An eco-intensity based method to assess environmental sustainability performance of multi-tier supply chains

by

Andrea Tuni

Department of Design, Manufacture and Engineering Management
University of Strathclyde
Glasgow, United Kingdom

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This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination, which has led to the award of a degree.

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To Giulio Regeni

“Live in each season as it passes;
breathe the air,
drink the drink,
taste the fruit,
and resign yourself
to the influence of the earth.”

Henry David Thoreau

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Abstract

The majority of environmental impacts in a typical supply chain arise beyond the focal firm boundaries. Nevertheless, focal companies are held liable for the behaviour of suppliers and sub-suppliers and face increasing pressure from stakeholders to improve their supply chain sustainability, calling for a holistic approach to assess the wider supply chain environmental performance. However, a systematic literature review investigation highlighted that existing supply chain environmental performance assessment methods have rarely expanded beyond first tier suppliers, with a limited consideration of lower-tier suppliers.

Therefore, this work introduces a novel method to quantitatively assess the environmental performance of multi-tier supply chains, which adopts eco-intensity indicators that relate the environmental performance of the supply chain to its economic output. The method expands the coverage of the existing performance assessment methods both in terms of supply chain extent and of environmental aspects considered, paving the way for an effective supply chain-wide environmental sustainability assessment.

The method is the first to allow assessing the environmental performance of multi-tier supply chains based on primary data sourced from actual practice, while respecting the multiple organisation nature and non-collaborative characteristics of the majority of real-life supply chains. This is achieved through a decentralised approach, materialised through a recursive mechanism to pass eco-intensity values from one tier to the next, which does not require visibility of the extended supply chain by any single member.

The method was evaluated against utility, accuracy and applicability criteria, through semi-structured interviews, a numerical example and multiple case studies respectively. The application of the method to two multi-tier supply chains identified practical implications spanning from external reporting and evaluation of suppliers to guidance towards operational improvement thanks to the identification of environmental hotspots along the supply chain.

The research and findings were critiqued to identify advantages and limitations of the research as well as future research directions.

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Research Outputs

The following research outputs have been published as part of this research work.

Journal articles

- Tuni, A., Rentizelas, A., Duffy, A., 2018. "Environmental performance measurement for green supply chains: a systematic analysis and review of quantitative methods", *International Journal of Physical Distribution & Logistics Management*, Vol. 48, Issue 8, pp. 765-793, 10.1108/IJPDLM-02-2017-0062
- Tuni, A., Rentizelas A., 2018. "An innovative eco-intensity based method for assessing extended supply chain environmental sustainability", *International Journal of Production Economics*, 10.1016/j.ijpe.2018.08.028
- Tuni, A., Rentizelas, A., Chinese, D., 2019 "An integrative approach to assess environmental and economic sustainability in a multi-tier supply chain: a case study", accepted for publication in *Production Planning & Control*.

Conference papers

1) Tuni, A., Rentizelas, A., 2017. "Measuring the eco-intensity of the supply chain: a novel approach", *4th International EurOMA Sustainable Operations and Supply Chains Forum*, Milan, Italy, 27th – 28th February 2017
2) Tuni, A., Rentizelas, A., 2017. "Benchmarking the environmental performance of supply chains through eco-intensity", *24th EurOMA Conference*, Edinburgh, Scotland, United Kingdom, 1st – 5th July 2017
3) Tuni, A., Rentizelas, A., 2018. "Measuring eco-intensity in a multi-tier food supply chain: a case study", *5th International EurOMA Sustainable Operations and Supply Chains Forum*, Kassel, Germany, 5th – 6th March 2018

Conference presentation

1) Tuni, A., Rentizelas, A., 2015. "Mapping and Evaluation of Approaches for Supply Chain Environmental Sustainability Performance", *27th European Conference on Operational Research*, Glasgow, Scotland, United Kingdom, 12th – 15th July 2015
2) Tuni, A., Rentizelas, A., 2015. "Quantitative assessment of supply chain environmental performance, with a focus on benchmarking", *ISIR Workshop on Sustainable Logistics and Supply Chain Management*, Lyon, France, 7th – 9th October 2015
3) Tuni, A., Rentizelas, A., 2016. "From a literature review to an innovative model to assess environmental performance for supply chains", *1st EWG on Sustainable Supply Chains*, Aachen, Germany, 1st – 2nd July 2016

Nomenclature

Abbreviation	Meaning
Generic abbreviations	
AHP	Analytical hierarchy process
ANP	Analytical network process
B2B	Business to business
B2C	Business to consumer
CDP	Carbon Disclosure Project
CS	Case study
DEA	Data envelopment analysis
DfE	Design for the environment
E	Enabler
EOL	End-of-life management
I	Interview
GHG	Greenhouse gas
GRI	Global Reporting Initiative
GSCM	Green supply chain management
KPI	Key performance indicator
LCA	Life cycle assessment
LF	"La Fattoria" - 2nd tier supplier, CS1
MILP	Mixed integer linear programming
MT	"Molino Tuzzi", 1st tier supplier, CS1
N	Normalised
O	Research objective
P	Participant
PI	"Panificio Iordan", focal company, CS1
PMS	Performance measurement system
SC	Supply chain
SCM	Supply chain management
SE	Scottish Enterprise
SI	Systeme Internationale (International System of Units)
SMEs	Small and medium enterprises
SSCM	Sustainable supply chain management
u	Units produced over a year timespan (CS2)
z	Number of parallel suppliers (CS2)
3Rs	Re-cycling re-using re-manufacturing

Abbreviation	Meaning
Mathematical model abbreviations	
e	Environmental indicator
EBP	Environmental backpack
EBP_{eik}	Environmental backpack with respect to environmental indicator e of organisation i associated to its output product k
EI	Eco-intensity
EI_{ei}	Eco-intensity with respect to environmental indicator e of organisation i
EI_{eik}	Eco-intensity with respect to environmental indicator e of organisation i associated to its output product k
EI_{ej}	Eco-intensity with respect to environmental indicator e of supplier j
EI_{ejk}	Eco-intensity with respect to environmental indicator e of supplier j associated to its output product k
EP	Environmental performance
EP_{ei}	Environmental performance with respect to environmental indicator e of organisation i
EP_{eij}^{tr}	Environmental impact of transport from supplier j to customer i with respect to environmental indicator e
EP_{eik}	Environmental performance with respect to environmental indicator e of organisation i associated to its output product k
i	Customer of each dyad for each iteration of the recursive mechanism
j	Supplier of each dyad for each iteration of the recursive mechanism
k	Products offered from an organisation i to its customer for each iteration of the recursive mechanism
n	Intermediate products purchased by organisation i from supplier j for its output product k for each iteration of the recursive mechanism
Q	Quantity
Q_{ik}	Quantity of product k sold by organisation i
Q_{ijkn}	Quantity of product n purchased by organisation i from supplier j for its output product k
P	Price
P_{ik}	Price of product k sold by organisation i
P_{ijkn}	Price of product n purchased by organisation i from supplier j for its output product k
T	Turnover
T_i	Turnover of organisation i
T_{ik}	Turnover of organisation i generated by product k
T_{ijk}	Turnover of supplier j generated by organisation i through the purchase of product k
T_j	Turnover of supplier j
tr	Transport

1 Introduction

The majority of human activities on planet Earth, which generate economic prosperity and societal well-being, depend on the ecosystems and natural resources provided from the planet (Borucke et al., 2013; Hay, 2015). The Earth could approximately be considered a thermodynamically closed system and, as such, it has a limited capability to supply resources as well as to absorb pollution caused by human activities (Ayres and Kneese, 1969; Kleidon, 2012). Nevertheless, increasing world population, swelling global economy and wealthier standards of living are resulting in increasing levels of consumption, which are posing threats to the preservation of natural capital as “human demand is likely to be exceeding the regenerative and absorptive capacity of the biosphere” (Borucke et al., 2013; Smith-Gillespie and Chang, 2016). Moreover, human activity has become the main driver of global environmental changes, unbalancing mechanisms which used to be self-regulated (Mebratu, 1998; Rockström et al., 2009). As a result, the consequences of such an extensive exploitation of the environment are rising scrutiny, even posing questions on the future ability of the planet to sustain humanity in the long-term if the human pressure on the environment remains unchanged (Borucke et al., 2013). As the potentially irreversible effects of such environmental changes became more evident, some environmental issues, most noticeably global warming and climate change, started to become central to the agenda of the international community, triggering debate and capturing the interest of populations and policy makers due to the consequences they have not only on the environment, but also on the society and the economy (Bloemhof et al., 2015; Montoya-Torres et al., 2015; Rockström et al., 2009).

Sustainable development emerged as a new paradigm of development to find a solution to these concerns. Adopting an inter-generational perspective, sustainable development aims to preserve the same living conditions for future generations while still fulfilling needs of current generation (WCED, 1987). As such, it broadens the traditional scope of economic development, adding to this perspective the environmental and social implications arising from human activities (Elkington, 2004). Among anthropic activities, a prominent role in terms of environmental impact is associated to industrial operations due to the intense use and processing of natural resources required by manufacturing processes as well as the pollution caused by such activities (Ramani et al., 2010; UNEP, 2010).

Since the adoption of Kyoto Protocol in 1997, governments paid increasing attention to environmental themes and tried to limit the environmental impact arising from anthropic activities, focusing especially on industrial activities. The call for more sustainable development has been incorporated into their policy making actions, introducing stricter rules to control emissions of companies in specific sectors and to limit the overall environmental impact associated to industrial activities (Björklund et al., 2012). Other stakeholders demanding organisations to mitigate their environmental and social impact have joined regulatory bodies in their call for sustainable development. Customers are demanding more sustainable products and services with reduced impact on both the environment and the society, thus generating a 'pull' pressure from the market directed towards organisations (Bask et al., 2013). This pressure is further enhanced by other stakeholders, such as non-governmental organisations (NGOs) and local communities that are demanding increased transparency and adequate reporting about the environmental and social impact caused by production activities, potentially threatening the reputation of companies should these requirements not be met (Björklund et al., 2012; Meixell and Luoma, 2015).

The pressure to include environmental considerations within their operations initially targeted only single organisations, mostly focal companies, which are those firms that have a prominent role within the network as they "rule or govern the supply chain, provide the direct contact to the customer, and design the product or service offered" (Seuring and Müller, 2008). However, this pressure later expanded to include more organisations part of the supply chain for two reasons.

First, competition shifted from a company-versus-company to a supply chain-versus-supply chain form (Cabral et al., 2012; Hashemi et al., 2015). Increased specialisation of companies as a result of competitive pressure has pushed organisations to focus on a set of core skills, outsourcing other tasks to different companies and generating long and complex supply chains with a high number of interconnected organisations (Mena et al., 2013; Santibanez-Gonzalez and Diabat, 2013). Outsourcing practices have been often linked with offshoring practices, relocating parts of the supply chain to countries with low production cost, often coupled with less strict environmental regulations and standards (Harris et al., 2011; Hutchins and Sutherland, 2008; Reefke and Trocchi, 2013; Silvestre, 2015). Environmental challenges thus expanded outside of the boundaries of the company as well, becoming a supply chain issue that encompasses players in the extended upstream and downstream supply chain (Sigala, 2008; Varsei et al., 2014).

Second, there is significant evidence that the biggest portion of the overall environmental impact of the supply chain does not arise within focal firm boundaries, but it is caused by other companies part of the supply chain (Smith-Gillespie and Chang, 2016; Veleva et al., 2003). The contribution of the extended supply chain beyond the focal company has been estimated as typically accounting for 80% of the overall supply chain emissions, whereas the overall supply chain environmental impact contribution was estimated as much as 90% in the extreme case of Marks & Spencer, a British multinational retailer, with only 10% being attributed to the focal firm (Beavis, 2015; WBCSD and WRI, 2009). Therefore, environmental performance cannot be adequately addressed at the single company level anymore, but a holistic approach encompassing the wider supply chain environmental performance is needed (Fabbe-Costes et al., 2011; McIntyre et al., 1998).

This is particularly important in contemporary supply chains which are becoming increasingly complex with a high number of tiers and a limited visibility of the upstream supply chain by focal companies (Mena et al., 2013). The poor environmental performance of a single tier upstream in the supply chain may result in an overall environmentally unsustainable behaviour of the entire supply chain. Environmental scandals associated to lower-tier suppliers of several large organisations, including Unilever, Nestlé and Zara, were leaked to the public in the past, damaging the image of focal firms (Dou et al., 2017; Grimm et al., 2016; Hartmann and Moeller, 2014; Miemczyk et al., 2012). Companies therefore need to understand not only their first-tier suppliers environmental performance but also their extended supply chain environmental profile (Genovese et al., 2013; Miemczyk et al., 2012).

However, existing supply chain environmental performance assessment methods have been limited in terms of supply chain extent coverage, focusing on the focal firm performance in a supply chain perspective rather than addressing multiple tiers along the supply chain (Ahi and Searcy, 2015a). As a result, quantitative work on "the extended supply chain still require considerably more attention", as noted by Brandenburg et al. (2014) in their review on sustainable supply chain management models.

