set of sustainability goals for the SOI.*

   As discussed in Part 1, sustainability goals direct system behaviour towards maintaining a chosen target. Thus, to define sustainability goals for the SOI, it is necessary to reflect upon its current behaviour (analysed in Step 2) within the scope of analysis, in relation to its sustainability challenges (determined in Stage 1). The behaviour of the SOI should be considered from a holistic viewpoint – that is, considering all aspects of behaviour demonstrated by the S-Cycle model, i.e. the use of passive and active resources, and the production of intended resources, intended yield, and waste.

   To facilitate the reflective exercise described above, it is necessary to engage relevant decision makers in a process of (i) brainstorming, and (ii) consolidation [15]. With respect to (i), an initial large set of potential sustainability goals that may be appropriate for the SOI should be established via contributions by all relevant decision makers. Next, with respect to (ii), the decision makers involved should work to clarify the meaning of the goals that they have defined and eliminate any duplication, leading to a set of sustainability goals for the SOI that is understood and agreed upon by all decision makers.

5. *Ensure that the defined sustainability goals for the SOI are coherent, i.e. aligned with (i) the SOI's conventional goals, and (ii) one another.*

   As discussed in Step 3, the SOI will be subject to both sustainability goals and conventional goals, which may conflict with one another. To manage this conflict, it is necessary to align the defined sustainability goals with the conventional goals identified in Step 3 [15]. This alignment may be achieved through discussion with relevant decision makers to explore trade-offs, and subsequent amendments to the defined sustainability goals for the SOI. Where large numbers of sustainability and conventional goals must be considered (e.g. in the case of large scale, complex systems), it may be necessary to employ an appropriate formal technique to achieve alignment between the SOI's sustainability goals and conventional goals.

   It is also possible that conflict may exist among the defined sustainability goals. For instance, once again consider a technical system such as a ship. For sustainability, we may define a goal to minimise the amount of material consumed in building the ship. Fulfilling this goal may involve, for example, reducing the thickness of components in the system, which may have an effect on the overall durability of the ship. However, for sustainability, it may also be desired to maximise the length of the ship's life in service in order to reduce waste. Fulfilling this goal may require increased durability of the ship's components throughout its life. Clearly, a trade-off exists between the first sustainability goal, which may entail a reduction in the ship's durability, and the second goal, which may entail an increase in durability. To manage conflicts of this nature, the SOI's sustainability goals should be aligned with one another [15]. To achieve such alignment, the defined sustainability goals should first be prioritised using an appropriate technique. That is, they should be ranked in order of importance with respect to the overall goal of achieving sustainability in the SOI. Trade-offs existing among the prioritised goals may then be explored through discussion with relevant decision makers, and amendments may be made to the defined sustainability goals where necessary. As above, where large numbers of sustainability goals must be considered, it may be necessary to employ an appropriate formal technique to achieve alignment among them.

4. Outcomes

- Knowledge should have been gained on the behaviour of the SOI from the perspective of sustainability (i.e. knowledge on its use of passive and active resources, and production of intended resources, intended yield, and waste) within a defined scope of analysis.
- A set of sustainability goals that is: (i) reflective of the current behaviour of the SOI and its sustainability challenges; (ii) holistic with respect to the aspects of behaviour represented within the S-Cycle model; and (iii) coherent, i.e. the sustainability goals are aligned with one another and the conventional goals of the SOI, should have been defined and agreed upon by relevant decision makers.

5. Documentation

The *S-Cycle Goal Table* may be filled out to provide a formal record of the sustainability goals defined for the system. A copy of this table with example entries is provided at the end of Part 1. Additionally, an electronic copy is provided along with this guide.

STEP 3: ASSESSING SUSTAINABILITY PERFORMANCE

1. Aim

To assess the performance of the SOI against its sustainability goals by defining and evaluating sustainability metrics of efficiency and effectiveness.

2. Overview

To achieve sustainability, a system's behaviour should fulfil sustainability goals as discussed previously. In Stage 2, a set of sustainability goals was defined for the SOI, by reflecting upon its behaviour and sustainability challenges. In order to determine what actions (if any) need to be taken to ensure that the SOI's behaviour fulfils these goals, it is necessary to assess and then analyse the system's performance against the goals (as discussed in Part 1, Section 1.2). This performance is termed the SOI's "sustainability performance" throughout this guide. Stage 3 focuses upon the *assessment* of the SOI's sustainability performance, i.e. the definition and evaluation of performance metrics that will allow each of the SOI's sustainability goals to be measured.

When applying the S-Cycle model to a particular SOI, the E^2 performance model should be adopted as a basis for assessing the system's sustainability performance [15]. According to this model, the sustainability performance of a particular SOI is composed of two essential components: (i) efficiency, defined as "the relationship (often expressed as a ratio) between what has been materially gained and the level of resource (material) used" [15]; and (ii) effectiveness, defined as the "degree to which the result (output) meets the goal" [15], as shown in Figure 5 below.

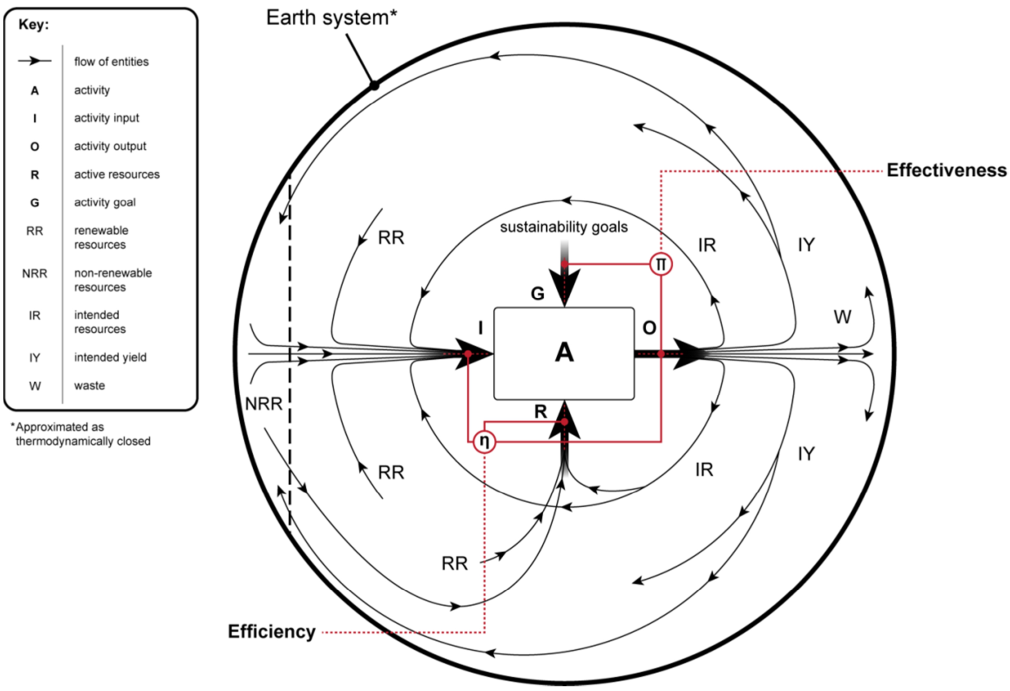


Figure 5: The E² performance model in the context of the S-Cycle model (adapted from [15])

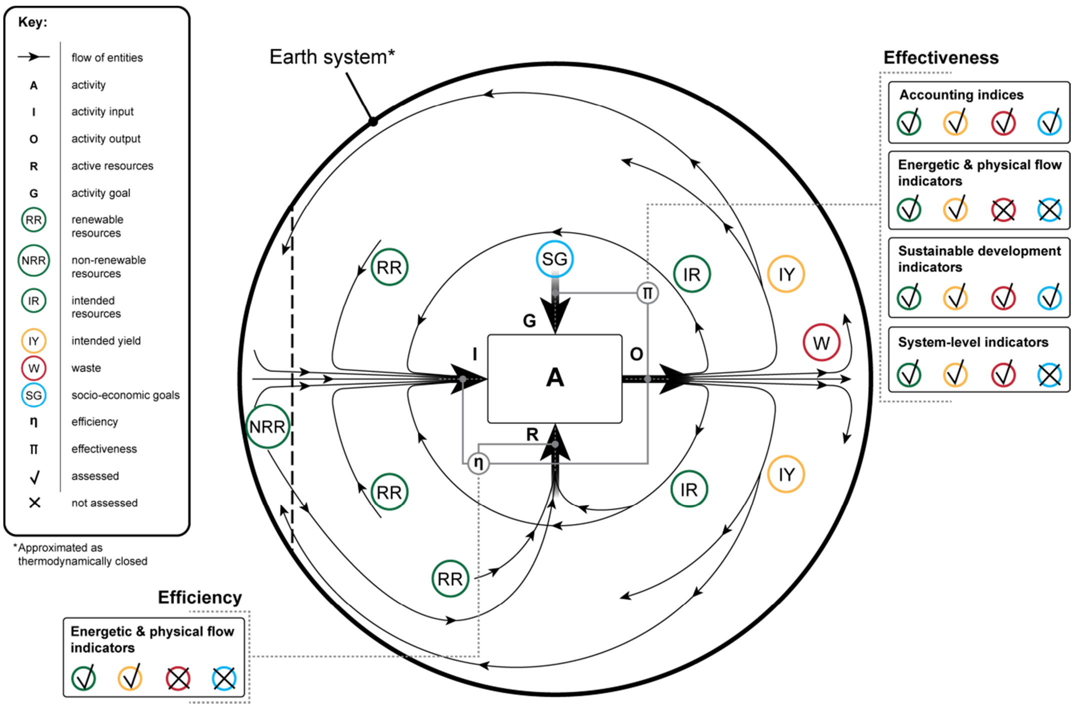


Figure 6: The S-Cycle Performance Map (from [32])

3. Steps

1. *For each of the SOI's sustainability goals, define sustainability metrics of efficiency and effectiveness that will allow the goal to be assessed.*

   A sustainability metric is a system parameter used to quantify the performance of the SOI against its sustainability goals (i.e. its sustainability performance). Sustainability metrics may also be referred to as "sustainability indicators" [1]. According to the E^2 performance model, the sustainability performance of the SOI is "completely described within the elements of efficiency and effectiveness" [15]. Measuring a single component in isolation may yield incomplete and misleading information on the SOI's sustainability performance. In turn, the use of such information in decisions on actions to be taken towards sustainability may have a negative impact on decision outcomes [31]. Therefore, it is crucial that sustainability metrics of both efficiency and effectiveness are defined for each of the SOI's sustainability goals (defined in Stage 2). For each of the defined sustainability metrics, corresponding measures should be determined. That is, the data that are required to evaluate the metric [18]. In turn, a formula and units should be specified for all defined metrics. As with the definition of sustainability goals in Stage 2, sustainability metrics may be defined for the SOI by engaging relevant decision makers in a process of brainstorming and consolidation.