Some exceptions to this narrow supply chain perspective exist, which are mostly based on lifecycle assessment (LCA)-based methods (Adhitya et al., 2011; Dong et al., 2018), however they suffer from two drawbacks. First, they limit the assessment with primary data to the focal company and adopt generic data for other organisations in the supply chain (Ahi and Searcy, 2015a), thus not capturing the differences between similar organisations and supply chains with a similar design. Second, they assume the existence of a central administration of the supply chain (Adhitya et al., 2011). As a consequence, they are capable to provide only a "high-level snapshot of the environmental implications over the product value chain without consideration of the dynamics arising from the multi-tiered structure and the interactions along the supply chain" (Adhitya et al., 2011).

Summarising, a gap was identified in the existing research, which lacks a method that simultaneously:

- Assesses multi-tier supply chains environmental sustainability performance, expanding the assessment beyond 1st tier suppliers and customers;
- Provides a comprehensive evaluation of environmental aspects;
- Uses primary data sourced from actual practice to assess the environmental performance;
- Respects the multiple organisation and non-collaborative nature of the majority of real-life supply chains.

A method to assess the environmental sustainability performance of multi-tier supply chains, which extends the assessment beyond direct suppliers and customers, while still respecting the multiple-organisation nature and non-collaborative characteristics of the majority of real life supply chains could provide insights in this respect.

1.1 Research question

In light of the above considerations, the following research question was defined to guide this research:

> *How can the environmental sustainability performance of multi-tier supply chains be quantitatively assessed?*

1.2 Aim and objectives

The research documented in this thesis was motivated by the lack of a method to assess the environmental sustainability of multi-tier supply chains based on primary data arising from actual practice, which respects the multi-organisation nature and non-collaborative characteristics of the majority of supply chains. The aim of this research was thus to *facilitate quantitative assessment of the environmental sustainability performance of multi-tier supply chains*, while using primary environmental data arising from actual practice and respecting supply chain relationship features mentioned above.

To attain the research aim, five objectives were defined:

O1. Identify quantitative methods developed to assess the environmental performance of supply chains and evaluate their key features

O2. Understand the key mechanisms regulating sub-supplier management in multi-tier supply chains, with a particular focus on green supply chain management (GSCM)

O3. Construct a method to quantitatively determine the environmental sustainability performance of multi-tier supply chains

O4. Apply the method to operating supply chains

O5. Evaluate the utility, accuracy and applicability of the method

The aim is primarily achieved by developing an eco-intensity method that relates the environmental performance of the supply chain to its economic output and adopts an indirect multi-tier supply chain approach.

1.3 Scope of the work

The research presented in this work focused on the assessment of the environmental sustainability performance of multi-tier supply chains. The following boundaries confine this research:

1. Only environmental and economic dimensions of sustainability are considered, whereas the social dimension is outside the scope of the work due to the lack of adequate quantitative social indicators to be merged into a quantitative assessment method, as detailed in Section 2.4.2.2.
2. The environmental performance is assessed for forward supply chains, adopting a cradle-to-gate approach, as detailed in Section 4.1.2.1. The use and end-of-life management of products are outside the scope of the work.

3. The unit of analysis is a single supply chain. Every product sold on the market is accounted as part of a different supply chain, hence a different unit of analysis.
4. The work is limited to commercial supply chains with a physical product actually sold on the market. Other types of supply chains, such as humanitarian supply chains, are outside of the scope of this research. As a result, the turnover generated from the product sold on the market by the supply chain over a year timespan must have a positive value.
5. Accordingly, the work is limited to operating supply chain, thus not considering supply chains at the design stage.

1.4 Thesis structure

The remaining part of this thesis is organised into seven additional chapters, whose contents are outlined below. The relationships between the objectives presented in Section 1.2 and different parts of the thesis are also highlighted.

- Chapter 2 provides a state-of-the art literature review about the existing body of literature in the field of green supply chain performance assessment (O1). After an introduction of the wider topics of sustainability and sustainable supply chain management (SSCM), the scope is progressively narrowed moving to GSCM, with a sub-section of the chapter addressing the key aspects of multi-tier GSCM (O2). The core of the chapter systematically reviews the literature at the intersection of GSCM and performance assessment to identify environmental indicators, supply chain extent and methodological approaches adopted in the existing literature, as well as the main purpose for undertaking the assessment and the relationships between these aspects. Based on the review performed, the shortcomings in the existing literature on GSCM performance assessment are identified, leading to the specification of the research problem and definition of aim and objectives.
- Chapter 3 presents the adopted research approach. The selected research philosophy and methodology are discussed and justified. Finally, the overall research design, including the documental outputs of this research, is presented.
- Chapter 4 introduces the novel method to assess the environmental sustainability performance of multi-tier supply chains (O3), which is based on the gaps in the existing literature identified in Chapter 2. A conceptual model to represent the reality of supply chains and their environmental performance is presented as well as a mathematical model allowing the operationalisation of the method.
- Chapter 5 presents the method evaluation approach, which is based on the criteria of utility, accuracy and applicability (O5). The overall evaluation approach is discussed, illustrating the feedback loops leading to a progressive revision of the method until its final version. The findings of the evaluation of the utility of the conceptual model and the accuracy of the mathematical model are illustrated. The approach to evaluate applicability is also discussed in this chapter.
- Chapter 6 further contributes to the applicability evaluation (O4), by presenting the findings of the application of the method in two operating supply chains. The

applicability of these results as well as the applicability of the method in an operating context are also discussed.

- Chapter 7 discusses the work as a whole identifying strengths, weaknesses and lessons learned. The discussion particularly focuses on the research findings and research methods as well as on the overall research design.
- Chapter 8 concludes this thesis by reviewing the research question and objectives and summarising the research outputs. Recommendations for future research directions are made on the basis of the limitations of this research. Finally, the main novel aspects of this research are highlighted, summarising the key contributions to knowledge. Implications for practitioners and policy makers are also outlined.

1.5 Summary

This chapter introduced the research presented in this thesis. The problem statement and research gap defined in the opening sections led to the definition of the research question, outlined in Section 1.1. The research question informed the delineation of the aim of this research, which is further developed into multiple research objectives throughout Section 1.2, while Section 1.3 lists the boundaries of this research investigation. Finally, Section 1.4 illustrates the structure of the remaining part of this document. In the next chapter (Chapter 2), the outcomes of the literature review are presented.

2 Literature Review

The literature review aims to determine the state of the art of the knowledge in the field of GSCM performance assessment as well as to detail the research problem, the aim and objectives, as they were illustrated in Chapter 0.

The review chapter follows a funnel approach, moving from the general topic of sustainability (Section 2.1) and progressively narrowing the scope to sustainable supply chain management (Section 2.2) and green supply chain management (Section 2.3), including a sub-section dedicated to multi-tier GSCM. Section 2.4 first introduces the topic of performance assessment, with a specific focus on performance assessment for sustainability and supply chain management performance assessment. Section 2.5 brings the three areas together, by illustrating the findings of the systematic literature review on methods to assess GSCM performance. A visual overview of the literature review funnel approach is depicted in Figure 2.1. Finally, Section 2.6 briefly states the research problem based on the gaps identified through the literature review process and a summary of the literature review section ends this chapter (Section 2.7).

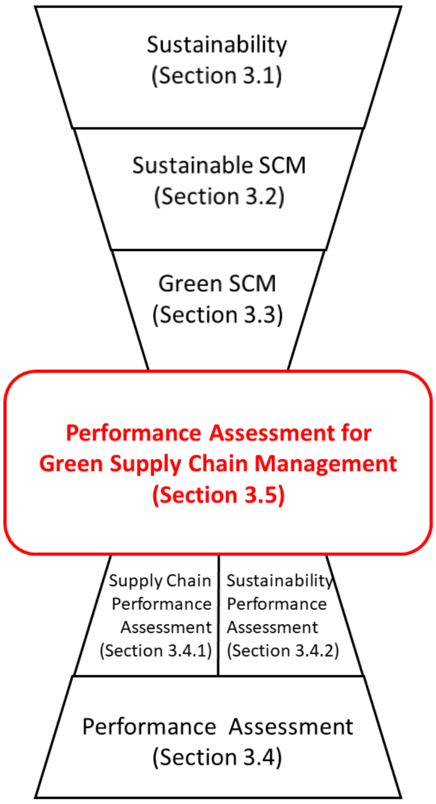

Figure 2.1: Overview of the literature review funnel approach

2.1 Sustainability

Sustainability is a broad discipline, which has a number of implications on multiple aspects of the human world. As a result, sustainability stands at the boundary of politics and science and is capturing increasing interest from multiple actors (Hay, 2015). The expanding importance of sustainability has been reflected in an exponentially growing body of literature addressing sustainability themes (Hay, 2015). However, sustainability has not been confined only to the academic field, becoming also very popular both in the public and in the private sector (Bjørn, 2015). Sustainability appeared on the agenda of several government and policy makers under the umbrella of sustainable development (Wang et al., 2009), whereas companies have also lately begun to become aware of the sustainability of their businesses in order to meet legislative requirements, capture needs of customers to increase market shares and comply with requests from other stakeholders (Abdallah et al., 2012; Bask et al., 2013; Björklund et al., 2012; Bloemhof et al., 2015; Gerbens-Leenes et al., 2003; Meixell and Luoma, 2015; Montoya-Torres et al., 2015). As a result, the concept of sustainability is associated to a wide spectrum of fields, lying at the confluence of physical and social sciences from an academic perspective and being associated to a broad number of sectors and industries (Hay, 2015).

2.1.1 Theoretical concept and definitions of sustainability

Despite the widespread of the concept of sustainability in a variety of areas, an univocal definition of sustainability does not exist and several attempts to specify this concept can be found in the literature (Vos, 2007). Sustainability is literally defined as “the ability to maintain something undiminished over some time period” (Hay, 2015). The object to be sustained remains undisclosed through this definition, however it is widely acknowledged that this is identified with the human society (Hay, 2015). The process to sustain human society over time is described as sustainable development, a concept that was originally developed by the World Commission on Environment and Development in 1987, as part of the Brundtland Report. Sustainable development is there defined as “using resources to meet the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987). This definition stresses the intra-generational perspective of sustainability (Clift, 2003) and stresses the concept of the capability of sustaining a system over time (Hay, 2015). Thanks to its broad scope, this definition is applicable to different fields. At the same time, stating its theoretical perspective and broad scope, it does not directly suggest any practical implications for sustainability in operations management.

Therefore, another definition, proposed by Elkington (2004), is more often quoted when referring to sustainability within business environment. Elkington (2004) introduced the concept of the triple-bottom-line-approach (3BL), the most widely used approach to sustainability nowadays: “the 3BL focuses corporations not just on the economic value that they add, but also on the environmental and social value that they add – or destroy” (Elkington, 2004). This definition is now widely recognised as the standard focus to sustainability and has been adopted by United Nations as well. The three dimensions of sustainability are alternatively indicated by some scholars as the 3Ps: profit, planet and people (Christopher, 2011; Hassini et al., 2012).

The nature of the interrelation between the three dimensions of sustainability has generated debates in the literature, determining whether a weak or a strong sustainability stance is adopted. Weak sustainability adopts a techno-centric stance, implying a perfect substitutability between the manufactured capital and the natural capital (Ashby, 2014; Ness et al., 2007; Ukidwe and Bakshi, 2005). On the contrary, strong sustainability claims that the natural capital cannot be substituted from the economic capital and must be maintained (Ashby, 2014; Ness et al., 2007).

The different definition of sustainability also affects the visual representation of the interrelation between the three dimensions. These are depicted as overlapping shapes in the weak sustainability perspective, as illustrated in Figure 2.2, which defines an interconnection between the dimensions of sustainability and the existence of shared goals between the dimensions in the central overlapping areas (Ali-Toudert and Ji, 2017). On the other hand, the dimensions of sustainability are portrayed as three concentric shapes according to the strong sustainability view, highlighting a hierarchical classification of the dimensions (Ali-Toudert and Ji, 2017). In this perspective, the environment is a prerequisite for any society to develop and thus is given a prominent role, which embraces both society and economy as shown in Figure 2.3. Similarly, economies do not occur if societies do not exist. The strong sustainability thus offers a hierarchical perspective over the three dimensions of sustainability instead of an interconnected one and avoids the definition of intersection areas between dimensions.

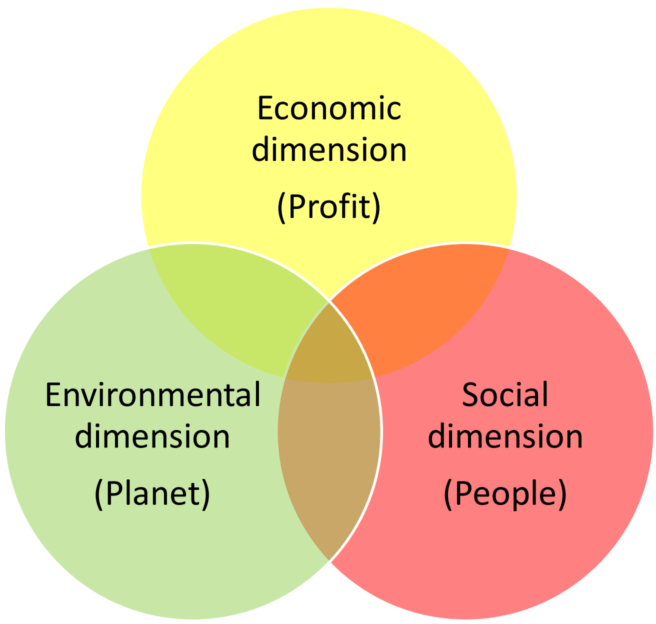

Figure 2.2: Pillars of sustainability according to weak sustainability

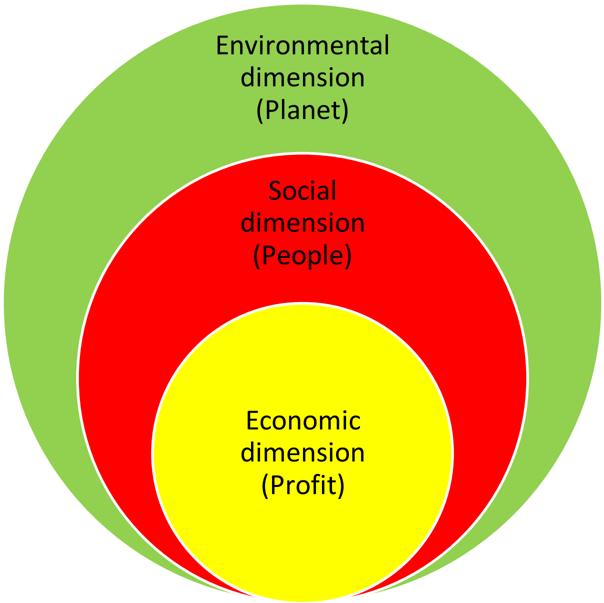

Figure 2.3: Pillars of sustainability according to strong sustainability

Within this classification, this research adopts a weak sustainability perspective for two reasons. First, the economic dimension of sustainability cannot be neglected in an operations management context, as the economic survival of organisations is necessary to guarantee the existence of supply chains in the first place. Second, the primary objective of organisations, which are the expected practical users of this research, is to generate profits. As such, organisations share the weak sustainability view and the majority of companies already "implement a weak definition of sustainability" (Ashby, 2014).

Table 2.1: Definitions for overlapping areas of weak sustainability

Dimensions of sustainability	**Overlap area definition**	**Source**
Economic and Environmental	Eco-efficiency Responsibility Valuable Viable	(Valentin and Spangenberg, 2000) (Ali-Toudert and Ji, 2017) (Tajbakhsh and Hassini, 2015a) (Kleine, 2009)
Economic and Social	Burden Sharing Equitable Equity Reputable Viability	(Valentin and Spangenberg, 2000) (Kleine, 2009) (Curwell et al., 2005) (Tajbakhsh and Hassini, 2015a) (Ali-Toudert and Ji, 2017)
Environmental and Social	Access Bearable Equitable Equity	(Valentin and Spangenberg, 2000) (Kleine, 2009) (Tajbakhsh and Hassini, 2015a) (Ali-Toudert and Ji, 2017)

While a general consensus exists in the literature about 'sustainable' meaning a simultaneous consideration of all three dimensions, the same does not apply when only two dimensions of sustainability are taken into consideration. Multiple terms have been adopted to identify the overlapping areas between two dimensions identified in Figure 2.2, as displayed in Table 2.1. This research focuses only on the economic and environmental dimension sustainability, without targeting the social dimension. The rationale behind this choice is explicated in Section 2.4.2.2.

2.1.2 Sustainability in the business world

The adoption of the Kyoto Protocol in 1997 acted as a significant milestone for the progressive inclusion of sustainability concerns within businesses, as governments have started to introduce stricter rules to control emissions of organisations in specific sectors and to limit the overall impact arising from industrial activities since the protocol was ratified (Björklund et al., 2012). However, regulatory bodies have been joined by other stakeholders in pressuring organisations to include sustainability concerns within their operations, due to the substantial impact industrial activities have on both the environment and the society (Abdallah et al., 2012; Bask et al., 2013; Björklund et al., 2012; Bloemhof et al., 2015; Frota Neto et al., 2008; Montoya-Torres et al., 2015). As themes such as climate change and global warming triggered international debate, organisations have faced increased pressure from the market, as customers are demanding more sustainable products and services, as well as from other stakeholders, such as NGOs and local communities (Abdallah et al., 2012; Bask et al., 2013; Björklund et al., 2012; Bloemhof et al., 2015; Gerbens-Leenes et al., 2003; Meixell and Luoma, 2015; Montoya-Torres et al., 2015).

This pressure to include sustainability concerns within management and decision making initially targeted single organisations, most noticeably focal companies, which are those organisations that have a prominent and powerful role within the network (Seuring and Müller, 2008). However, this pressure later expanded to include more organisations part of the supply chain for two factors. First, competition shifted from a company-versus-company to a supply chain-versus-supply chain form as a result of increased outsourcing and global competition (Cabral et al., 2012; Hashemi et al., 2015; Reefke and Trocchi, 2013). Outsourcing has been often coupled with offshoring of production to countries with low production costs and loose sustainability standards, making sustainability challenges a supply chain issue (Awasthi et al., 2018; Harris et al., 2011; Hutchins and Sutherland, 2008; Reefke and Trocchi, 2013; Sigala, 2008; Silvestre, 2015; Varsei et al., 2014). Second, as a result of the increased length and complexity of supply chains, it was verified that the majority of the environmental impacts arise outside of the focal firm boundaries, being caused by other companies in the extended supply chain (Beavis, 2015; Veleva et al., 2003; WBCSD and WRI, 2009)

In light of the above considerations, it is evident that sustainability challenges cannot be adequately addressed at the single company level anymore (Fabbe-Costes et al., 2011; McIntyre et al., 1998), determining the emergence of the concepts of sustainable supply chain management and green supply chain management, which are illustrated in Section 2.2 and Section 2.3 respectively.

2.2 Sustainable Supply Chain Management

The concept of 'supply chain' first appeared in the 1980s, however only in the following decade it gained popularity differentiating itself from logistics management and developing as a self-standing concept (Cooper et al., 1997). A classic supply chain entails "all activities associated with the flow and transformation of goods from the raw materials stage (extraction), through to the end user, as well as the associated information flows" (Handfield and Nichols, 1999). However, the material and information flows are not strictly directed only towards the end user, but can also move in the opposite direction, determining bi-directional flows up and down the chain (Seuring and Müller, 2008).

In the 1990s the increasing importance of supply chain to achieve competitive advantage became evident, as the competition shifted from a company-versus-company format to a supply chain-versus-supply chain format (Cabral et al., 2012; Hashemi et al., 2015; Reefke and Trocchi, 2013). As a result, organisations tried to develop activities and processes to manage this new scenario, leading to what is nowadays known as supply chain management (SCM), which is "the integration of key business processes from end-user through original suppliers that provides products, services, and information that add value for customers and other stakeholders" (Lambert, 2008). Having a clear focus on the integration of value-adding activities, SCM thus aims to achieve competitive advantage through improved relationships among the organisations building up the supply chain (Seuring and Müller, 2008).

Sustainable supply chain management (SSCM) expands this view by blending the concept of sustainability, as defined according to the 3BL approach, with SCM in order to generate sustainable competitive advantage (Seuring and Müller, 2008). Long-term sustainability can not longer be achieved at the single firm level, but it has become a supply chain issue, involving all upstream and downstream players (Sigala, 2008). SSCM can therefore be defined as "the management of material, information and capital flows as well as cooperation among companies along the supply chain while taking goals from all three dimensions of sustainable development, i.e., economic, environmental and social, into account which are derived from customer and stakeholder requirements" (Seuring and Müller, 2008).

2.3 Green Supply Chain Management

Green Supply Chain Management (GSCM) narrows the scope compared to SSCM by focusing only on the incorporation of the environmental dimension of sustainability within supply chain management. Therefore, Srivastava (2007) defines GSCM as the integration of "environmental thinking into supply chain management, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers, as well as end-of-life (EOL) management of the product after its useful life". According to this definition, GSCM encapsulates a number of activities, spanning from product design down to end-of-life management, which are detailed in Section 2.3.1. Following sections discuss additional aspects related to GSCM, such as GSCM practices (Section 2.3.2), drivers of GSCM (Section 2.3.3), as well as the specific features of multi-tier GSCM (Section 2.3.4), which is the specific area tackled by this research within GSCM. Section 2.3.5 further expands the investigation of multi-tier GSCM by specifically overviewing the key mechanisms to manage sub-supplier within multi-tier GSCM.

2.3.1 GSCM activities

Spanning through the entire lifecycle of a product, from product design and raw material extraction down to the end-of-life management, the concept of GSCM embraces a number of different activities, which are part of the operations management and SCM of companies and can be integrated with environmental sustainability considerations.

Building on the GSCM definition by Srivastava (2007), GSCM practices can be clustered in five key supply chain management activities (Kafa et al., 2013): eco-design, green purchasing, green manufacturing, green distribution and end-of-life management, as shown in Figure 2.4. The clusters also mirror the categories identified by Ramani et al. (2010) for sustainable life cycle design, although green purchasing and green distribution are kept separate in this work, given the specific supply chain focus of this research.

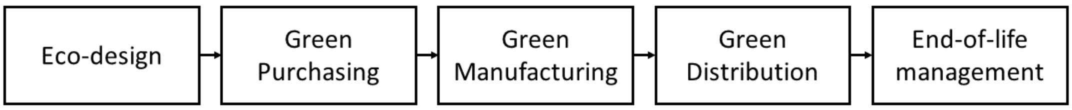

Figure 2.4: GSCM practices clusters

2.3.1.1 Eco-design

Product design occurs at the early stages of product development; however, it is a critical activity that significantly influences the sustainable performance of a product throughout the product lifecycle (Ramani et al., 2010). Most decisions taken at this stage prove to be irreversible, with up to 85% of the lifecycle costs of a product determined at this stage (El Saadany et al., 2011; Lozano, 2012a; Ramani et al., 2010). Similarly, a large share of the environmental impact of a product is decided at the design stage (Ramani et al., 2010). Trying to reduce this impact, Design for the Environment (DfE), also known as eco-design, is a set of design techniques falling under the design-for-X techniques umbrella, which pose environmental concerns as a central goal of the design process in a lifecycle perspective (WBCSD, 2004). DfE is indeed the "systematic consideration during new product and process development of design issues associated with environmental safety and health over the full product life-cycle" (Arnette et al., 2013). As such, DfE aims to reduce material and energy consumption and to promote the reuse of products (Lozano, 2012a). DfE has a broad environmental scope encompassing a variety of techniques, depending on the specific goal of the design process, including techniques such as Design for Energy Conservation, Design for Material Conservation, Design for Waste Minimisation and

Recovery and Design for Remanufacture, Reuse and Recycling (Arnette et al., 2013). Once the design stage is completed, organisations move on to manufacture the product, thus requiring to acquire certain inputs necessary to support production through purchasing activities. These are defined as green purchasing or green sourcing when they include environmental considerations.

2.3.1.2 Green purchasing

Green purchasing, also referred as green procurement or green sourcing, is the "process of formally introducing and integrating environmental issues and concerns into the purchasing process" (Shen et al., 2013). Green purchasing aims to reduce the environmental impact of inputs purchased by an organisation (Malik et al., 2015). At the basic level, this is performed to meet legislative requirement and comply with requests from customers, in order to avoid potential threats to the image of the company (Malik et al., 2015; Nagel, 2003). At an advanced level, green purchasing becomes part of the strategy of organisations in order to strengthen the long-term sustainability of their business (Blome et al., 2014; Shi et al., 2015). Green purchasing strategies can be classified as reactive or proactive (Freeman and Chen, 2015). In the former case, the supplier's environmental performance is assessed according to environmental standards and regulations, whereas in the latter case, a future perspective is adopted evaluating the competencies of suppliers to implement environmental programs (Freeman and Chen, 2015). Therefore, green purchasing strategies include the selection of products with greener features on the supply side and/or the selection of suppliers that are able to deliver products in a green manner (Blome et al., 2014; Malik et al., 2015). As a result, green supplier selection and evaluation plays a key role towards green sourcing, integrating environmental considerations in the supplier selection process along criteria such as cost and quality (Freeman and Chen, 2015). Green supplier selection criteria target environmental competence, eco-design capabilities, environmental performance, ability to develop environmentally friendly goods and ability to support the environmental objectives of the buyer (Kannan et al., 2015; Nagel, 2003). Moreover, the adoption of environmental management systems, such as ISO 14000 series, or eco-labelled products are also considered a guarantee of the environmentally sustainable behaviour of suppliers (Hashemi et al., 2015; Kuo et al., 2010; Nagel, 2003). Once the inputs for production are acquired through purchasing, manufacturing follows to transform inputs into finished products.