   From a sustainability perspective, the S-Cycle model provides a broad indication of the kinds of metrics that may be defined to assess sustainability performance, i.e. metrics focusing on renewable/non-renewable passive and active resource use, intended resource production, intended yield production, and waste production. Clearly, the specific metrics defined will depend upon the nature of the SOI and its sustainability goals. The S-Cycle Performance Map, shown in Figure 6, may be used to support the identification of specific sustainability metrics for a particular SOI [32]. An electronic copy of the map is provided along with this guide.

   Additionally, from a data-oriented perspective, three kinds of metrics may be defined for the SOI [18]:
   - *Accumulative*, i.e. individual metrics. For example, the accumulative consumption of a particular kind of resource by the activities in a system.
   - *Derived*, i.e. calculated metrics. For example, a formula for calculating the "environmental impact" of a particular system may be derived from its inputs of passive and active resources, and its outputs of intended resources, intended yield, and waste.
   - *Independent*, i.e. metrics where the value is directly measured from data and can be used in other metric types as a measure. For example, the number of kilograms of carbon dioxide emitted by a particular system in a year.

   All metrics defined for the SOI should be tested against NEAT criteria to ensure their robustness. That is, metrics should be:
   - *Numeric*, i.e. the measures should be quantitative as opposed to qualitative in nature;
   - *Explicit*, i.e. they should clearly and directly indicate achievement;
   - *Appropriate*, i.e. they should be: (i) applied in a consistent manner, (ii) relevant to the defined sustainability goals and the SOI, and (iii) coherent with both the E^2 and S-Cycle models; and
   - *True*, i.e. they should be objective as opposed to subjective in nature and therefore open to impartial analysis [18].

   As with the sustainability goals defined in Stage 2, the sustainability metrics and measures defined for the SOI should be agreed upon by all relevant decision makers.

2. *Assign initial values to each sustainability metric and measure.*

   In order to analyse the SOI's sustainability performance in Stage 4, it is necessary to assign values to the metrics defined in Step 1 above. To do so, the data on sustainability performance that is required for each metric must first be collected, i.e. the measures defined for each metric must be evaluated. In turn, the metrics may be computed according to their formulae to yield initial values that can be presented and analysed.

   Evaluating measures, i.e. collecting data on the SOI's sustainability performance, may not always be straightforward. In certain cases, processes may already exist for collecting the required data (e.g. in an organisation that already makes some effort to assess its sustainability performance). However, in other cases, it may be necessary to define and implement new processes that will allow the required data to be collected within the context in question (e.g. in an organisation with no existing sustainability assessment programme). Where data collection processes do not exist for sustainability performance measures, the necessary processes should be defined through discussion with relevant decision makers, and agreed upon by all involved. When defining such processes, it is important to consider: where the data will be collected from, i.e. the data source; and who will collect the data, i.e. the data collector.

3. *Present initial values obtained for the SOI's sustainability metrics and measures.*

   Once values have been assigned to all of the SOI's sustainability metrics and measures, they should be presented in a form that is appropriate for performance analysis in Stage 4. The precise form adopted will largely depend upon the decision makers involved, and the method of analysis used in Stage 4.

4. Outcomes

- A set of sustainability metrics of efficiency and effectiveness, and corresponding measures, should have been defined for the SOI, tested against NEAT criteria, and agreed upon by all relevant decision makers.
- Where necessary, processes for collecting data on the SOI's sustainability performance should have been defined, agreed upon by all relevant decision makers, and implemented.
- Knowledge should have been gained on the performance of the SOI against its sustainability goals in the form of initial values for the defined sustainability metrics and measures.

5. Documentation

The *S-Cycle Metric Table* may be filled out to provide a formal record of the sustainability metrics and measures defined for the system. A copy of this table with example entries is provided at the end of Part 2. Additionally, an electronic copy is provided along with this guide.

STEP 4: ANALYSING SUSTAINABILITY PERFORMANCE

1. Aim

To understand where and how the SOI's sustainability performance should be improved.

2. Overview

To achieve sustainability, a system's behaviour should fulfil sustainability goals as discussed previously. In Stage 2, a set of sustainability goals was defined for the SOI, by reflecting upon its behaviour and sustainability challenges. In Stage 3, sustainability metrics of efficiency and effectiveness, and corresponding measures, were defined and evaluated to yield information on the SOI's performance against these goals (i.e. its sustainability performance). In order to know whether the SOI is fulfilling its sustainability goals or not, it is necessary to analyse the information obtained on its sustainability performance in Stage 3. If the SOI is not fulfilling its sustainability goals, then it is necessary to take action to improve its performance. Stage 4 centres on the *analysis* of the SOI's sustainability performance, to determine areas where performance should improve, targets for improvement, and actions to be taken in order to bring about this improvement.

3. Steps

1. *Identify areas for the improvement of sustainability performance in the SOI.*

   In Stage 3, values were assigned to each of the SOI's sustainability metrics and measures. Each of these metrics was defined to measure a specific sustainability goal for the SOI (defined in Stage 2). As discussed in Stage 3, efficiency is defined as the relationship between what has been gained and the level of resource used, whilst effectiveness is defined as the degree to which the result meets the goal. If the SOI is found to perform with low efficiency and/or effectiveness in relation to a particular sustainability goal, this implies that the goal is not being fulfilled and thus, that the SOI's performance in relation to this goal needs to improve. As such, to identify areas for the improvement of sustainability performance, the values assigned to each metric and measure during Stage 3 should be analysed in relation to their corresponding sustainability goals to highlight instances of low efficiency and/or effectiveness.

   To conduct this analysis objectively, some method should be adopted for determining what constitutes "low efficiency and effectiveness" for each of the SOI's sustainability goals. This method may be as simple as discussion with decision makers who have significant experience of the SOI. Such people may hold valuable knowledge on how the SOI would be expected to perform against the sustainability goals defined in Stage 2. In certain cases, it may be possible to consider the SOI's sustainability performance relative to that of another similar system to develop some estimation of how the SOI should be performing in relation to its sustainability goals. In other cases, identifying areas with low efficiency and effectiveness may require further analysis of the SOI's behaviour using an appropriate method. For instance, it may be possible to determine the maximum efficiency and/or effectiveness theoretically possible in relation to the SOI's sustainability goals by conducting further analysis on the inputs and outputs identified in Stage 2. Areas where the SOI's assessed efficiency and effectiveness was found to deviate markedly from these theoretical maximum levels may then be considered as potential areas for improvement.

2. *Set targets for the improvement of sustainability performance in the areas identified in Step 1.*

   Having identified areas where the SOI is performing with low efficiency and effectiveness in Step 1, the next step towards sustainability involves setting targets for the improvement of sustainability performance in these areas. In the context of the S-Cycle model, targets specify the values required for the SOI's sustainability metrics in order for the SOI to fulfil its sustainability goals [18]. In Stage 3, the sustainability metrics defined for the SOI were tested against NEAT criteria to ensure their robustness. Similarly, during this stage, the sustainability performance targets set for the system should be formulated in line with 3B criteria, to ensure that they are realistic. According to the 3B criteria, sustainability performance targets should be:

   - *Value-bound*, i.e. they should indicate the level of sustainability performance to be attained (the required value) by the SOI;

- *Time-bound*, i.e. they should indicate the date by which the required sustainability performance is to be attained by the SOI; and
- *Benchmarked*, i.e. they should indicate the required standard of sustainability performance to be achieved based on assessed performance, data gathering, and an objective basis [18].

When considering what the required value may be for a particular sustainability metric during target setting, it will likely be useful to consider any information on how the SOI *should* be performing in relation to its sustainability goals that was obtained during Step 1. For instance, it may be beneficial to secure the involvement of decision makers with significant experience of the SOI in efforts to set sustainability performance targets. In practice, the identification of areas for improvement and the definition of sustainability performance targets will likely be closely related activities. In any case, all sustainability performance targets for the SOI should be discussed and agreed upon by all relevant decision makers.

3. *Determine actions to be taken on the SOI to drive its performance towards the defined sustainability performance targets.*

To improve the SOI's sustainability performance, setting sustainability performance targets alone is not sufficient. It is also necessary to determine what action needs to be taken with respect to the inputs of passive and active resources, and outputs of intended resources, intended yield, and waste in the SOI in order to drive its sustainability performance towards the required level.

To ensure that this activity is carried out objectively, and that effective actions are defined for the SOI, some appropriate method should be adopted. Again, this method may be as simple as discussion with decision makers who have significant experience of the SOI, or consideration of another, similar system. However, in certain cases, it may be necessary to carry out further analysis of the SOI's behaviour using an appropriate method. For instance, it may be useful to determine the relationships between the SOI's sustainability goals, and the individual inputs and outputs in the system. That is, the inputs of passive and active resources, and the outputs of intended resources, intended yield, and waste in the SOI, identified during Stage 2. Knowledge on these relationships may then be used to explore the potential effects on sustainability performance of suggested actions to be taken with respect to the SOI's inputs and outputs. Actions that are predicted to have the greatest effects may then be implemented in Stage 5.

Initially, a relatively large set of actions to be taken to improve the SOI's sustainability performance may be suggested. Before moving on to Stage 5, this range should be discussed, and a finalised set of actions to be implemented should be agreed upon by all relevant decision makers.

4. Outcomes

- Shortcomings in the SOI's performance against the sustainability goals defined in Stage 2 (i.e. areas for improvement) should have been identified.
- Targets to improve the sustainability performance of the SOI should have been defined in line with 3B criteria, and agreed upon by all relevant decision makers.
- A set of actions to be taken to improve the SOI's sustainability performance so that it meets its sustainability performance targets should have been determined, and agreed upon by all relevant decision makers.

5. Documentation

The *S-Cycle Performance Improvement Table* may be filled out to provide a formal record of the sustainability performance targets defined for the system, and the actions to be taken to improve performance. A copy of this table with example entries is provided at the end of Part 2. Additionally, an electronic copy is provided along with this guide.

STEP 5: TAKING ACTION TOWARDS SUSTAINABILITY

1. Aim

To bring about improvement in the SOI's sustainability performance through action.