2.3.1.3 Green manufacturing

Product manufacturing is the lifecycle stage traditionally responsible for the most significant share of natural resources depletion and emissions of polluting substances (Despeisse et al., 2012a, 2012b; Ramani et al., 2010). Green Manufacturing, also referred as environmental conscious manufacturing or sustainable manufacturing, introduces environmental considerations within the manufacturing process (Despeisse et al., 2012a; Faulkner and Badurdeen, 2014). Green manufacturing aims to reduce the environmental impact of production activities by using appropriate material, through the acquisition of environmentally friendly inputs flowing in the organisation, as described in Section 2.3.1.2, and by adopting green technologies to limit environmental outputs (Abdallah et al., 2012; Despeisse et al., 2012b; Smith and Ball, 2012; Srivastava, 2007). Green manufacturing embraces productions processes that convert inputs into outputs by reducing use of hazardous substances, limiting consumption of virgin materials, increasing energy efficiency and minimising emissions and waste (Chin et al., 2014; Srivastava, 2007). End-of-pipe pollution control is the most basic application of green manufacturing, with more advanced applications involving pollution prevention and eco-innovation (OECD, 2009). This can be achieved through process improvement and optimisation, new process development or improved process planning (Ramani et al., 2010), as well as through improved management practices (OECD, 2009). Once the manufacturing stage is completed, products are shipped to the customers through the distribution network.

2.3.1.4 Green distribution

Green distribution goes beyond organisational boundaries and focuses on the downstream part of the supply chain. It is defined as “the integration of environmental issues into packaging, transportation and logistics activities” (Kafa et al., 2013). Green distribution therefore is the combination of green packaging and green logistics. Green packaging aims to reduce the generation of waste due to packaging material by downsizing packaging, promoting recycling and reusing programs for packaging and pallets and adopting returnable packaging policies (Chan, 2007; Chin et al., 2014; Kafa et al., 2013). Moreover, material substitution applies to packaging too, shifting towards environmentally friendly materials and recycled packaging (Chin et al., 2014; Kafa et al., 2013). Green logistics aims to reduce energy consumption in warehouses through environmentally-efficient inventory (Chin et al., 2014; Ramani et al., 2010), as well as to reduce the environmental impact of transportation, with a specific focus on energy consumption and greenhouse gas (GHG) emissions (Pimenta and Ball, 2014). Possible solutions for greening the transportation include reducing the number of echelons involved, reducing the distance travelled by selecting local suppliers, adopting less polluting transportation options, switching towards alternative fuel vehicles, reducing the frequency of transportation by consolidating and grouping orders as well as optimising routing of vehicles (Bouchery et al., 2012; Brandenburg and Rebs, 2015; Büyüközkan and Ifi, 2012; Chin et al., 2014; Dües et al., 2013; Kafa et al., 2013; Mansouri et al., 2015). Products then reach the final customers, who are the final users of the products.

2.3.1.5 End-of-life management

Once products reach the end of their lifecycle, they can be either disposed or become part of a reverse supply chain, which is considered the natural extension for GSCM in order to minimise the amount of waste disposed (Srivastava, 2007). Reverse supply chain is often referred as reverse logistics, which is "the process of planning, implementing, and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal" (Rogers and Tibben-Lembke, 1999). Product recovery activities, namely remanufacturing, reusing and recycling (3Rs), provide renewed value to the products at the end of the lifecycle (Kafa et al., 2013; Srivastava, 2007). The environmental objective of such activities is to maintain products and materials within the techno-sphere in a circular economy perspective without dispersing them into the natural environment (Despeisse et al., 2012b). These activities differ in terms of the industrial processes products undergo:

- Reuse: the entire product, when it still in decent conditions and meets demand of customers, can be distributed again, thus expanding the life span of the product (Despeisse et al., 2012b; Krikke, 2010). Reused products are typically sold in secondary markets due to their perceived inferior value for customers (Srivastava, 2007). Such markets include less lucrative market segments or different geographical areas. Alternatively, the product can be disassembled and only parts of it, such as modules or components, may be re-used in new product (Krikke, 2010; Srivastava, 2007). No virgin resources are used for reuse (Despeisse et al., 2012b).
- Remanufacture: industrial process in which worn out products or parts of products are restored to like-new condition (Srivastava, 2007; Wee et al., 2011). Alike reuse, remanufacture expands life span of products and can be applied at the product level or at the level of single components, although disassembly is more frequent for remanufacturing due to the necessary industrial processes required (Despeisse et al., 2012b). On the other hand, contrary to reuse, remanufactured items do not show differences in price and quality compared to new products (Krikke, 2010). While more profitable, remanufactured products consume some virgin resources to achieve closed-loop circulation of material (Despeisse et al., 2012b).
- Recycle: industrial process in which the old product is dismantled back to obtain its raw materials which are then entered into a new production process (Krikke, 2010; Srivastava, 2007). No identifiable parts of the original product can be found in the new product (Krikke, 2010). Recycling results in a partial loss of value compared to the original product and requires significant energy consumption to restore materials to a quality suitable to be re-introduced in a forward supply chain (Despeisse et al., 2012b). As a result, companies favour remanufacturing and reuse over recycling both for economic and environmental reasons, whenever such options are available (Despeisse et al., 2012b).

3Rs activities are supported by reverse supply chain, which is coordinated through a complex reverse logistics. Challenges specific to reverse supply chains include the coordination requirement of two markets and supply uncertainties (Srivastava, 2007). Supporting activities before products can undergo through 3Rs activities include collection of used products, sorting and quality inspections (Srivastava, 2007).

2.3.2 GSCM practices

The spectrum of green activities identified in Section 2.3.1 can be further elaborated in a number of GSCM practices. These can be categorised in internal and external GSCM practices, depending on their application within or outside organisational boundaries

(Zhang et al., 2018). Internal GSCM practices can be implemented and managed by single organisations to improve their own internal environmental performance and thus contributing to the overall environmental sustainability of the supply chain (Zhang et al., 2018). On the other hand, external GSCM practices entail an inter-organisational perspective, requiring some degree of cooperation with supply chain partners or other stakeholders to reach environmental goals (Zhang et al., 2018; Zhu et al., 2008).

The implementation level of GSCM practices typically increases “the closer a company is located toward the end consumer”(Schmidt et al., 2017). Focal companies are typically found downstream along the supply chain and the environmental pressure arising from consumers held them responsible for the unsustainable behaviour of their upstream suppliers, given their prominent role within the supply chain, thus promoting the adoption of GSCM practices downstream along the supply chain (Gimenez and Tachizawa, 2012).

Certain practices can be both adopted internally, as part of the GSCM practices, and externally, in order to evaluate suppliers. As an example, the adoption of environmental management systems or the ISO 14001 certification can fall among both categories. Table 2.2 provides an extensive list of GSCM practices mentioned in the literature.

Table 2.2: GSCM practices

GSCM Practice	**Source**
Adherence to environmental policies	(Chithambaranathan et al., 2015; Pimenta and Ball, 2015)
Compliance with environmental laws and regulations	(Chithambaranathan et al., 2015; Liou et al., 2015; Malik et al., 2015; Pimenta and Ball, 2015)
Cross-functional cooperation for environmental improvements	(Azevedo et al., 2013)
Eco-design, including cooperation with suppliers/customers for eco-design, lifecycle based design	(Azevedo et al., 2013; Chithambaranathan et al., 2015; Liou et al., 2015; Malik et al., 2015; Pimenta and Ball, 2015)
Eco-labels	(Malik et al., 2015)
Environmental auditing	(Malik et al., 2015)
Environmental collaboration with suppliers/customers	(Azevedo et al., 2013; Chithambaranathan et al., 2015; Kafa et al., 2013; Liou et al., 2015; Pimenta and Ball, 2015)
Environmental Management System (EMS)	(Azevedo et al., 2013; Chardine-Baumann and Botta-Genoulaz, 2014; Chithambaranathan et al., 2015; Liou et al., 2015; Malik et al., 2015; Shen et al., 2013; Tseng, 2011)
Environmental management programs	(Pimenta and Ball, 2015)
Environmental monitoring of suppliers/by customers	(Azevedo et al., 2013; Erol et al., 2011; Pimenta and Ball, 2015)

Environmental risk management systems	(Azevedo et al., 2013)
Environmental training: at the focal company/at suppliers	(Chithambaranathan et al., 2015; Erol et al., 2011; Liou et al., 2015; Pimenta and Ball, 2015; Shen et al., 2013)
Green certifications	(Liou et al., 2015; Malik et al., 2015; Tseng, 2011)
Green innovation	(Chithambaranathan et al., 2015)
Green logistics, including vehicle routing, reverse logistics programs	(Azevedo et al., 2013; Erol et al., 2011; Malik et al., 2015; Miemczyk et al., 2012)
Green operations	(Azevedo et al., 2013; Rao and Holt, 2005; Tseng, 2011)
Green procurement/sourcing, including assessment of suppliers	(Azevedo et al., 2013; Chithambaranathan et al., 2015; Miemczyk et al., 2012; Tseng, 2011)
Green supplier development	(Pimenta and Ball, 2015)
Hazardous materials: reduction of hazardous inputs, hazardous materials management systems	(Azevedo et al., 2013; Chardine-Baumann and Botta-Genoulaz, 2014; Liou et al., 2015; Malik et al., 2015; Pimenta and Ball, 2015; Tseng, 2011)
Integration of total quality environmental management into operations	(Azevedo et al., 2013)
ISO 14000 series certification	(Azevedo et al., 2013; Carvalho et al., 2017; Erol et al., 2011; Malik et al., 2015; Pimenta and Ball, 2015; Rao and Holt, 2005)
Packaging: take-back policy by suppliers, reuse/recycling of packaging, green packaging, take-back policy from customers	(Azevedo et al., 2013; Carvalho et al., 2017; Kafa et al., 2013; Malik et al., 2015; Pimenta and Ball, 2015; Rao and Holt, 2005)
Partnership with green organisations	(Chithambaranathan et al., 2015)
Public disclosure of environmental records	(Malik et al., 2015)
Reduction of energy consumption and/or adoption of renewable sources	(Azevedo et al., 2013; Baumann, 2011; Erol et al., 2011; Rao and Holt, 2005)
Reduction of inventory levels	(Azevedo et al., 2013)
Use of environmentally friendly materials, including recycled inputs	(Azevedo et al., 2013; Chardine-Baumann and Botta-Genoulaz, 2014; Chithambaranathan et al., 2015; Erol et al., 2011; Rao and Holt, 2005; Shen et al., 2013)
Use of environmentally friendly technologies	(Chithambaranathan et al., 2015; Liou et al., 2015; Pimenta and Ball, 2015; Shen et al., 2013; Tseng, 2011)
Waste management: reduction of hazardous and dangerous waste, recyclable waste, waste minimisation	(Azevedo et al., 2013; Chardine-Baumann and Botta-Genoulaz, 2014; Chithambaranathan et al., 2015; Malik et al., 2015; Pimenta and Ball, 2015)
3Rs activities	(Malik et al., 2015; Pimenta and Ball, 2015)

2.3.3 Drivers of GSCM

The GSCM practices identified in Section 2.3.2 are motivated by drivers pushing organisations to initiate such practices (Gimenez and Tachizawa, 2012; Hsu et al., 2013). Factors motivating the adoption of GSCM may arise both from internal and external sources (Rostamzadeh et al., 2015; Varsei et al., 2014; Walker et al., 2008) and are summarised in Table 2.3.

Internal drivers are organisation-related drivers (Walker et al., 2008). These can span from internal values of the organisations, both in the form of environmental mission (Zhu and Sarkis, 2006), socio-cultural responsibility (Hsu et al., 2013; Kannan et al., 2015) or of values transmitted from funders and owners throughout the organisational culture (Walker et al., 2008), to brand reputation (O'Rourke, 2014), green image (Zhu and Sarkis, 2006) or wider company reputation (Abubakar, 2014). Direct win-win situations are also sought by organisations through GSCM, aiming to improve the economic performance by reducing costs (Walker et al., 2008; Zhu and Sarkis, 2006). Indirect economic advantages are also among the internal motivations to adopt GSCM including reducing supply chain disruption risks (O'Rourke, 2014) and improving quality of products (Walker et al., 2008).

On the other hand, external drivers are motivations pushing organisations to adopt GSCM which arise outside organisational boundaries. These drivers are usually classified according to four categories: regulatory drivers, customers drivers, competition drivers and society drivers (Walker et al., 2008).