2. Overview

As discussed throughout this guide, to achieve sustainability, a system's behaviour must fulfil sustainability goals. To determine what actions (if any) need to be taken to ensure that the SOI's behaviour fulfils these goals, it is necessary to assess and then analyse the system's performance against the goals. In Stage 3, sustainability metrics of efficiency and effectiveness, and corresponding measures, were defined and evaluated to yield information on the SOI's performance against its sustainability goals (i.e. its sustainability performance). In Stage 4, this information was analysed to determine: (i) areas where sustainability performance needs to improve in order for the SOI to fulfil its sustainability goals; (ii) targets for the improvement of sustainability performance in these areas; and (iii) actions to be taken with respect to the inputs (of passive and active resources) and outputs (of intended resources, intended yield, and waste) in the SOI to drive its performance towards the defined sustainability performance targets. In Stage 5, the actions defined during Stage 4 are implemented, with the aim of bringing about improvement in the SOI's sustainability performance. To determine whether the actual improvement achieved by the SOI is sufficient to meet the sustainability performance targets, it is necessary to assess and then review the SOI's sustainability performance post-action. In Stage 5, the former activity is carried out. That is, post-action values are assigned to each of the sustainability metrics and measures defined in Stage 3.

3. Steps

1. *Implement the actions defined in Stage 4.*

   In Stage 4, a set of actions to be taken to improve the SOI's sustainability performance should have been determined and agreed upon by all relevant decision makers. These actions should have been defined in relation to the inputs of passive and active resources, and outputs of intended resources, intended yield, and waste in the SOI. The actions should now be implemented to alter the SOI's behaviour in these aspects, using appropriate tools and techniques wherever necessary.

2. *Assign post-action values to each metric and measure defined in Stage 3.*

   In Stage 3, initial values were assigned to each of the SOI's defined sustainability metrics and measures. Once the effects of actions taken on the SOI in Step 1 have been realised, post-action values should be assigned to these metrics and measures. That is, the data on sustainability performance that is required for each metric must be collected (i.e. the measures defined for each metric must be evaluated), following the same processes adopted in Stage 3. In turn, the SOI's sustainability metrics may be computed according to their formulae to yield post-action values that can be displayed and analysed.

3. *Present post-action values obtained for the SOI's sustainability metrics and measures.*

   In Stage 3, the initial values assigned to the SOI's sustainability metrics and measures were presented in a form that was appropriate for performance analysis in Stage 4. In Stage 5, once post-action values have been assigned to all of the SOI's sustainability metrics and measures, they should be presented in a form that is appropriate for review in Stage 6. Given that this activity focuses on determining whether the SOI has met its sustainability performance targets or not, it may be useful to present the post-action values alongside the initial values obtained in Stage 3, and the target values defined in Stage 4.

4. Outcomes

- The actions to improve the SOI's sustainability performance defined in Stage 4 should have been implemented.
- Knowledge should have been gained on the performance of the SOI against its sustainability goals in the form of post-action values for the defined sustainability metrics and measures.

5. Documentation

Post-action values assigned to the SOI's sustainability metrics and measures may be presented alongside the initial values obtained in Stage 3, and the targets defined in Stage 4, in the *S-Cycle Performance Review Table.* A copy of this table with example entries is provided at the end of Part 2. Additionally, an electronic copy is provided along with this guide.

STEP 6: REVIEWING THE OUTCOMES

1. Aim

To review the sustainability performance of the SOI, and capture any knowledge gained from applying the S-Cycle model.

2. Overview

In Stage 3, the performance of the SOI against its sustainability goals (i.e. its sustainability performance) was assessed. That is, initial values were assigned to each of the SOI's sustainability metrics and measures. In Stage 4, shortcomings in the performance of the SOI against its sustainability goals were identified, and targets for the improvement of sustainability performance in these areas were set. In turn, actions to be taken on the SOI (with respect to its inputs of passive and active resources, and outputs of intended resources, intended yield, and waste) to bring about this improvement were determined. In Stage 5, these actions were implemented and the performance of the SOI against its sustainability goals was assessed for a second time, yielding post-action values for each of the system's sustainability metrics and measures. In Stage 6, these post-action values are reviewed in relation to the targets set in Stage 4, to determine whether or not the targets have been met.

As discussed in Part 1 (Section 1.1), sustainability can be defined as the ability to maintain something *over time*. Therefore, to achieve sustainability, a system must continue to fulfil its sustainability goals over time. To ensure that the SOI continues to fulfil its sustainability goals, it is advisable to monitor its sustainability performance over time and set new performance targets where needed. This continuous monitoring may not be possible in the case of every system. However, where it is appropriate, a process for monitoring and periodically reviewing the SOI's sustainability performance is defined and implemented during Stage 6.

Finally, as discussed in Stage 2, having applied the S-Cycle model to a system at one level in a particular context, it may be desired to apply it to another system at a different level in future. For instance, if the model has been applied to a manufacturing system within an organisation, it may be desired in future to expand efforts to achieve sustainability by applying the model to the whole organisation. In applying the S-Cycle model to a particular SOI, decision makers gain knowledge on that system and its behaviour from the perspective of sustainability. Additionally, they gain knowledge on the process involved in applying the model, and on sustainability and its achievement generally. This knowledge may be useful in future efforts to apply the S-Cycle model, and may in fact be used to improve the process. To ensure that this knowledge is not lost, the specific outcomes of each stage in the process are reviewed during Stage 6, and any knowledge gained from each stage is captured.

3. Steps

1. *Determine whether targets for the improvement of the SOI's sustainability performance have been met.*

   As discussed above, targets to improve the sustainability performance of the SOI were set in Stage 4. In Stage 5, actions were taken on the SOI to bring about this improvement. To determine whether these actions have been effective in improving the SOI's sustainability performance, it is necessary to ascertain whether the sustainability performance targets have been met. To this end, the post-action values assigned to the SOI's sustainability metrics and measures in Stage 5 should be reviewed in relation to the targets defined in Stage 4.

   As discussed in Stage 4, sustainability performance targets should be formulated in line with 3B criteria. The second of these criteria specifies that targets should be time-bound, i.e. they should indicate the date by which the required sustainability performance is to be attained by the SOI. Thus, when considering whether targets have been met, it is important to consider the date that the measures for each metric were evaluated (that is, the date that data on the SOI's sustainability performance was collected), in addition to the actual values assigned to each metric and measure.

   If sustainability performance targets are found not to have been met, then it is important to (i) consider why this may be the case, and (ii) define new targets for the SOI. With respect to (i), relevant decision makers should identify and discuss potential reasons for any failure to meet targets. For example, upon discussion, the targets set in Stage 4 may be found to be overly challenging for the SOI, or the actions taken in Stage 5 may have simply been ineffective in improving performance. It is wise to record the outcomes of such discussions, to avoid identified reasons for failure being repeated in future. With respect to (ii), decision makers should return to Stage 4 in the process to analyse the post-action values obtained for the SOI's sustainability metrics and measures in greater detail. In turn, new sustainability performance targets may be set for the SOI, and new actions to improve performance may be defined.

2. *Define and implement a process for monitoring and periodically reviewing the SOI's sustainability performance, if appropriate.*

   As discussed above, to achieve sustainability, a system must continue to fulfil its sustainability goals over time. Thus, where possible and appropriate, the sustainability performance of the SOI should be monitored over time so that if necessary, new targets can be set to ensure that the system continues to fulfil its sustainability goals. To this end, it is necessary to define a process for monitoring and periodically reviewing the SOI's sustainability performance. This process should consist of mechanisms for: (i) continuously assessing the SOI's sustainability performance, i.e. regularly assigning values to the SOI's sustainability metrics and measures, and developing performance trends; and

(ii) periodically analysing these values and trends to determine whether the SOI is meeting its sustainability performance targets, and to define new targets if necessary. From a methodological perspective, it is also important to review the metrics and measures employed in the assessment of the SOI's sustainability performance. Specifically, it may be useful to ask:

- Are the right things being measured?
- Are these things being measured in the right way?
- Is the data on the SOI's sustainability performance being collected and displayed effectively?
- Is the data on the SOI's sustainability performance being analysed, and is action being taken on the basis of the findings?

More fundamentally, it is possible that the nature of the sustainability challenges for a particular SOI may change over time in response to, for instance, changes occurring in the system's environment. In turn, these changes would require the definition of new sustainability goals for the SOI. Thus, the SOI's sustainability goals and major sustainability challenges should also be reviewed periodically.

Any process for monitoring and periodically reviewing the SOI's sustainability performance should be discussed and agreed upon by all relevant decision makers. It is also wise to create a formal record of the process, to ensure that it: (i) is transparent and carried out in an objective manner; and (ii) may itself be periodically reviewed and improved where necessary.

3. *Review the process undertaken to apply the S-Cycle model to determine knowledge gained and lessons learned.*

As discussed previously, knowledge gained from applying the S-Cycle model to a particular SOI may be useful in future efforts to apply the model to other systems. It may also be used to improve the process involved in applying the model. Thus, the final step in Stage 6 focuses on discussing and capturing this knowledge, and considering the lessons learned from applying the S-Cycle model to the SOI.

During this step, relevant decision makers should discuss all stages undertaken in the process of applying the S-Cycle model, as well as the specific outcomes of each stage. In doing so, they should consider what knowledge was gained from each stage, and create and agree upon a formal record of this knowledge. When discussing and capturing knowledge gained from the process, it may be useful to consider the distinction between *tacit* knowledge, and *explicit* knowledge. The former refers to knowledge that may have been gained informally during the process and thus, be somewhat personal to the decision makers involved in the process. In contrast, the latter refers to knowledge that has been formalised during the process (e.g. in the supporting documentation). In light of these distinctions, it may be beneficial to interview decision makers directly involved in carrying out each stage, and to review the documentation associated with each stage. Additionally, it may be useful to make a distinction between knowledge that is (i) *generalisable* to other systems (and thus, may be used in future efforts to apply the S-Cycle model to other systems), and (ii) knowledge that is *contextual*, i.e. specific to the SOI (and thus, typically not reusable in the context of other systems).

When discussing the stages and their outcomes, consideration should also be given to any lessons learned during the process. That is, what has been learned from any mistakes made or failures occurring during the process. Again, these lessons learned should be formally recorded for future reference. The identification of lessons learned may be particularly useful with respect to improving the process of applying the S-Cycle model in future efforts.

4. Outcomes

- Sustainability performance targets set in Stage 4 should have been reviewed.
- A process for monitoring and periodically reviewing the SOI's (i) sustainability performance targets, (ii) sustainability metrics and measures, and (iii) sustainability goals should have been defined and agreed upon by all relevant decision makers, where appropriate.
- Knowledge gained from applying the S-Cycle model to the SOI should have been discussed by all relevant decision makers, and formally recorded.

5. Documentation

- The *S-Cycle Performance Review Table* may be filled out to provide a formal record of the outcomes of reviewing the SOI's sustainability performance targets, i.e. an indication of whether the targets were met, the reasons for any failure to meet targets, and the actions to be taken on the basis of this information. A copy of this table with example entries is provided at the end of Part 2. Additionally, an electronic copy is provided along with this guide.
- The *S-Cycle Learning Table* may also be filled out during this stage, to provide a formal record of the knowledge gained and lessons learned from applying the S-Cycle model to the SOI. Again, a copy of this table with example entries is provided at the end of Part 2. Additionally, an electronic copy is provided along with this guide.

S-Cycle Goal Table (example)

	No.	Behaviour considered	Goal defined	Rank	Originator	Agreed	Notes
Use of passive & active resources	1	Use of fossil fuels.	Minimise fraction of passive resource input that comes from fossil fuels.	2	LH	Y	
	2	Use of solar energy.	Maximise fraction of passive resource input that comes from solar energy.	1	JS	Y	
Production of IR	3	Production of electricity by generators.	Minimise energy losses in the generators.	4	JS	Y	
Production of IY	4	Production of product type X.	Maximise value of product type X for the customer.	5	LH	Y	
Production of W	5	Production of carbon dioxide.	Minimise CO2 emissions per unit of product type X produced.	3	LH	Y	

S-Cycle Metric Table (example)

No.	Sustainability goal	Metric	Measures	Measure units	Measure data source	Data collector	Metric formula	Metric units	Originators	Agreed	Notes
1	Minimise fraction of passive resource input that comes from fossil fuels.	Annual fossil fuel consumption as a % of total passive resource consumption	1. Amount of diesel consumed in one year	kilograms	Contact with purchasing department	LH	Annual fossil fuel consumption = (1 + 2) x 100/3	%	LH & JS	Y	
			2. Amount of oil consumed in one year	kilograms	Contact with purchasing department	JS					
			3. Total amount of passive resources consumed in one year	kilograms	Contact with purchasing department	LH					
2	Minimise CO2 emissions per unit of product type X produced.	Annual CO2 emissions per unit of product type X	1. Mass of CO2 emitted by system in one year	kilograms	Contact with environmental monitoring department	JS	Annual CO2 emissions per unit of product type X = 1/2	kilograms per unit	LH	Y	
			2. No. of units of product type X produced in one year	none	Contact with environmental monitoring department	JS					

S-Cycle Performance Improvement Table (example)

No.	Goal	Metric	Target	Actions to improve performance	Originator	Initiator	Agreed
1	Minimise fraction of passive resource input that comes from fossil fuels.	Annual fossil fuel consumption as a % of total passive resource consumption	Annual fossil fuel consumption = 20% of total passive resource consumption by 2 July 2013.	Identify and allocate renewable passive resources to replace fossil fuels consumed by system.	LH	JS	Y
2	Minimise CO2 emissions per unit of product type X produced.	Annual CO2 emissions per unit of product type X	Annual CO2 emissions = 100kg per unit of product type X by 2 July 2013.	Identify and eliminate major sources of CO2 in the system.	JS	JS	Y

S-Cycle Performance Review Table (example)

Sustainability goal	Metric	Initial value	Post-action value	Target	Target met?	Reasons for failure	Actions	Initiator
Minimise fraction of passive resource input that comes from fossil fuels.	Annual fossil fuel consumption as a % of total passive resource consumption	80% on 30 June 2012	70% on 2 July 2013	Annual fossil fuel consumption = 20% of total passive resource consumption by 2 July 2013.	N	Target too challenging	Define new target that is more realistic	LH
Minimise CO_2 emissions per unit of product type X produced.	Annual CO_2 emissions per unit of product type X	300 kg/unit on 30 June 2012	90 kg/unit on 2 July 2013	Annual CO_2 emissions = 100kg per unit of product type X by 2 July 2013.	Y	N/A	Define new target to reduce CO_2 emissions further	JS

S-Cycle Learning Table (example)

Stage	Knowledge gained		Mistakes/shortcomings	Lessons learned
	Generalisable knowledge	Contextual knowledge		
3	Knowledge on the process of defining sustainability metrics and measures.	The specific sustainability metrics and measures for the SOI.	Failure to define metrics of both efficiency and effectiveness for all goals.	Ensure that all decision makers have a thorough understanding of the E^2 performance model before defining sustainability metrics and measures.
	Knowledge on different kinds of metric.			
4	A method for analysing the sustainability performance of a system.	The specific sustainability performance targets for the SOI.	A high proportion of the targets defined for the SOI were found, upon review, to be too challenging.	Ensure that targets for a system's sustainability performance are set from an objective basis, and that all decision makers understand how to set realistic targets before sustainability performance targets are set.
	Knowledge on how to set realistic targets for a system's sustainability performance.			

PART 3: Glossary of terms

Term	Meaning	Example
Active resource	A resource that uses passive resources in activities [17].	Human beings, intelligent software, machinery
Activity	A goal-directed physical or cognitive action, where passive resources use active resources to produce an output that should satisfy the goals of the activity [17].	Design, development, production
Coherence	The notion that the goals for a particular system of interest should be aligned (i) *within* each set of goals; and (ii) *across* different sets of goals [15].	Sustainability goals for a system should be aligned (i) with one another, i.e. *within* the set; and (ii) with the system's conventional goals
Conventional goal	A system goal that does not pertain to sustainability.	Design goals in aspects such as function and technical performance, and business goals in aspects such as cost and value
E^2 performance model	A model demonstrating that performance is completely described in the elements of efficiency and effectiveness [15].	N/A
Effectiveness	One of two fundamental components of performance, describing the degree to which the result/output meets the goal [15].	N/A
Efficiency	One of two fundamental components of performance, describing the relationship between what has been gained and the level of resource used in delivering the gain [15].	N/A
Goal	A goal refers to a future situation, that is perceived by the originator to be more desirable than the current situation [15].	Please see the entry "Sustainability goal" for examples of goals.
Intended resources	The fraction of an activity's output that is intended to be used as passive and/or active resources in the activity itself [1].	A production activity may produce electricity that can be reused in the activity itself as an energy source (i.e. passive resource).
Intended yield	The fraction of an activity's output that is intended to be yielded to the wider system, to either contribute to resource stocks in the system, or to be used directly as passive and/or active resources in other	A design activity may produce outputs such as products, services, and systems as yield to be used by humans in a range of different activities.

	activities within the system [1].	
Measure	An item of data required in order to evaluate a sustainability metric [18].	Please see the entry "Sustainability metric" for an example of a measure.
Non-renewable resource	An active or a passive resource originating from a stock that does not regenerate over time.	Fossil fuels such as coal, oil, and gas
Passive resource	A resource that is used by active resources in activities [17].	Knowledge, physical materials such as paper, plastic, stone, etc.
Renewable resource	An active or a passive resource originating from a stock that regenerates over time.	Solar energy, timber, water
S-Cycle model	A generic model of sustainability that may be used as a tool to support the analysis of system behaviour from the perspective of sustainability.	N/A
Sustainability	The ability to maintain something over time [1].	N/A
Sustainability goal	A goal that directs system behaviour towards maintaining some chosen target entity [1].	"Minimise the use of non-renewable resources," "Maximise the use of renewable resources"
Sustainability metric	A system parameter used to quantify the performance of a system against its sustainability goals.	*Metric:* economic resource productivity *Metric formula:* Gross Domestic Product ÷ Domestic Material Consumption *Measures:* (i) Gross Domestic Product; and (ii) Domestic Material Consumption
Sustainability performance	The performance of a system against its sustainability goals.	N/A
Sustainability performance target	A target for the improvement of a system's sustainability performance.	Resource productivity of 70% by 1 July 2013.
System	A "collection of elements […] that are each interrelated with at least one other, and which possesses properties different from the collection of properties of the individual parts" [33].	Economies, organisations, production systems, societies
System of interest	The system that the S-Cycle model is being applied to (i.e. a system considered by decision makers to have significant challenges from the perspective of sustainability).	An organisational system, a technical system
Target	Quantifiable "required values of measures that define desired	Please see the entry, "Sustainability performance

	performance/progress" [18].	target" for an example of a target.
Target entity	An entity, or some aspect of an entity, that is desired to be maintained over time [1].	A system attribute, capability, or function, and whole systems
Waste	The fraction of an activity's output that is intended neither as yield nor resources and as such, has no utility in relation to the activity [1].	Excess materials and energy, noxious fumes, obsolete products

PART 4: References

[1] L. Hay, A. Duffy, R.I. Whitfield, Modelling and understanding sustainability, Journal of Environmental Management. (2013).

[2] United Nations Environment Programme, GEO5 - Environment for the future we want, United Nations Environment Programme, Valletta, Malta, 2012.

[3] A. Voinov, Understanding and communicating sustainability: global versus regional perspectives, Environment, Development and Sustainability. 10 (2007) 487–501.

[4] S. Lele, R.B. Norgaard, Sustainability and the Scientist's Burden, Conservation Biology. 10 (1996) 354–365.

[5] J. Chapman, Emotionally Durable Design, 3rd ed., Earthscan, London, Washington DC, 2011.

[6] M. Reber, A theory of value in design, University of Strathclyde, 2011.

[7] G.R. Conway, Agroecosystem analysis for research and development, Winrock International, Bangkok, 1986.

[8] Eurostat, Sustainable development in the European Union - 2011 monitoring report of the EU sustainable development strategy, Publications Office of the European Union, Luxembourg, 2011.

[9] D.C. Wahl, S. Baxter, The Designer's Role in Facilitating Sustainable Solutions, Design Issues. 24 (2008) 72–83.

[10] B.S. Blanchard, W.J. Fabrycky, Systems Engineering and Analysis, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1981.

[11] A.B. Urken, A. "Buck" Nimz, T.M. Schuck, Designing evolvable systems in a framework of robust, resilient and sustainable engineering analysis, Advanced Engineering Informatics. 26 (2012) 553–562.

[12] B. Gagnon, R. Leduc, L. Savard, From a conventional to a sustainable engineering design process: different shades of sustainability, Journal of Engineering Design. 23 (2012) 49–74.

[13] T.M. Parris, R.W. Kates, Characterizing a sustainability transition: goals, targets, trends, and driving forces, Proceedings of the National Academy of Sciences of the United States of America. 100 (2003) 8068–73.

[14] N. Quental, J.M. Lourenço, F.N. da Silva, Sustainable Development Policy: Goals, Targets and Political Cycles, Sustainable Development. 19 (2011) 15–29.