Regulatory pressure from governments was mentioned as the most prominent external driver to the implementation of GSCM (Diabat and Govindan, 2011; Zhu and Sarkis, 2006), as organisation are forced to exit the market if they do not comply with legislations (Abubakar, 2014). The relevance of the regulatory driver was also confirmed by Brandenburg and Rebs (2015), who identified the government as the most influential stakeholder group in their study on the source of pressures and incentives for SSCM adoption. Although a proactive approach towards legislative requirements is more economically beneficial (Gopalakrishnan et al., 2012), in the majority of instances, a reactive approach is adopted by organisations towards government regulation and legislation in order to achieve compliance, with few exceptions of organisations acting pro-actively anticipating forthcoming regulations (Walker et al., 2008). Regulations at the regional, national or international level are equally acting as a driver depending on the range of operations of the supply chain, potentially with different regulations to comply with for international supply chains (Gopalakrishnan et al., 2012; Zhu and Sarkis, 2006).

Other stakeholders act as driving forces towards the implementation of GSCM, most noticeably customers and competitors. Final consumers are increasingly expecting to minimise the environmental impact associated to their purchases, thus requesting more green products (Hitchcock, 2012; Hsu et al., 2013; Walker et al., 2008). This pressure typically moves upstream along the supply chain, as customers require their suppliers to adopt green supply chain initiatives, especially in the case of large focal organisations which are constantly under scrutiny of media (Walker et al., 2008). Therefore, companies willing to preserve or increase their market shares need to comply with requests from the market.

The second large stakeholder group acting as a motivating force to adopt GSCM are competitors. Pressure from competitors can take the form of technology leaders setting industry norms or legal mandates to be followed or the form of environmental innovation, inducing organisations to adopt GSCM to gain competitive advantage (Hsu et al., 2013; Walker et al., 2008). Finally, other stakeholders, such as NGOs and the wider public, are also calling for transparency on supply chain practices (O'Rourke, 2014; Varsei et al., 2014; Walker and Jones, 2012) and have the potential to damage the image of organisations, thus constituting a last group acting as a driving force towards adoption of GSCM (Walker et al., 2008).

Table 2.3: Drivers for GSCM

Driver	**Source**
Internal	
Organisation-related	
Brand reputation	(O'Rourke, 2014)
Business benefits	(Kannan et al., 2015)
Company reputation	(Abubakar, 2014)
Employee involvement	(Walker et al., 2008)
Environmental mission	(Zhu and Sarkis, 2006)
Green image	(Zhu and Sarkis, 2006)
Internal values	(Baden et al., 2009; Walker et al., 2008)
Investors pressure	(Walker et al., 2008; Walker and Jones, 2012)
Manage economic risk	(Walker et al., 2008)
Quality improvement	(Walker et al., 2008)
Reduce costs	(Walker et al., 2008; Zhu and Sarkis, 2006)
Reduce risks from supply chain disruption	(O'Rourke, 2014)
Socio-cultural responsibility	(Hsu et al., 2013)
Social responsibility	(Kannan et al., 2015)
External	
Regulatory	
Government legislation	(Gopalakrishnan et al., 2012)
Government policy	(Walker and Jones, 2012)
Government pressure	(Brandenburg and Rebs, 2015)
Government regulation	(Walker and Jones, 2012; Zhu and Sarkis, 2006)

Government regulation and legislation	(Diabat and Govindan, 2011) (Abubakar, 2014)
Institutional pressure	(Varsei et al., 2014)
Legislation	(Fabbe-Costes et al., 2011)
Legislative and regulatory compliance	(Walker et al., 2008)
Policy pressure	(Hitchcock, 2012)
Proactive action pre-regulation	(Walker et al., 2008)
Regulation	(Kannan et al., 2015)
Regulatory compliance	(Walker et al., 2008)
Regulatory measures	(Hsu et al., 2013)
Regulatory pressure	(Dubey et al., 2015; Hitchcock, 2012; O'Rourke, 2014)
Customers	
Consumer demand for green products	(Hitchcock, 2012)
Customer pressure	(Brandenburg and Rebs, 2015; Fabbe-Costes et al., 2011; Hsu et al., 2013; Kannan et al., 2015; Walker et al., 2008; Walker and Jones, 2012)
Marketing pressure	(Abubakar, 2014; Dubey et al., 2015; Walker et al., 2008)
Reduce risk of consumer criticism	(Walker et al., 2008)
Competition	
Competitive advantage	(Varsei et al., 2014; Walker and Jones, 2012)
Competitors' green strategy	(Zhu and Sarkis, 2006)
Competitive pressure	(Abubakar, 2014; Dubey et al., 2015)
Competitive pressure for cost reduction	(O'Rourke, 2014)
Competitive pressure for supply chain innovation	(O'Rourke, 2014)
Competitor pressure	(Hsu et al., 2013)
Society	
NGOs pressure	(Varsei et al., 2014; Walker and Jones, 2012)
Public pressure	(Walker et al., 2008)
Stakeholder pressure	(Abubakar, 2014; Varsei et al., 2014; Walker et al., 2008)
Stakeholder pressure for transparency	(O'Rourke, 2014)

2.3.4 Multi-tier GSCM

Traditionally, the driving forces from stakeholders pressuring organisations to include sustainability concerns within their supply chain operations initially targeted focal firms, as they play a leading role within the supply chain. As a result, SSCM and GSCM naturally stemmed from focal companies towards other supply chain members. Focal companies identified 1st tier suppliers and customers as the natural business partners to implement SSCM and GSCM (Ahi and Searcy, 2015a).

However, this approach is not sufficient in the contemporary competitive environment, where supply chains are increasingly long and complex due to increasing outsourcing and offshoring practices, being built by a higher number of tiers (Mena et al., 2013). In this context, organisations are required to understand not only their first-tier suppliers sustainability profile but also to capture the environmental and social profiles of the lower-tier suppliers in order to avoid underestimating the actual sustainability impact of the supply chain (Genovese et al., 2013; Miemczyk et al., 2012). Multiple organisations were confronted with social and environmental scandals due to unsustainable behaviours of their lower-tier suppliers leading to corporate reputation damage and economic losses (Grimm et al., 2016, 2014; Miemczyk et al., 2012; Vachon and Mao, 2008). For example, social scandals hit Nike, whose sub-suppliers were found to employ children in their facilities, Zara, whose Brazilian 2nd tier suppliers were charged with "sweatshop-like working conditions" and Apple that was criticised for modern slavery conditions at its Chinese sub- suppliers (Gimenez and Tachizawa, 2012; Grimm et al., 2016; Jabbour et al., 2018; Vachon and Mao, 2008; Wilhelm et al., 2016a). Environmental scandals affected Unilever, Nestlé and Kimberley Clark, which were all associated with deforestation and unsustainable forestry practices in their extended supply chain as well as Zara and Mattel, whose subcontractors used toxic chemicals and lead paint in their production processes respectively (Dou et al., 2017; Grimm et al., 2016; Hartmann and Moeller, 2014; Miemczyk et al., 2012; Wilhelm et al., 2016).

None of these companies was directly involved in any unsustainable practice, however they were held responsible for the misconduct by consumers, as their prominent role within the supply chain was recognised, determining a "chain liability effect" (Gimenez and Tachizawa, 2012; Hartmann and Moeller, 2014). Focal companies require therefore to reduce such chain liabilities by managing their multi-tier supply chains and not only their 1st tier suppliers (Hartmann and Moeller, 2014; Tachizawa and Wong, 2014). A synthesised landscape of the state-of-the-art in multi-tier GSCM is provided in Appendix A.2, showing the recent emergence of the topic, with the oldest publication by Mena et al. (2013). Section 2.3.5 specifically explores approaches for sub-supplier management in multi-tier GSCM in order to address objective 2 (O2): "Understand the key mechanisms regulating sub-supplier management in multi-tier supply chains, with a particular focus on green supply chain management (GSCM)".

2.3.5 Approaches for sub-supplier management in multi-tier GSCM

Focal companies may embrace a number of different approaches to deal with lower-tier suppliers. In their work focused on a three-tiers supply chain, Mena et al. (2013) identified open, transitional and closed triads as the options faced by focal firms to interact with each 2nd tier suppliers, depending on the existence and nature of the contact between focal company and 2nd tier suppliers (Figure 2.5). An 'open' triad resembles a traditional supply chain structure with a linear flow of product and information and no direct contact between the buyer and supplier's supplier. On the other hand, such direct contact exists in a ‘closed’ triad. Finally, the ‘transitional’ is a temporary supply chain structure, where the triadic approach is shifting from ‘open’ triad to ‘closed’ triad by establishing links between the buyer and supplier’s supplier. A direct contact between focal company and 2nd tier supplier is deemed necessary to influence key product characteristics and generates stronger perceived stability, whereas the open triad approach require fewer management resources from the focal company (Mena et al., 2013).

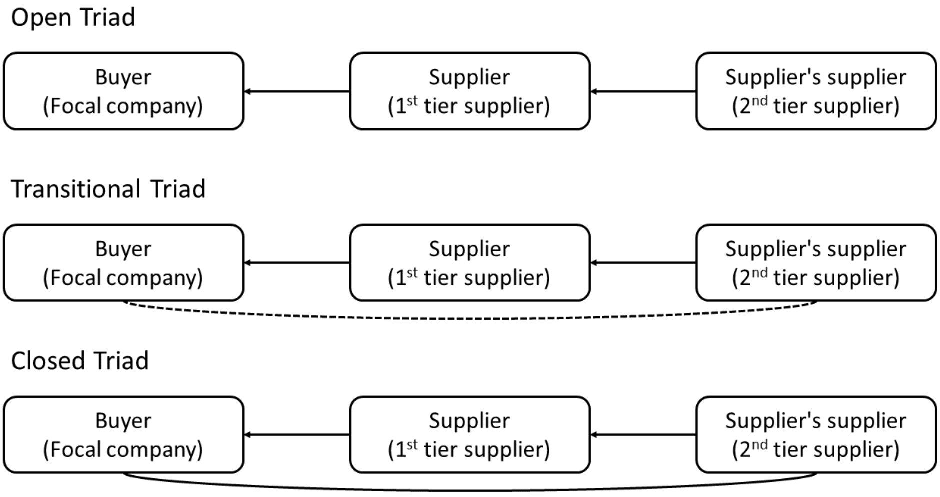

Figure 2.5: Triadic multi-tier SCM approaches (adapted from Mena et al., 2013)

A similar framework is proposed by Tachizawa and Wong (2014), who focused specifically on multi-tier sustainable supply chains and extend their focus to any lower-tier supplier beyond triadic supply chains. Focal companies can select from four potential approaches to deal with lower-tier suppliers regarding sustainability, as illustrated in Figure 2.6: ‘Don’t bother’, ‘Working with third party’, ‘Direct’ and ‘Indirect’. These approaches are typically implemented separately, although hybrid approaches have emerged recently, as a result of a combination of ‘Direct’ and ‘Indirect’ approaches (Dou et al., 2017).

While the ‘Don’t bother’ approach neglects any interest for the sustainability of lower-tier suppliers with considerations of sustainability aspects limited to 1st tier suppliers only (Meinlschmidt et al., 2018; Tachizawa and Wong, 2014), the ‘Direct’ approach implies a stringent control of focal companies over lower-tier suppliers (Tachizawa and Wong, 2014). The ‘Direct’ approach can be holistic, thus being applied to all lower-tier suppliers, or be selectively applied to specific products or geographical regions (Meinlschmidt et al., 2018). Finally, a ‘Direct’ approach can be triggered by specific events, such as sustainability scandals in the multi-tier supply chains (Meinlschmidt et al., 2018).

Two alternative options are faced by focal firms that can reach indirectly the lower-tier suppliers either through third party, such as non-governmental organisation, industry association or governmental bodies, or through their 1st tier suppliers. The ‘Third party’ approach, also referred as alliance-based indirect approach (Meinlschmidt et al., 2018), rely on external entities to elaborate sustainability standards and monitor lower-tier suppliers (Meinlschmidt et al., 2018; Tachizawa and Wong, 2014). On the other hand, the 'Indirect' approach prescribes that focal company establishes contact with lower-tier suppliers through 1st tier suppliers (Tachizawa and Wong, 2014), which is an example of cross-tier collaboration (Koh et al., 2012). The 'Indirect' approach thus implies that 1st tier suppliers evaluate, select and develop their own suppliers in a SSCM perspective (Meinlschmidt et al., 2018). The approach can be applied consistently through all 1st tier suppliers, thus being a compliance-based indirect approach, or to a sub-set of 1st tier suppliers, which is referred as multiplier-based indirect approach (Meinlschmidt et al., 2018). This logic can be replicated in the upstream supply chain until the *n-th* tier supplier is reached (Tachizawa and Wong, 2014).