[15] F.J. O'Donnell, A.H.B. Duffy, Design Performance, Springer-Verlag, London, 2005.

[16] S. Derissen, M.F. Quaas, S. Baumgärtner, The relationship between resilience and sustainability of ecological-economic systems, Ecological Economics. 70 (2011) 1121–1128.

[17] I.M. Boyle, A.H.B. Duffy, R.I. Whitfield, S. Liu, Towards an understanding of the impact of resources on the design process, in: 17th International Conference on Engineering Design (ICED `09), The Design Society, Stanford, 2009.

[18] A. Duffy, Design process and performance, in: J. Clarkson, M. Huhtala (Eds.), Engineering Design - Theory and Practice, A Symposium in Honour of Ken Wallace, Engineering Design Centre, University Of Cambridge, 2005: pp. 76–85.

[19] R. Costanza, H.E. Daly, Natural Capital and Sustainable Development, Conservation Biology. 6 (1992) 37–46.

[20] P. Ekins, Environmental sustainability: From environmental valuation to the sustainability gap, Progress in Physical Geography. 35 (2011) 629–651.

[21] C.C. Williams, A.C. Millington, The diverse and contested meanings of sustainable development, The Geographical Journal. 170 (2004) 99–104.

[22] M.. Brown, S. Ulgiati, Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation, Ecological Engineering. 9 (1997) 51–69.

[23] D.E. Campbell, A.S. Garmestani, An energy systems view of sustainability: emergy evaluation of the San Luis Basin, Colorado, Journal of Environmental Management. 95 (2012) 72–97.

[24] H.E. Daly, Toward some operational principles of sustainable development, Ecological Economics. 2 (1990) 1–6.

[25] W. Liao, R. Heijungs, G. Huppes, Is bioethanol a sustainable energy source? An energy-, exergy-, and emergy-based thermodynamic system analysis, Renewable Energy. 36 (2011) 3487–3479.

[26] N. Marchettini, R. Ridolfi, M. Rustici, An environmental analysis for comparing waste management options and strategies., Waste Management. 27 (2007) 562–71.

[27] H. Yang, Y. Li, J. Shen, S. Hu, Evaluating waste treatment, recycle and reuse in industrial system: an application of the eMergy approach, Ecological Modelling. 160 (2003) 13–21.

[28] X. Zhang, S. Deng, Y. Zhang, G. Yang, L. Li, H. Qi, et al., Emergy evaluation of the impact of waste exchanges on the sustainability of industrial systems, Ecological Engineering. 37 (2011) 206–216.

[29] S. Barles, Society, energy and materials: the contribution of urban metabolism studies to sustainable urban development issues, Journal of Environmental Planning and Management. 53 (2010) 439–455.

[30] M.A. Rosen, I. Dincer, M. Kanoglu, Role of exergy in increasing efficiency and sustainability and reducing environmental impact, Energy Policy. 36 (2008) 128–137.

[31] I.M. Boyle, A.H.B. Duffy, R.I. Whitfield, S. Liu, The impact of resources on decision making, Artificial Intelligence for Engineering Design, Analysis and Manufacturing. 26 (2012) 407–423.

[32] L. Hay, A. Duffy, R.I. Whitfield, Rationalising sustainability performance, Journal of Cleaner Production. (2013).

[33] B. Thomé, Definition and Scope of Systems Engineering, in: B. Thomé (Ed.), Systems Engineering: Principles and Practice of Computer-based Systems Engineering, John Wiley & Sons Ltd., Chichester, 1993: pp. 1–23.

Appendix 8B: Guideline documentation from case studies 1 and 3

As discussed in Chapter 7 (Sections 7.1.3.1 and 7.1.3.3), both Students A and B filled out guideline documentation to record goals, metrics, and suggested actions to improve the sustainability performance of the systems studied during CS1 and CS3. The completed documentation is presented below.

Student A documentation (CS1, HVAC system):

A.1. S-Cycle Goal Table

	No.	Behaviour considered	Goal defined	Rank
Use of passive & active resources	1	Consumption of Electrical Energy	Minimise consumption of electrical power to produce a X value of cooling/heating power	2
	2	Consumption of Refrigerant	Minimise the mass of refrigerant harmful to the environment	1
Production of IR	3	Production of fresh air by the HVAC system	Maximise the volume of fresh air produced	5
Production of IY	4	Production of Cooling Power	Maximise the cooling power for a fixed electrical power	6
	5	Production of Heating Power	Maximise the heating power for a fixed electrical power	7
Production of W	6	Emissions of CO_2	Minimise the emissions of CO_2 per m^3 of fresh air produced	3
	7	Use of non-recyclable materials	Minimise the weight of components using non-recyclable materials	4

A.2. S-Cycle Metric Table for Railcool D228-348 System

S-Cycle Metric Table

SYSTEM: RAILCOOL D228-348

No.	Sustainability goal	Metric	Measures	Measure units	Measure Result	Metric	Metric units	Metric Result
1	Minimize consumption of electrical power to produce a X value of cooling/heating power	Consumption in cooling mode in regards to the maximal electrical power of the system	1-Maximal Electrical Consumption in Cooling	kW	26	1/2	none	0.650
			2-Maximal Electrical Power	kW	40			
		Consumption in heating mode in regards to the maximal electrical power of the system	1-Maximal Electrical Consumption in Heating	kW	32	1/2	none	0.800
			2-Maximal Electrical Power	kW	40			
2	Minimize the mass of refrigerant harmful to the environment	Refrigerant Characteristics (as replacement for the data on refrigerant mass which is missing)	1-ODP	none	0	Measure taken as metric	none	0.000
			2-GWP	none	1600			1600.000
3	Maximize the volume of fresh air produced	Air flow in cooling mode in regards to the electricity consumption	1-Maximal air flow	m3	4400	1/2	m3/kW	169.231
			2-Maximal electricity consumption in cooling mode	kW	26			
		Air flow in heating mode in regards to the electricity consumption	1-Maximal air flow	m3	4400	1/2	m3/kW	137.500
			2-Maximal electricity consumption in heating mode	kW	32			

4	Maximize the cooling power for a fixed electrical power	Cooling Power and corresponding electrical energy consumption	1-Maximal Cooling Power	kW	40	1/2	none	1.538
			2-Maximal electricity consumption in cooling mode	kW	26			
5	Maximize the heating power for a fixed electrical power	Heating Power and corresponding electrical energy consumption	1-Maximal Heating Power	kW	30	1/2	none	0.938
			2-Maximal electricity consumption in heating mode	kW	32			
6	Minimize the emissions of CO2 per m3 of fresh air produced	Annual CO2 production per m3 of fresh air produced	Mass of CO2 produced each year	kgs	NO DATA			
			m3 of fresh air produced/year	m3				
7	Minimize the weight of components using non-recyclable materials	Quantity of non-recyclable materials used	Weight of non-recyclable material in use	kgs				

A.3. S-Cycle Metric Table for ICE3 HVAC Sytem

S-Cycle Metric Table

SYSTEM: ICE3 HVAC SYSTEM

No.	Sustainability goal	Metric	Measures	Measure units	Measure Result	Metric	Metric units	Metric Result
1	Minimise consumption of electrical power to produce a X value of cooling/heating power	Consumption in cooling mode in regards to the maximal electrical power of the system	1-Maximal Electrical Consumption in Cooling	kW	21	1/2	none	0.467
			2-Maximal Electrical Power	kW	45			
		Consumption in heating mode in regards to the maximal electrical power of the system	1-Maximal Electrical Consumption in Heating	kW	30	1/2	none	0.667
			2-Maximal Electrical Power	kW	45			
2	Minimise the mass of refrigerant harmful to the environment	Refrigerant Characteristics (as replacement for the data on refrigerant mass which is missing)	1-ODP	none	0	Measure taken as metric	none	0.000
			2-GWP	none	0			0.000
3	Maximise the volume of fresh air produced	Air flow in cooling mode in regards to the electricity consumption	1-Maximal air flow	m3	3400	1/2	m3/kW	161.905
			2-Maximal electricity consumption in cooling mode	kW	21			
		Air flow in heating mode in regards to the electricity consumption	1-Maximal air flow	m3	3400	1/2	m3/kW	113.333
			2-Maximal electricity consumption in heating mode	kW	30			
4	Maximise the cooling power for a fixed electrical power	Cooling Power and corresponding electrical energy consumption	1-Maximal Cooling Power	kW	35	1/2	none	1.667
			2-Maximal electricity consumption in cooling mode	kW	21			
5	Maximise the heating power for a fixed electrical power	Heating Power and corresponding electrical energy consumption	1-Maximal Heating Power	kW	27	1/2	none	0.900
			2-Maximal electricity consumption in heating mode	kW	30			
6	Minimise the emissions of CO2 per m3 of fresh air produced	Annual CO2 production per m3 of fresh air produced	Mass of CO2 produced each year	kgs	NO DATA			
			m3 of fresh air produced/year	m3				
7	Minimise the weight of components using non-recyclable materials	Quantity of non-recyclable materials used	Weight of non-recyclable material in use	kgs				

A.4. S-Cycle Performance Improvement Table

No.	Goal	Metric	Target	Actions to improve performance
1	Maximize the volume of fresh air produced in cooling mode	Air flow in cooling mode in regards to the electricity consumption	169,2308	Actions for those three sustainability goals have to be taken early in the design phase. It is not possible to modify them in the use phase. The actions would focus on increasing efficiency of compressor, turbine and heat exchangers.
2	Maximize the volume of fresh air produced in heating mode	Air flow in heating mode in regards to the electricity consumption	137,5	
3	Maximize the heating power for a fixed electrical power	Heating Power and corresponding electrical energy consumption	0,9375	
4	Minimise the emissions of CO2 per m3 of fresh air produced	Annual CO2 production per m3 of fresh air produced	Reduction in %	Data missing to set a target and defining the actions to take.
5	Minimise the weight of components using non-recyclable materials	Quantity of non-recyclable materials used	Reduction in %	

Student B documentation (CS3, CW plant system):

I. PERFORMANCE CRITERIA

1. Performance Criteria Table

	No.	Behaviour considered	Goal defined	Rank	Agreed	Notes
Use of passive and active resources	1	Use of renewable resources with high environmental effect	Minimise the use of oil per kW of heat transfer	/		
	2	Use of renewable resources with high environmental effect	Minimise the use of refrigerant per kW of heat transfer	/		
	3	Use of Electricty	Minimise the use of electricity per kW of heat transfer	1		
Production of Intended Resources						
Production of Intended Yield	4	Production of Chilled Water	Achieved the cooling effect at the lowest price	2		
Production of Waste	5	Oil Losses	Minimise oil losses per kW of heat transfer	4		
	6	Refrigerant Losses	Minimise refrigerant losses per kW of heat transfer	5		
	7	Release of hazardous gases into the atmosphere	Minimise the Global Warming Impact per kW of heat transfer	3		
	8	Release of Hot Water in the Sea	Minimise the release of hot water in the sea per kW of heat transfer	/		

Rank	Sustainable Goal	Metric	Measures	Measure units	Measure data source	Freq.	Metric formula	Metric units	Agreed	Notes
1	Minimise the use of electricity per kW of	Coefficient of Performance	1. Cooling Capacity of the CWP	kW	Define by test plant reports	/	COP = 1/2	%	Y	
			2. Compressor Shaft Power	kW	Define by test plant reports	/				
2	Achieved the cooling effect at the lowest price	Cost Index	1. Consumption of Refrigerant per kW of heat transfer	kg/H/hkW	Refrigerant consumption defined by the model.	/	Cost Index = 1*2+3*4+5*6+7	£/H/hkW	Y	Carburant, refrigerant and oil consumption has been defined thanks to a model. This model has been built thanks to 'Test Plant Performance Report' supplied by the company.
			2. Price of refrigerant	£/kg	Benchmarking on suppliers price	/				
			3. Consumption of oil per hkW	L/H/hkW	Oil consumption per kW is defined by the model. The price has been defined by a benchmarking	/				
			4. Price of oil	£/L	Benchmarking on suppliers price	/				
			5. Consumption of carburant per hkW	L/H/hkW	Carburant consumption is defined by the model.	/				
			6. Carburant price	£/L	Benchmarking on suppliers price	/				
			7. Operation cost	£/H/hkW	Contact with engineers and sub-contractors of CWP	/				
3	Minimise the Global Warming Impact per hkW	Environmental Impact Index	1. Consumption of Refrigerant per hkW	kg/H/kW	Refrigerant consumption is defined by the model	/	EII = 1*2+3*4	kg of CO2 per hour and per hkW	Y	
			2. GWP of the refrigerant	kg of CO2/kg	Information collected from report	/				
			3. Consumption of carburant per hkW	L/H/hkW	Carburant consumption is defined by the model	/				
			4. GWP of the carburant	kg of CO2/kWh	Information collected from report	/				
4	Minimise oil losses per hkW	Consumption of oil	1. Consumption of oil per hkW	L/H/kW	Define by the model	/	Consumption of oil = 1	L/H/kW	Y	
5	Minimise refrigerant losses per hkW	Consumption of refrigerant	1. Consumption of Refrigerant per hkW	kg/H/kW	Define by mathematical mode	/	Consumption of refrigerant = 1	kg/H/kW	Y	

Appendix 9: Sustainability interpretation of CW system function model

As discussed in Section 7.1.3.2 (Chapter 7), the S-Cycle interpretation of the CW system function model developed during case study 2 (CS2) was captured in a spreadsheet. An excerpt from this is presented below, to convey the interpretation process.

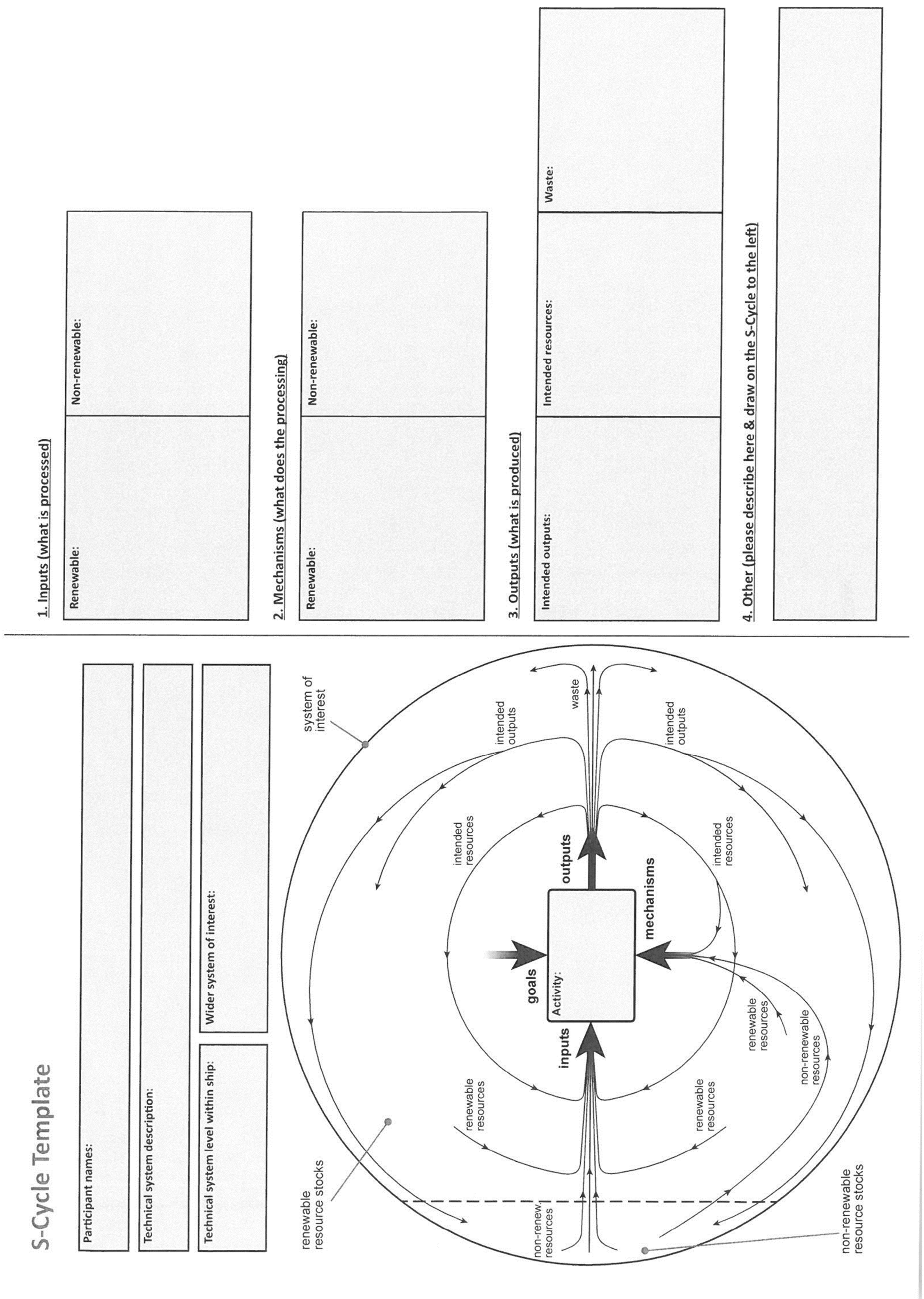
Activity being interpreted	Node	Box ID	Major sub-activities	Node	Box ID	IDEF0 input [1]	Originating/replenishing stock within SOI	S-Cycle classification [5]	IDEF0 mechanism [2]	Originating/replenishing stock within SOI	S-Cycle classification [5]	IDEF0 output [4]	Destination within SOI	S-Cycle classification [5]
Remove waste heat from equip. aboard ship	A-0	N/A	Absorb waste heat from CW users	A0	1	Demin. water	Stock of water in demin. water storage tank aboard ship	R-PR	Humans	Ship's staff, which can be R-at-S (although rare)	R-AR	Flow of warm sea water o/b	Sea	R-IY
			Control & configure CWS		2	Sea water	Sea	R-PR	CWS control sys.	Stock of CWS equipment aboard ship	NR-AR	Energy & material losses	CWS environment	W
			Accumulate & store cooling medium		3	Refrigerant	Stock of refrigerant aboard ship, which can be R-at-S.	R-PR	CWS equip.	Stock of CWS equipment aboard ship	NR-AR	Unwanted air	Atmosphere	W
			Circulate cooling medium in CWS		4	Oil	Stock of oil aboard ship, which can be R-at-S.	R-PR	CW users	Stock of equipment aboard ship	NR-AR			
			Chill cooling medium		5	Electricity	Stock of diesel in ship's fuel tank	R-PR						
						Waste heat	Stock of diesel in ship's fuel tank	R-PR						
						Human control interface	Stock of CWS equipment aboard ship	NR-PR						
Absorb waste heat from CW users	A0	1	None	N/A	N/A	CW flow & supply temp.	Energy originates from stock of diesel in ship's fuel tank; water is replenished by stock of demin. water in ship's storage tank	R-PR	CW users	Stock of CW user equip. aboard ship	NR-AR	CW flow & return temp.	Input to Box 4 in A0	Ac-IY
Control & configure CWS	A0	2	Trigger remote control signals	A2	1	Human control interface	Stock of CWS equipment aboard ship	NR-PR	Humans	Ship's staff, which can be R-at-S (although rare)	R-AR	CWS configuration	N/A	N/A
			Start/stop CW plants		2	Local control mechs.	Stock of CWS equipment aboard ship	NR-PR	CWS control sys.	Stock of CWS equipment aboard ship	NR-AR			
			Adjust cooling capacity of CW plants		3	Electricity to CWS control sys.	Stock of diesel in ship's fuel tank	R-PR	Controllable CWP equip.	Stock of CWS equipment aboard ship	NR-AR			
			Start/stop CW circ. pumps		4				Controllable CW circ. sys. equip.	Stock of CWS equipment aboard ship	NR-AR			
			Configure CW flow path		5									
Accumulate & store cooling medium	A0	3	None	N/A	N/A	Air	Atmosphere (via LP air system), and stock of water in demin. water storage tank aboard ship	R-PR	H-tank equip.	Stock of CWS equipment aboard ship	NR-AR	Info on H-tank pressure	N/A	N/A
						Water for storage in H-tanks	Stock of water in demin. water storage tank aboard ship	R-PR				Flow of water between H-tanks & CW circ. sys.	Input to Box 4 in A0	Ac-IY
Circulate cooling medium in CWS	A0	4	Maintain flow of cooling medium in CWS	A4	1	CW flow & return temp.	Energy originates from stock of diesel in ship's fuel tank; water is replenished by stock of demin. water in ship's storage tank	R-PR	CW circ. sys. equip.	Stock of CWS equipment aboard ship	NR-AR	Info on state of CW circ. sys.	N/A	N/A
			Remove air from cooling medium		2	Air bubbles in CW circ. sys.	Atmosphere	Possibly new category of "input waste"				Air from vacuum degassers	Atmosphere	W
			Contain & direct flow of cooling medium		3	Electricity to CW circ. sys. equip.	Stock of diesel in ship's fuel tank	R-PR				CW flow & return temp.	Input to Box 5 in A0	Ac-IY
			Provide info on state of CW circ. sys.		4							Water losses from CW circ. sys.	CWS environment	W
												Energy losses in CW circ. sys.	CWS environment	W
Chill cooling medium	A0	5	Chill cooling medium in CW plant 1	A5	1	CW flow & return temp.	Energy originates from stock of diesel in ship's fuel tank; water is replenished by stock of demin. water in ship's storage tank	R-PR	CWP equip.	Stock of CWS equipment aboard ship	NR-AR	Info on state of CWP equip.	N/A	N/A
			Chill cooling medium in CW plant 2		2	Electricity to CWP equip.	Stock of diesel in ship's fuel tank	R-PR				Refrig. losses from CWP equip.	CWS environment	W
			Chill cooling medium in CW plant 3		3	Oil in CWP compressors	Stock of oil aboard ship, which can be R-at-S.	R-PR				Energy losses in CWP equip.	CWS environment	W
			Chill cooling medium in CW plant 4		4	Flow of sea water (cool)	Energy originates from stock of diesel in ship's fuel tank; water originates from sea	R-PR				Flow of warm sea water o/b from CWPs	Sea	W
			Insulate cooling medium flow		5	Refrig. in CWPs	Stock of refrigerant aboard ship, which can be R-at-S.	R-PR				CW flow & supply temp.	Input to Box 1 in A0	Ac-IY