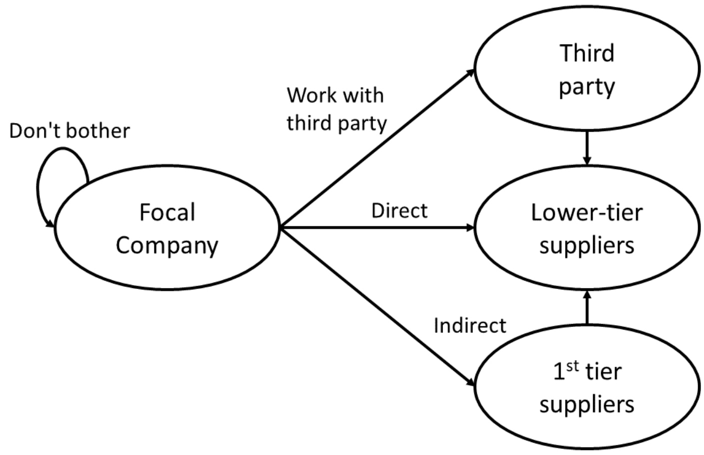

Figure 2.6: Multi-tier SSCM approaches (adapted from Tachizawa and Wong, 2014)

Wilhelm et al. (2016) built up on the 'Indirect' approach, recognising the complexity and substantial inapplicability of other approaches for the majority of lower-tier suppliers due to the limited control and power of focal companies on them, thus calling for an active role of 1st tier suppliers in disseminating sustainability requirements of focal companies further upstream in the supply chain.

2.4 Performance assessment

Performance assessment aims to evaluate the efficiency and/or the effectiveness of an action (Neely et al., 1995). In the field of operations management, such action is identified in the whole of operations of an organisation. Efficiency is associated to the economical use of resources, while effectiveness to the degree objectives are being met (Tajbakhsh and Hassini, 2015a).

Performance assessment is a crucial element to "underpin improvement and the reporting of business performance" (Taticchi et al., 2013), with both external and internal applications. Externally, it can support reporting, while internally it can support controlling the business in a historical perspective as well as driving the business in a prospective orientation in a continuous improvement perspective (Hervani et al., 2005).

Several taxonomies for organisational performance assessment have been proposed in the literature, including the management level to measure (strategic, tactical, operational), tangible vs. intangible measures, product vs. process level (Hervani et al., 2005). Moreover, the assessment needs to be linked to corporate strategy and define clear accountability paths for results (Hervani et al., 2005).

Performance assessment is usually integrated into organisational operations through performance measurement and management systems, which gather, elaborate and analyse information to support decision-making (Taticchi et al., 2013). Performance measurement systems need to be balanced to bring together different metrics and perspectives of organisations in a holistic view, while being at the same time dynamic, constantly reviewing objectives and priorities in order to be up-to-date with evolving internal and external contexts (Kaplan and Norton, 1992; Taticchi et al., 2013).

The topic of performance assessment is further explored in Section 2.4.1, with respect to supply chain performance assessment, and in Section 2.4.2, with respect to sustainability performance assessment.

2.4.1 Supply chain performance assessment

Assessing performance at the supply chain level poses a number of additional challenges compared to organisational performance assessment, due to the increased complexity caused by the involvement of multiple organisations (Hassini et al., 2012; Hervani et al., 2005; Shaw et al., 2010; Yakovleva et al., 2012). Challenges include lack of trust among organisations; lack of understanding and control of inter-organisational metrics; lack of standardised data and metrics; conflicting objectives and goals among organisations; cultural differences among organisations; inclination towards local optimisation rather than systemic approaches; information systems not designed for supply chain performance; difficulties linking measures to customer value (Gopal and Thakkar, 2012; Hervani et al., 2005; Qorri et al., 2018; Taticchi et al., 2013). Moreover, from a methodological perspective, it is difficult to attribute performance results to one particular entity within the chain (Hervani et al., 2005).

Critical success factors for the implementation of supply chain performance assessment include a coordination of different supply chain members and the definition of common supply chain-wide goals against which each entity in the supply chain should be measured (Hervani et al., 2005). The supply chain perspective should not be limited to the design stage of the performance measurement system but should be consistently present throughout the implementation through constant monitoring (Hervani et al., 2005). Finally, the inclusion of non-financial metrics along with the development of new measures specifically designed for the supply chain context are also considered critical success factors for supply chain performance assessment (Hervani et al., 2005).

The Supply Chain Operations Reference (SCOR) model is an example of a reference model to evaluate and compare supply chain activities and performance developed by the practitioners' community (APICS, 2014). The SCOR model is extensively adopted by different industries worldwide (Bai and Sarkis, 2014; Slack et al., 2013). It captures the 'as-is' state of each process and the desired 'to-be' state of six management processes: Plan, Source, Make, Deliver, Return and Enable (APICS, 2014; Huang et al., 2005). The SCOR model targets primarily the economic dimension to determine supply chain performance (Bai and Sarkis, 2014). As a result, it was targeted with criticism due to the lack of non-financial metrics, especially of environmental and social metrics, limiting its extension from SCM to SSCM (Bai and Sarkis, 2014). Moreover, while functional to improve process understanding and supply chain performance, its implementation for SMEs still remains critical (Slack et al., 2013).

2.4.2 Sustainability performance assessment

Performance assessment traditionally targeted only economic aspects, but increased competition on non-financial aspects forced companies to broaden their horizon to other factors (Gopal and Thakkar, 2012; Jakhar, 2014; Taticchi et al., 2013). As a result, assessing environmental and social performance has become increasingly popular as its strategic role was recognised (Carter and Rogers, 2008; Rao and Holt, 2005).

Devuyst et al. (2001) defined sustainability assessment as "a tool that can help decision-makers and policy-makers decide which actions they should or should not take in an attempt to make society more sustainable" (Angelakoglou and Gaidajis, 2015; Ness et al., 2007). Sustainability assessment supports the decision-making process by providing information targeting different spatial spectrum, i.e. local and global impacts, as well as different temporal spectrum, i.e. short and long term perspectives (Abubakar, 2014).

Sustainability performance assessment manages to achieve a holistic view of the performance of an organisation beyond economic dimension, however the sustainability complexity and its multi-dimensional issues increase the challenges associated to the assessment process (Lozano, 2012a). The multidisciplinary and interdisciplinary nature of sustainability was also pinpointed by Sala et al. (2015), as one of the main challenge of sustainability assessment along with ensuring transparency of the assessment and the replicability and comparability of the assessment in complex systems.

Extensive research has covered traditional economic and operational performance assessment within sustainability performance assessment, therefore Section 2.4.2.1 and Section 2.4.2.2 provide a synthetic overview of environmental and social sustainability performance assessment respectively.

2.4.2.1 Environmental sustainability performance assessment

According to ISO 14031, environmental performance assessment is “an internal process and management tool designed to provide management with reliable and verifiable information on an ongoing basis to determine whether an organization’s environmental performance is meeting the criteria set by the management of the organization” (Jasch, 2000).

According to Jasch (2000), environmental performance assessment has the following purposes:

- Communication for environmental reports
- Cross-case benchmarking: evaluation of environmental performance between firms
- Longitudinal benchmarking: comparison of environmental performance over time
- Derivation and pursuit of environmental target
- Highlighting of optimisation potential
- Identification of market chances and cost reduction potentials
- Technical support for Environmental Management Systems

Indicators are typically used to assess the environmental sustainability performance, in order to synthesise the vast amount of environmental data available at organisations in a comprehensive and concise way (Abubakar, 2014; Jasch, 2000). An indicator is a piece of information that summarizes or highlights what is happening in a dynamic system (Tajbakhsh and Hassini, 2015a). Environmental indicators need to satisfy a number of criteria to be effective, including being reliable, relevant to organisations’ objectives and to the needs of the stakeholders, comparable across entities and against relevant benchmarks and easy to understand (Schaltegger et al., 1996).

A first classification of environmental indicators is offered by the European Environment Agency typology, which distinguishes five types of indicators (European Environment Agency, 2003):

- Descriptive indicators (Type A): showing the development of a variable over time, they aim to describe what is happening to the environment;
- Performance indicators (Type B): similar to descriptive indicators, but connected to target values, they provide context to descriptive indicators, determining the gap between current and expected performance;
- Efficiency indicators (Type C): providing insights on the efficiency of processes and products, they capture the relationship between environmental pressures and human activities, highlighting improvements;
- Policy-effectiveness indicators (Type D): relate environmental variables to policy efforts, thus being mostly used at high level by policy makers;
- Total-welfare indicators (Type E): aggregated indicators, that relate the environmental variables to wider socio-economic context.

Additionally, environmental indicators could be based on their qualitative or quantitative nature (Vasileiou, 2002), in line with the performance assessment definition by Neely et al. (2002). Environmental indicators are predominantly quantitative, increasing the reliability of the results (Ahi and Searcy, 2015a). Moreover, environmental indicators could be further divided among absolute environmental indicators, which are expressed according to a fixed measurement scale and relative indicators that relate the impact value to a reference value (Mintcheva, 2005). Absolute values are helpful to understand the overall environmental impact associated with an activity of the system under analysis; however, they are prone to fluctuation as a result of changes in the produced outputs thus hiding the real changes in the environmental performance (Michelsen et al., 2006). As different systems naturally present different features, absolute indicators lose validity in the benchmarking of different systems, as they do not meet the criterion of comparability across entities. As a result, different systems are not strictly comparable using absolute indicators (Wiedmann et al., 2009). On the contrary, relative indicators overcome this limitation (Brent and Visser, 2005; Michelsen et al., 2006; Schaltegger et al., 2008; Wiedmann et al., 2009), with multiple reference values available in the literature to obtain relative indicators.

Life cycle analysis (LCA) is a widely recognised technique to evaluate the environmental performance of products in a lifecycle perspective. LCA adopts as reference value the concept of functional unit, closely associated to the benefit given to the final user by a product (Finnveden et al., 2009; Kravanja and Čuček, 2013; Mellor et al., 2002; Nasir et al., 2017). A typical example is the comparison of paper towel against electric hand dryer, both providing the benefit to dry hands of the user. However, the selection of the functional unit is based on the design stage of the LCA study and thus is heavily affected by assumptions (Dong et al., 2018). Additionally, LCA studies embody assumptions also in the data adopted which typically are not primary data sourced from actual practices but are collected from dedicated databases increasing the uncertainty of results and ultimately compromising even the comparability of similar studies assessing the environmental performance of the same type of products (Guldbrandsson and Bergmark, 2012; Kravanja and Čuček, 2013). Alternative reference units include the units produced (Abdallah et al., 2012; Du et al., 2015; Koh et al., 2012; Lee, 2012), the weight of product output (Chaabane et al., 2011; Tan et al., 2014), the volume of the product output (Tokos et al., 2012), as well as economic reference units (Acquaye et al., 2017; Huppes and Ishikawa, 2005; Kicherer et al., 2006). Section 2.4.2.2 expands on the use of monetary units to generate relative environmental indicators.

2.4.2.2 Eco-efficiency and eco-intensity

Relative indicators obtained adopting economic reference units fall within the type C indicators according to European Environment Agency classification scheme (European Environment Agency, 2003; Vasileiou, 2002). As such, they belong to the family efficiency indicators, leading to the definition of several intertwined concepts and definitions (Huppes and Ishikawa, 2005). Eco-efficiency has been often used to refer to the broad family of indicators using economic reference units and was defined in its broadest meaning as “the efficiency with which ecological resources are used to meet human needs” by the Organisation for Economic Co-Operation and Development (OECD). However, more specific terms have been adopted to describe different relative environmental indicators using monetary units as the reference unit. The different definitions depend on the economic reference unit adopted and on the direction of the ratio, e.g. environmental impact divided by economic reference unit or vice versa, leading to four options summarised in Table 2.4.

Table 2.4: Type C environmental indicators (adapted from Huppes and Ishikawa, 2005)

Ratio	Economic cost	Economic value
Economic divided by environment	Environmental improvement cost	Eco-efficiency
Environment divided by economy	Environmental cost-effectiveness	Eco-intensity

Adopting cost as the economic reference unit, the focus is on reducing costs per environmental impact, which is labelled as environmental improvement cost (Huppes and Ishikawa, 2005). Inverting the ratio, this becomes the environmental cost-effectiveness (Huppes and Ishikawa, 2005). Eco-efficiency and eco-intensity are the two rations generated using economic value as the economic reference unit. In its strict sense, eco-efficiency is thus defined as the ratio of the economic value created and the sum of environmental pressures generated by an economic activity (WBCSD, 2000). The value is usually defined as the value of production (Huppes and Ishikawa, 2005; Ichimura et al., 2009; WBCSD, 2000), however few exceptions refer to the added value instead (European Environment Agency, 2003). In line with the more wide-spread definition, value of production is considered to be the numerator of the ratio in this research. Eco-intensity reverses this ratio, being the “environmental impact per unit of production value” (Huppes and Ishikawa, 2005).

2.4.2.3 Social sustainability performance assessment

Performance assessment of the social dimension of sustainability has received less attention compared to the environmental dimension (Ahi and Searcy, 2015a; Govindan et al., 2017; Miemczyk et al., 2012; Seuring, 2013; Taticchi et al., 2013). Social sustainability performance assessment tools need to capture two sub-areas of social sustainability, namely human and social. The former one is directly linked to economic growth as it includes all individual skills that enhance an improved performance on the working place, whereas the latter one refers to collective actions that provide benefit to the entire society (Yusuf et al., 2013). An extended impact categorisation is offered by Jørgensen et al. (2008), who define two further categorisation for each of the sub-area. “Human rights” and “Labour practices and decent working conditions” fall within the human sub-area, whereas “Society” and “Product responsibility” within the social sub-area. Based on these categorisation and mirroring the development of LCA, Jørgensen et al. (2008) tried to set the grounds of social life cycle assessment (SLCA) methodologies, which however do not reach the same degree of standardisation of environmental LCA (Halog and Manik, 2011).