Appendix 10: Workshop documentation

Appendix 10A: Final versions of practical exercise, questionnaire, and activity set

As discussed in Chapter 7 (Section 7.2), 27 engineering designers participated in the expert appraisal workshops (WS1 and WS2). During the workshops, they completed a practical exercise in groups, and filled out a self-report questionnaire individually. Additionally, groups of participants in WS1 carried out an exercise to check the author's S-Cycle interpretation of the CW system function model developed during case study 2 (CS2). The S-Cycle template used during the practical exercise, the questionnaire, and an example of the format adopted for the activity sets used in the checking exercise are presented overleaf.

1. S-Cycle template



2. Questionnaire

University of Strathclyde
Engineering

Feedback questionnaire

Please rate the following aspects of the S-Cycle model by circling your response. If you have specific comments to add, please write them in the box provided.

1. Ease of understanding

Poor	Fair	No opinion	Good	Excellent

Comments:

2. Ease of use as a tool for interpreting the behaviour of a technical system

Poor	Fair	No opinion	Good	Excellent

Comments:

3. Effectiveness as a tool for explaining the concept of sustainability

Poor	Fair	No opinion	Good	Excellent

Comments:

4. Comprehensiveness in describing the physical aspects of a technical system's behaviour

Poor	Fair	No opinion	Good	Excellent

Comments:

3. Format of activity sets used to check the interpretation of the CW system function model

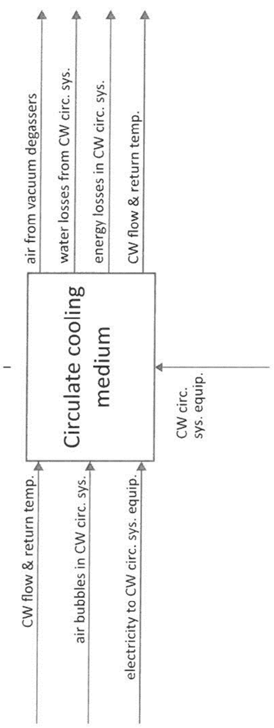
3

1. INPUTS

No.	Description	S-Cycle classification	Agree/ disagree?	Comments
1	CW flow & return temp.	renewable resource		
2	air bubbles in CW circ. sys.	unwanted input		
3	electricity to CW circ. sys. equip.	renewable resource		

3. OUTPUTS

No.	Description	S-Cycle classification	Agree/ disagree?	Comments
1	air from vacuum degassers	waste		
2	water losses from CW circ. sys.	waste		
3	energy losses in CW circ. sys.	waste		
4	CW flow & return temp.	intended output		



2. MECHANISMS

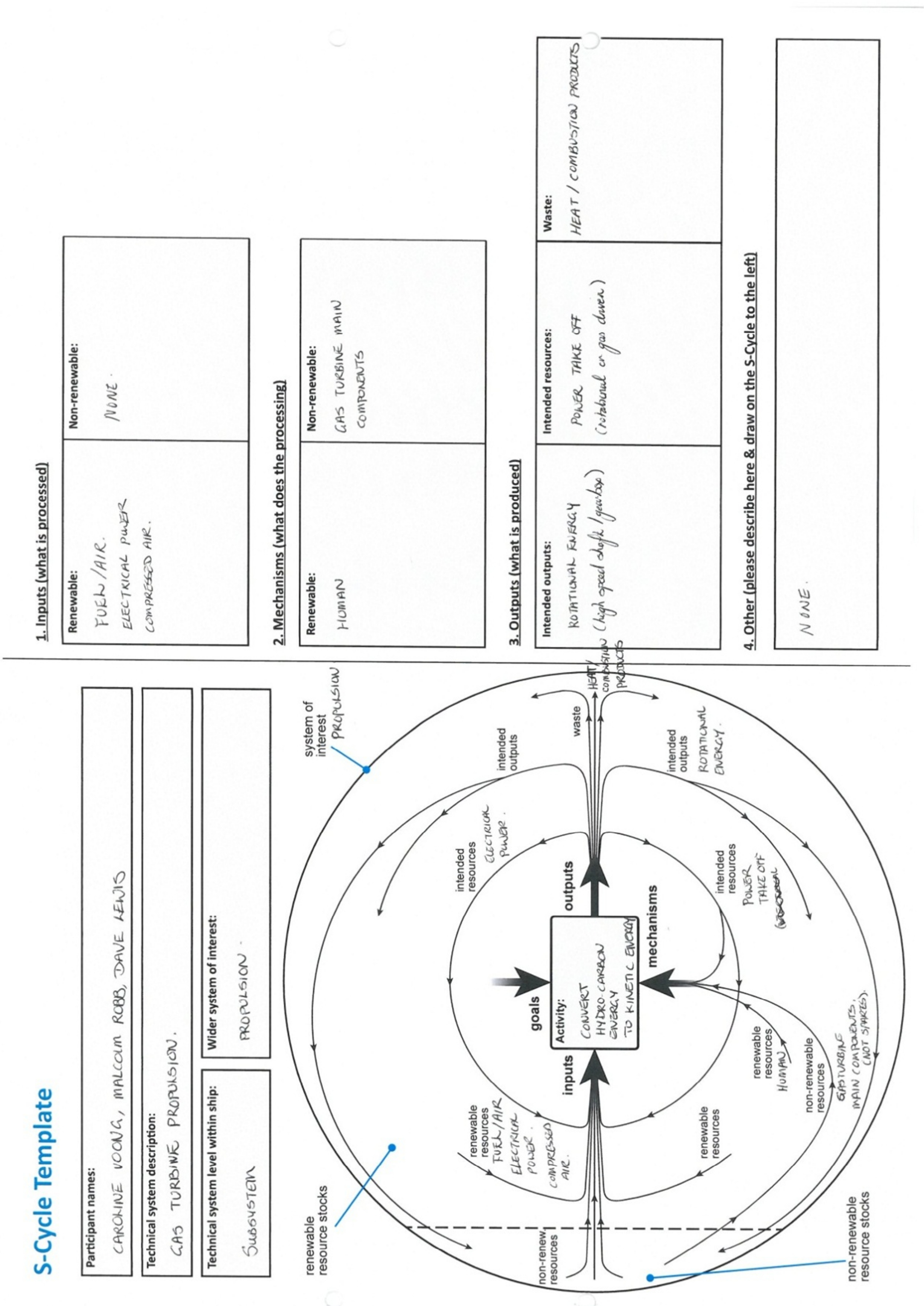
No.	Description	S-Cycle classification	Agree/ disagree?	Comments
1	CW circ. sys. equip.	non-renewable resource		

Appendix 10B: Examples of output from workshops 1 and 2

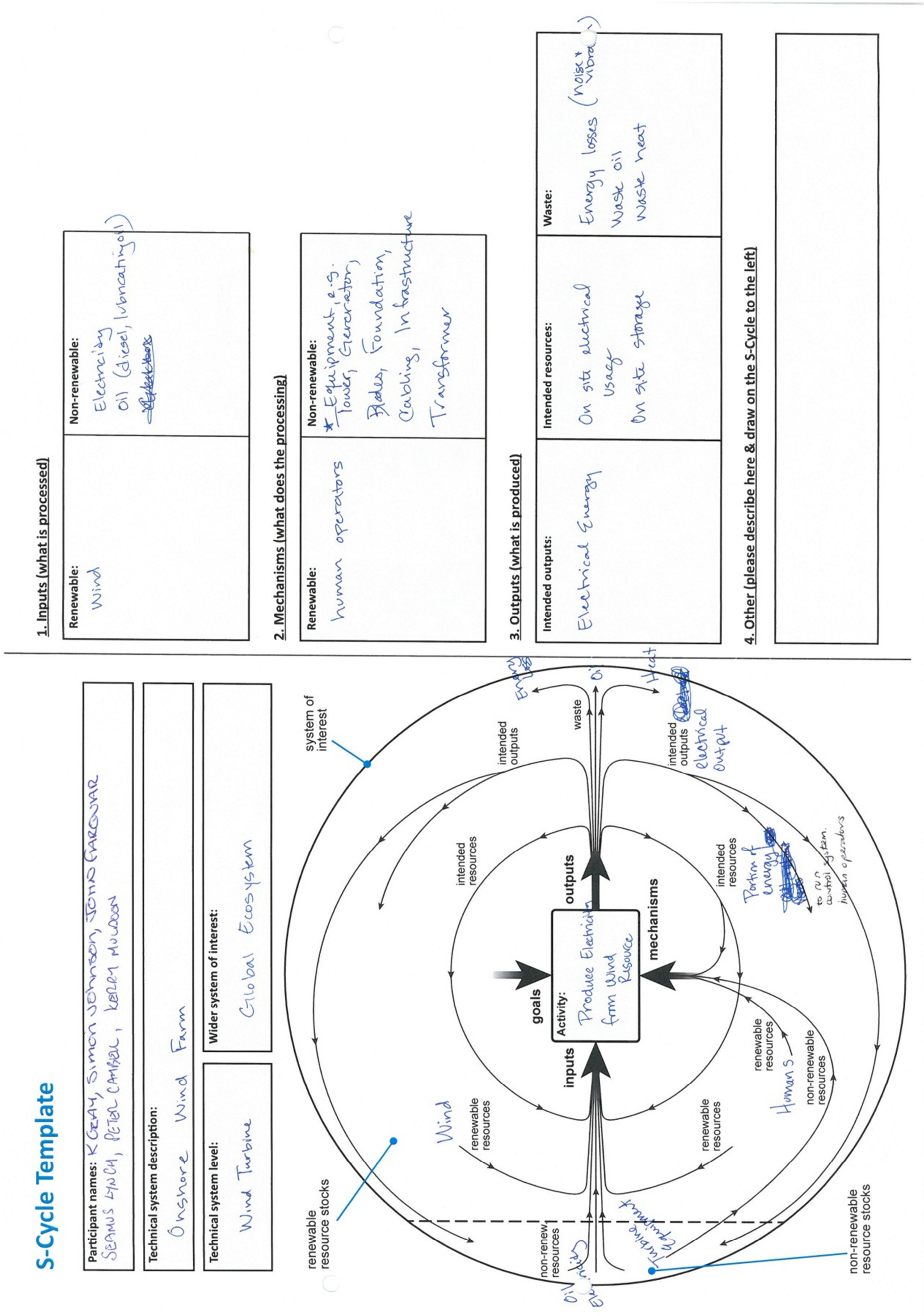
Owing to the number of participants in the workshops (i.e. 27 in total across the two workshops), coupled with space limitations, it is not possible to present all of the output generated by participants. However, the following are presented overleaf for the purposes of example: one completed S-Cycle template from the practical exercise delivered at each workshop; one completed questionnaire from each workshop; and one completed activity set from the function model checking exercise conducted at WS1.

1. Examples of completed S-Cycle templates

Workshop 1:



Workshop 2:


S-Cycle Template
Participant names: K GRAY, SIMON JOHNSON, JOHN FARQUHAR, SEAMUS LYNCH, PETER CAMPBELL, KERRY MULDOON
Technical system description: Onshore Wind Farm
Technical system level: Wind Turbine
Wider system of interest: Global Ecosystem
1. Inputs (what is processed)
Renewable: Wind
Non-renewable: Electricity, Oil (diesel, lubricating oil)
2. Mechanisms (what does the processing)
Renewable: human operators
Non-renewable: * Equipment, e.g. Tower, Generator, Blades, Foundation, Cabling, Infrastructure, Transformer
3. Outputs (what is produced)
Intended outputs: Electrical Energy
Intended resources: On site electrical usage, On site storage
Waste: Energy losses (noise + vibration), Waste oil, Waste heat
4. Other (please describe here & draw on the S-Cycle to the left)
Activity: Produce Electricity from Wind Resource
inputs
goals
outputs
mechanisms
system of interest
renewable resource stocks
non-renewable resource stocks
renewable resources
non-renewable resources
intended resources
intended outputs
waste
Wind
Humans
electrical output
Heat
Energy
Oil
Electricity

2. Examples of completed questionnaires

Workshop 1:

University of Strathclyde Engineering

Feedback questionnaire

Please rate the following aspects of the S-Cycle model by circling your response. If you have specific comments to add, please write them in the box provided.

1. Ease of understanding

Poor	Fair	No opinion	Good	Excellent
				(circled)

Comments:

2. Ease of use as a tool for interpreting the behaviour of a technical system

Poor	Fair	No opinion	Good	Excellent
			(circled)	

Comments: But you don't necessarily want or expect an analytical tool to be easy to use – must match the complexity of the problem

3. Effectiveness as a tool for explaining the concept of sustainability

Poor	Fair	No opinion	Good	Excellent
				(circled)

Comments:

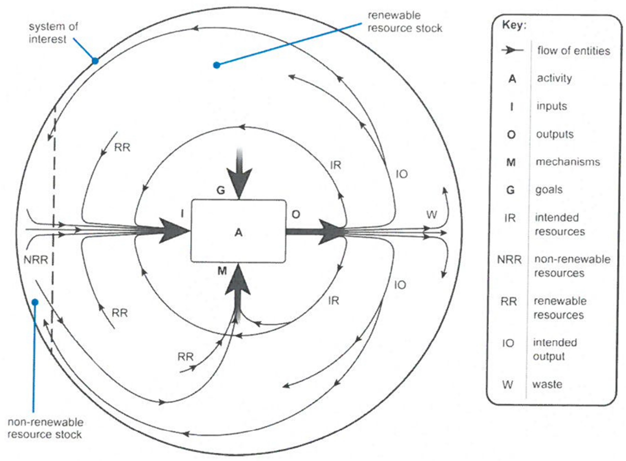
4. Comprehensiveness in describing the physical aspects of a technical system's behaviour

Poor	Fair	No opinion	Good	Excellent
			(circled)	**(circled)**

Comments: Unsure – would need to look at it longer but seemed to be comprehensive.

Workshop 2:

A. Please rate the following aspects of the S-Cycle model by circling your response. If you have specific comments to add, please write them in the box provided.



A1. Ease of understanding.

Poor	Fair	No opinion	Good	Excellent

Comments:
I think this is easy to understand, However, defining the system ~~is~~ and any assumptions is key.

A2. Effectiveness as a tool for interpreting a technical system's behaviour from a sustainability perspective.

Poor	Fair	No opinion	Good	Excellent

Comments:
Would need to see a more detailed example to judge. Feel this could be very useful with modelling/ it's to back up the diagram, but I don't know at present.

A3. Effectiveness as a tool for explaining the concept of sustainability.

Poor	Fair	No opinion	Good	Excellent

Comments:
Potentially good if system definition/assumptions explained. Again, would apply points from A2, as I am not sure my understanding is enough

A4. Coverage of the sustainability aspects of a technical system's behaviour.

Poor	Fair	No opinion	Good	Excellent

Comments:

3. Example of completed activity set from WS1

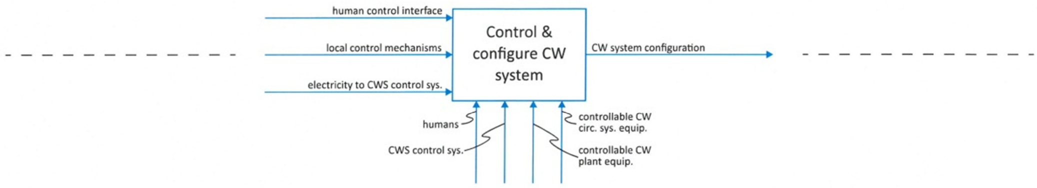
1

1. INPUTS

No.	Description	S-Cycle classification	Agree/ disagree?	Comments
1	human control interface	non-renewable resource	Agree.	
2	local control mechanisms	non-renewable resource	✓ Agree	
3	electricity to CWS control sys.	renewable resource	Agree.	

3. OUTPUTS

No.	Description	S-Cycle classification	Agree/ disagree?	Comments
Output is informational & therefore excluded from S-Cycle interpretation.				



2. MECHANISMS

No.	Description	S-Cycle classification	Agree/ disagree?	Comments
1	humans	renewable resource	Agree.	
2	CWS control sys.	non-renewable resource	Agree.	
3	controllable CW plant equip.	non-renewable resource	Agree.	
4	controllable CW circ. sys. equip.	non-renewable resource	Agree.	

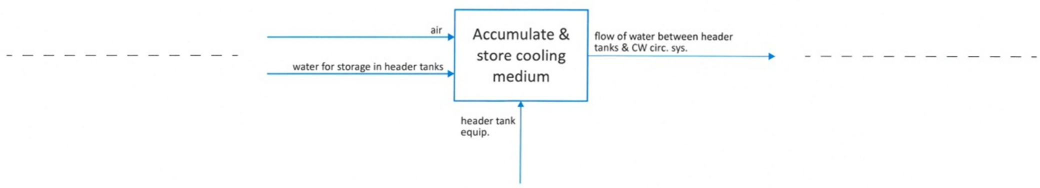
2

1. INPUTS

No.	Description	S-Cycle classification	Agree/ disagree?	Comments
1	air	renewable resource	Agree.	
2	water for storage in header tanks	renewable resource	Agree.	

3. OUTPUTS

No.	Description	S-Cycle classification	Agree/ disagree?	Comments
1	flow of water between header tanks & CW circ. sys.	intended output	Agree.	



2. MECHANISMS

No.	Description	S-Cycle classification	Agree/ disagree?	Comments
1	header tank equip.	non-renewable resource	Agree.	

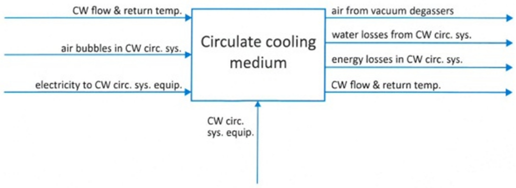
3

1. INPUTS

No.	Description	S-Cycle classification	Agree/ disagree?	Comments
1	CW flow & return temp.	renewable resource	Agree.	
2	air bubbles in CW circ. sys.	unwanted input	Agree.	
3	electricity to CW circ. sys. equip.	renewable resource	Agree.	

3. OUTPUTS

No.	Description	S-Cycle classification	Agree/ disagree?	Comments
1	air from vacuum degassers	waste	Agree	
2	water losses from CW circ. sys.	waste	Agree	
3	energy losses in CW circ. sys.	waste	Agree.	
4	CW flow & return temp.	intended output	Agree.	



2. MECHANISMS

No.	Description	S-Cycle classification	Agree/ disagree?	Comments
1	CW circ. sys. equip.	non-renewable resource	Agree.	Dependent on lead time (if no spares) and mission profile

and also no redundancy
System has redundancy & reconfigurability built in.

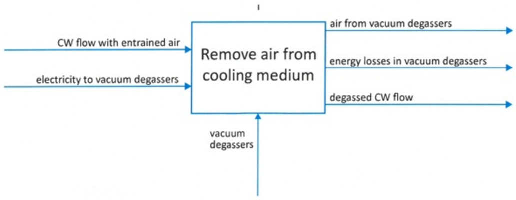
4

1. INPUTS

No.	Description	S-Cycle classification	Agree/ disagree?	Comments
1	CW flow with entrained air	renewable resource	Agree.	
2	electricity to vacuum degassers	renewable resource	Agree.	

3. OUTPUTS

No.	Description	S-Cycle classification	Agree/ disagree?	Comments
1	air from vacuum degassers	waste	Agree	
2	energy losses in vacuum degassers	waste	Agree	
3	degassed CW flow	intended output	Agree.	



2. MECHANISMS

No.	Description	S-Cycle classification	Agree/ disagree?	Comments
1	vacuum degassers	non-renewable resource	Agree.	