Nevertheless, the reduced amount of literature tackling social sustainability performance assessment in contrast to environmental sustainability performance assessment is largely due to the critical multi-faceted nature of social sustainability and the difficulty to capture social performance into quantitative indicators. Qualitative indicators typically adopted in social sustainability performance assessment are not considered as reliable as quantitative ones, suffering from biases in their definition and calculation, as well as being more difficult to compare and communicate (Ahi and Searcy, 2015b; Tsoulfas and Pappis, 2008). On the other hand, Hutchins and Sutherland (2008) highlighted in their review on social sustainability indicators that the “majority of the social indicators are subjective and qualitative”, a finding confirmed in a later review by Ahi and Searcy (2015b). This is seen as a drawback of social indicators as it limits the incorporation of such data into decision support methods required by organisations (Hutchins and Sutherland, 2008). As the prevailing mode of enquiry of this research is quantitative, the inclusion of social indicators would affect the overall structure, reliability and comparability of results. As a result, social dimension of sustainability remained outside of the scope of this research, as detailed in Section 1.3.

2.4.2.4 Industrial Standards in Sustainability Assessment

Practitioners and industry also captured the need to track the environmental performance of companies. Several tools to assess the sustainability of organisations have been developed, including environmental management systems, socially responsible investment indices and sustainability reporting schemes.

Environmental Management Systems

An Environmental Management System (EMS) is a set of processes and practices that enable an organisation to reduce its environmental impacts and increase its operating efficiency (U.S. Environmental Protection Agency, 2017). The International Organization for Standardization, being the leading international non-governmental organisation for standards setting, developed a series of standard to address environmental management, which are labelled as ISO 14000 series. ISO 14001 is the cornerstone of this series, detailing the basic requirements to establish an EMS and offering to organisations a certification associated to their environmental processes (Beske et al., 2008; Nagel, 2003). The adoption of environmental management systems is voluntary, however given its international recognition, it is often necessary to meet customer requirements in the supply chain (Nawrocka et al., 2009). ISO 14001 is highly regarded in the green supplier selection process to limit environmental risk associated to the upstream supply chain (Beske et al., 2008; Chiarini, 2015; Tseng and Chiu, 2013). The ISO 14000 family also include standards tackling environmental labels, eco-design and environmental performance (Nawrocka et al., 2009). ISO 14015 addresses the environmental assessment of sites and organisations, ISO 14031 provides guidelines to environmental performance evaluation, while ISO 14040 focuses on life cycle assessment (ISO, 2009). The ISO 14000 family however deals with guidelines and practices linked to sustainability assessment, rather than prescribing detailed methods to carry out the assessment (Tsoulfas and Pappis, 2006).

Socially responsible investment indices

Socially responsible investment indices have been developed to capture environmental and social metrics of organisations, along with economic indicators, which are considered essential features to inform shareholders on the long-term value outlook of companies (Salvado et al., 2015). Socially responsible investment indices include the Dow Jones Sustainability Index (DJSI) and the FTSE4Good Sustainability Indexes (Ahi and Searcy, 2015a). DJSI, launched in 1999, assess the sustainable performance of globally leading organisations through a composite sustainability index, which adopts a best-in-class method to classify and rank companies (Angelakoglou and Gaidajis, 2015; Carter and Rogers, 2008; OECD, 2009). A set of sustainability criteria are used, with economic dimension weighting 50% more heavily than the other two sustainability dimensions (Angelakoglou and Gaidajis, 2015; Jakhar, 2015). Environmental aspects evaluated include environmental reporting, environmental management systems, operational eco-efficiency and environmental policies (Angelakoglou and Gaidajis, 2015). The FTSE4Good Sustainability aims to assess the performance of companies that meet globally accepted corporate sustainability standards (Angelakoglou and Gaidajis, 2015; Singh et al., 2012). Assessment criteria are revised on a regular basis, and differently from DJSI, do not include economic indicators (Jakhar, 2015; Singh et al., 2012). Environmental evaluated aspects include environmental management and climate change, with a focus on the accountability of organisations towards these aspects rather than on the actual performance (Angelakoglou and Gaidajis, 2015). While both socially responsible investment indices are widely accepted by industries and markets (Angelakoglou and Gaidajis, 2015), they limit the evaluation to single organisations and do not “capture the challenges of measuring sustainability at the level of the supply chain” (Ahi and Searcy, 2015a).

Sustainability Reporting

Sustainability reporting is a voluntarily action taken by organisations to share their sustainability practices and performance with stakeholder and the wider public (Finkbeiner, 2016). Sustainability reporting is focused on achieving three main goals: transparency and communication to stakeholders, improvement of the operations and strategy alignment (Taticchi et al., 2013). Leading schemes for sustainability reporting include Global Reporting Initiative (GRI), Carbon Disclosure Project (CDP) and United Nations Global Compact (Finkbeiner, 2016; Wilhelm et al., 2016).

GRI, first launched in 1997, provides a framework to assess the triple-bottom-line performance of organisations through over one hundred indicators and to report it to stakeholders (Ahi and Searcy, 2015a; Angelakoglou and Gaidajis, 2015; Lee, 2012; Meixell and Luoma, 2015). Coming from a third-party non-profit organisation, GRI framework is aiming to progressively institutionalise sustainability reporting in a more standardised format (Angelakoglou and Gaidajis, 2015; Morali and Searcy, 2012; Sloan, 2010). GRI reporting scheme is widely applied and recognised internationally, however it has been criticized for being unbalanced towards the accountability of organisations towards sustainability rather than targeting the actual sustainable performance (Angelakoglou and

Gaidajis, 2015; Meixell and Luoma, 2015). Moreover, while GRI stresses that supply chain issues need to be addressed in the consideration of the sustainability context, organisations are largely not achieving to disclose “indirect carbon impacts produced from corporate operations”, thus showing a criticality in extending the reporting scheme from the single organisation to the supply chain level (Ahi and Searcy, 2015a; Angelakoglou and Gaidajis, 2015; Lee, 2012).

Carbon Disclosure Project (CDP) is an investor-driven initiative, founded in 2003, which also developed an environmental sustainability reporting scheme, focused originally on emissions to air and recently extended to water consumption (Finkbeiner, 2016; Fritz et al., 2017; Renewable Choice Energy, 2012). Organisations reporting through CDP are required to publish their emissions and water footprint and to identify actions to reduce environmental impact in the future (Trappey et al., 2012). In 2007, CDP expanded the reporting scheme to include also emissions arising from the supply chain – i.e. Scope 3 emissions – through a standardised global framework to raise awareness on the potential environmental impact of the supply chain and manage the associated risks (Renewable Choice Energy, 2012; Tidy et al., 2016), however CDP still collects primary data with a predominant gate-to-gate approach and thus lacks in adequately taking into account the supply chain environmental impact (Finkbeiner, 2016).

Finally, UN Global Compact is another voluntarily reporting scheme, launched in 1999 by United Nations. Adopted by over 7700 companies worldwide, UN Global Compact is based on ten principles tackling not only environmental but also social sustainability, including themes such as human rights and labour conditions (Lozano, 2015; OECD, 2009; Schaltegger et al., 2008).

However, similarly to the socially responsible investment indices, also sustainability reporting schemes adopted by organisations suffer from the drawback of not adequately capturing the supply chain of organisations in the assessment (Finkbeiner, 2016).

Green SCOR

Green SCOR is a performance evaluation framework, which has been an add-on to SCOR model since version 9.0, proposing a set of strategic environmental metrics to allow the SCOR Model to be used as a framework for environmental accounting as well (APICS, 2014; Boukherroub et al., 2014). Five metrics, listed in Table 2.5, can be measured for each of the SCOR level 3 processes and later be aggregated to create a level 2 and level 1 metrics, thus being applied at the strategic, tactical and operational level (APICS, 2014). Green SCOR encourages the use of secondary data to measure the environmental metrics, adopting sources such as environmental agencies, like U.S. Environmental Protection Agency, and industry associations (APICS, 2014).

The advantages of this framework include a clear allocation path of the environmental impacts to specific processes, thus guiding towards performance improvement and providing foundation for effective benchmarking (APICS, 2014). Benefiting from the same hierarchical structure of the SCOR model, Green SCOR allows both to narrow down strategic goals into specific activities to carry out a root cause analysis as well as end-to-end supply chain optimisation around environmental performance, spanning from the strategic to the operational level (APICS, 2014).

On the other hand, the limitations include its applicability and coverage of environmental impacts (APICS, 2014; Lenny S.C. Koh et al., 2012). Moreover, some environmental aspects are overlooked (Lenny S.C. Koh et al., 2012), as the framework only tackles environmental outputs released to the environment without considering the consumption of natural resources.

Table 2.5: Green SCOR (adapted from APICS, 2014)

Metric	Units	Basis
Carbon Emissions	Tons CO_2 equivalent	This is the unit of measure currently used for greenhouse gas emissions and is a measure of the climate impact from CO2 and other global warming air emissions
Air Pollutant Emissions	Tons or kg	This would include emissions of major air pollutants (COx, NOx, SOx, Volatile Organic Compounds (VOC) and Particulate). These are the major emissions that U.S. EPA tracks
Liquid Waste Generated	Tons or kg	This includes liquid waste that is either disposed of or released to open water or sewer systems (these emissions are generally listed on water emissions permits)
Solid Waste Generated	Tons or kg	The total solid waste generated by the process
% Recycled Waste	Per cent	The per cent of the solid waste that is recycled

2.5 Performance assessment methods for GSCM

The overlapping between the fields of GSCM (Section 2.3) and performance assessment (Section 2.4) defines the area of performance assessment for GSCM (Figure 2.7). This section constitutes the core of the literature review process, as detailed in Figure 2.1, and aims to identify quantitative methods developed to assess the environmental performance of supply chains and to classify and evaluate their key features, thus addressing objective 1 (O1).

The entire Section 2.5 is largely based on the systematic literature review presented in the work entitled “Environmental performance measurement for green supply chains: A systematic analysis and review of quantitative methods” (2018), published in the International Journal of Physical Distribution & Logistics Management, Volume 48, Issue 8, Pages 765-793 (Tuni et al., 2018). The main findings of the systematic literature review are reported in this section, whereas additional bibliometric material and an industry-based classification of the reviewed papers is available in Appendix A.1.

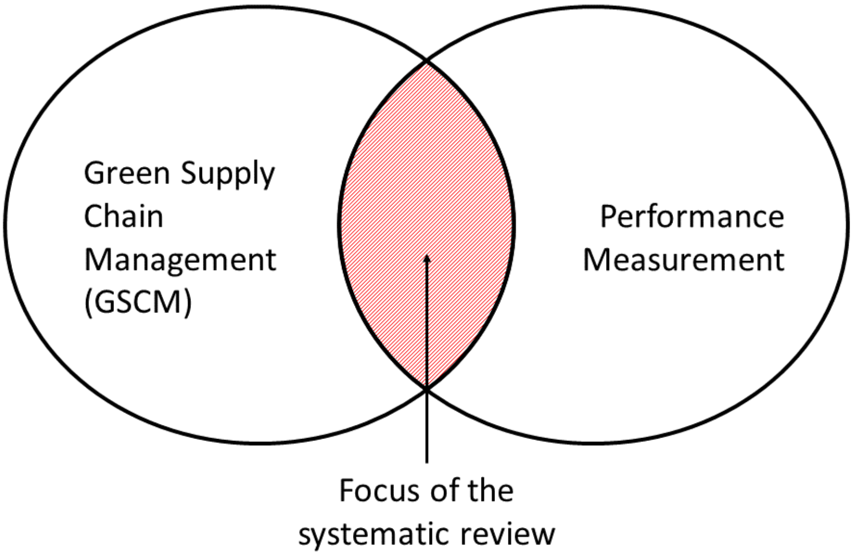

Figure 2.7: Focus of the systematic literature review

2.5.1 Systematic review approach

Since the literature review at the intersection of performance assessment and GSCM is the core of the literature investigation, a systematic process was adopted to search the literature, allowing a transparent and structured approach to investigate the body of knowledge in the field (Fink, 1998). A systematic review process was selected as it increases the reliability of the review as well as better informing the definition of the research gap and the justification of the research question (Tranfield et al., 2003). The process followed to conduct the systematic literature review (Figure 2.8) is based on Jesson et al. (2011) but applies the inclusion and exclusion criteria stage twice, during the database search before the quality appraisal stage and later at the stage of screening of titles, abstracts and articles.

Systematic reviews are guided by review questions (Tranfield et al., 2003). The review question (REVQ) directing this review process was phrased as: “What methods have been developed by researchers to measure the environmental performance of supply chains?” The review question was further developed into four research sub-questions:

REVQ1: What environmental performance metrics are adopted at the supply chain level?

REVQ2: What extent of the supply chain, both upstream and downstream from the focal firm, are environmental performance measurement methods and related metrics addressing?

REVQ3: What are the quantitative methods adopted to measure the environmental performance of supply chains?

REVQ4: What is the main purpose of the environmental performance assessment?

Review questions are the cornerstones in the development of the review and provide a basis to proceed in the subsequent stages of conducting the review (Tranfield et al., 2003), which include the selection of document sources and the determination of inclusion and exclusion criteria. Two databases were selected for sourcing the articles. Scopus, which is the largest database of peer-reviewed journals, specifically in the field of management and engineering, as acknowledged by other scholars (Ahi and Searcy, 2013; Fahimnia et al., 2015a), was combined with Web of Science, which has a particular focus on management issues (Mariano et al., 2015; Taticchi et al., 2014).

A structured combination of keywords was selected to conduct the database search, as illustrated in Figure 2.9. The four groups of terms encapsulate the scope of the review by highlighting the required supply chain context and focus on environmental dimensions in the first two keyword groups, whereas the third and fourth keyword groups target the approach of the environmental performance measurement.

Published articles up to 2015 were included in the search, whereas the selected subject areas, according to Scopus' classification were: "Engineering", "Business, Management and Accounting", "Decision Sciences", "Environmental Science", "Social Sciences", "Mathematics", "Energy", "Economics, Econometrics and Finance", "Chemical Engineering", "Materials Science", "Earth and Planetary Science", "Chemistry" and "Multidisciplinary". Web of Science offered similar research areas, despite a perfect matching between the areas of the two databases was not achievable. Since the literature review investigation is multidisciplinary in nature, the inclusion criteria for subject areas were not too restrictive on purpose in order to avoid the exclusion of any relevant paper through this constraint. Finally, only articles published in English language in peer-reviewed journals were considered: papers published in conference proceedings were excluded, as they do not always undergo the rigorous process of peer-reviewing, which is assumed as evidence of the quality appraisal of selected papers.

The total of 4,532 papers resulting from the keyword combination search went through a multiple stage-gate process. Initially, duplicate papers identified in both databases were removed, decreasing the sample size to 3,380. Then, article titles were screened for relevance, leaving 710 papers. Abstract screening was subsequently performed, reducing the total number to 185 papers. To increase the reliability of the research, two reviewers performed these stages independently and subsequently compared the results: whenever their opinions were not aligned, a discussion was undertaken until final consensus on inclusion or exclusion of papers was reached. The overall count of papers further dropped to 176, as nine papers were not accessible in full text. Finally, articles satisfying the inclusion criteria for both title and abstract were read in full and went through the content analysis stage.

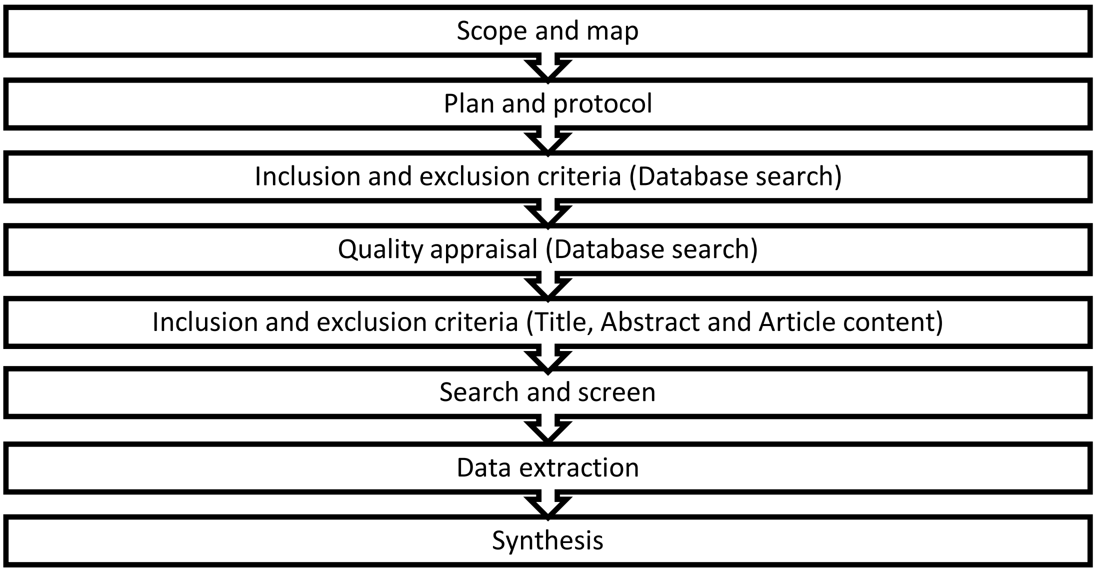

Figure 2.8: Systematic literature review process (based on Jesson et al., 2011)

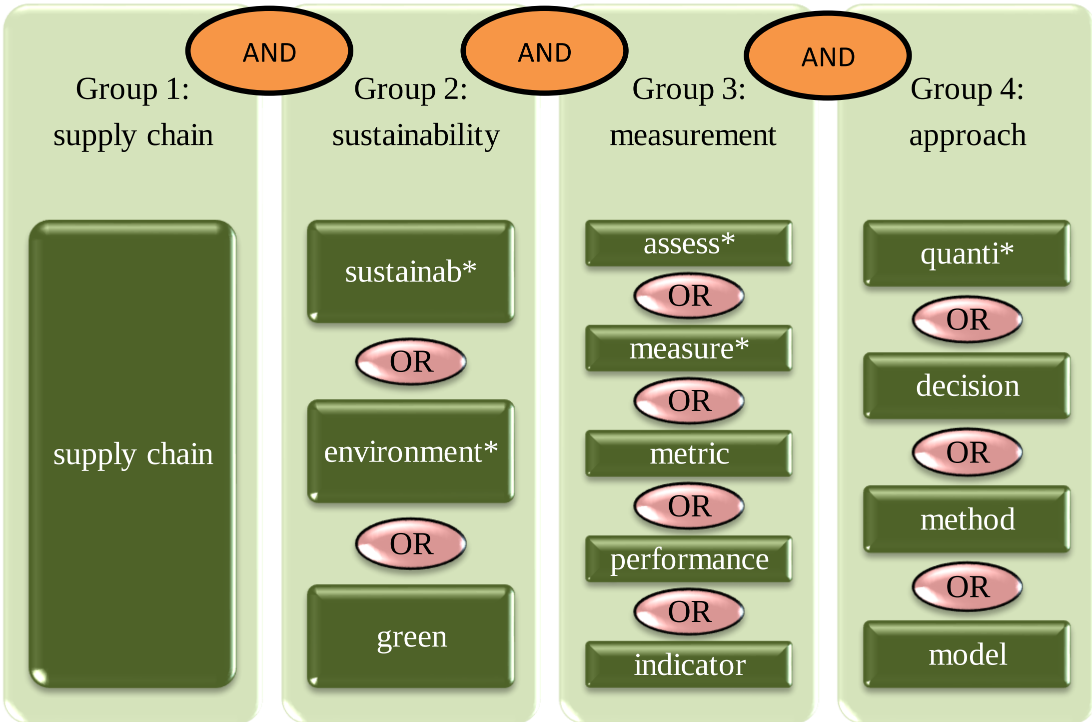

Figure 2.9: Keywords used in the systematic review

The criteria for inclusion at the content analysis stage were:

- Methodological dimension:

    - Explicit presentation of a method to assess environmental performance at the supply chain level. Applications or case studies only, without an explicit methodological contribution, were excluded;
    - Quantitative element in the methods should be explicit;
- Supply chain dimension:
    - Clear evidence of two or more tiers included in the environmental performance measurement;
    - Level of analysis limited to a single supply chain or single product. Papers with a wider level of analysis such as industrial network, industrial sectors and regional analysis were not considered;
- Environmental dimension: strong consideration of the environmental dimension of sustainability; the method should target the measurement of the environmental performance, rather than the enhancement and organisational efforts to achieve it.

After the full text screening, the final number of papers ultimately considered in the review was 78. Each paper included in the sample was analysed according to the following key aspects:

- Environmental performance: environmental inputs and outputs considered, distinct metrics adopted;
- Supply chain: number of tiers upstream and downstream of the focal firm involved in the environmental performance measurement; type of supply chain (forward, reverse, closed-loop); cradle-to-gate or cradle-to-grave approach;
- Methodology: model type, modelling technique and solution type;
- Scope of the work.

2.5.2 Bibliometric data

The temporal distribution of the 78 papers included in the analysis is depicted in Figure 2.10 The earliest publication is McIntyre et al. (1998), presenting the Environmental Performance Matrix to analyse the environmental performance of the Xerox supply chain. The chart indicates a steep increase in the published material starting from 2011 with the peak publications number reached in 2015 with 23 papers, indicating the novel and developing status of the research field.

The 78 publications were spread over 42 journals, showing the multidisciplinary nature of the field. Appendix A.1 provides a summary of the distribution of reviewed papers by journal, showing that journals with an environmental or production focus are currently addressing the supply chain environmental performance topic more than journal focused on supply chain management.

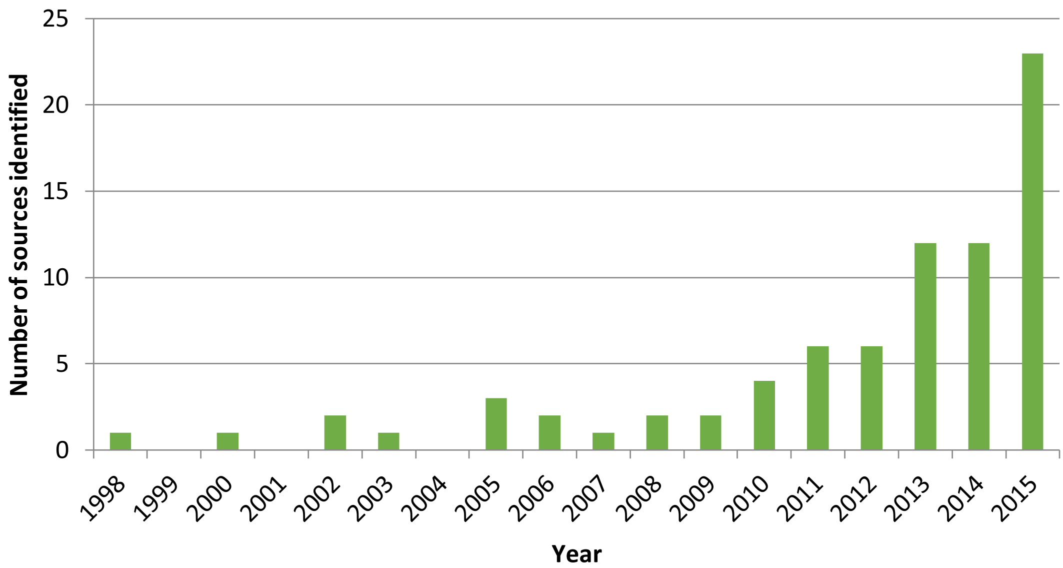

Figure 2.10: Temporal distribution of reviewed papers

2.5.3 Environmental aspects: what is measured

As GSCM is the core focus of this review, the first investigated aspect is what type of environmental performance is measured, answering to REVQ1. A classification based on environmental inputs and outputs flowing in and out of organisations part of the supply chain was used. The selection of inputs and outputs category for this review followed the classification of Brent and Visser (2005), which is depicted in Figure 2.11. Two input categories were considered, natural resources and energy, and three output categories, emissions to air, emissions to water and emissions to land.

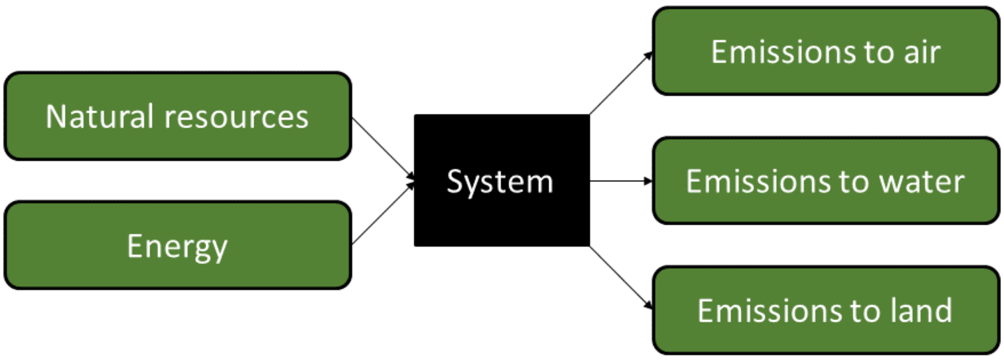

Figure 2.11: Classification framework of environmental inputs and outputs

2.5.3.1 Frequency analysis of environmental measurement

The first step aspect investigated to answer REVQ1 was to identify the individual measurements adopted within each work and their positioning within the proposed classification framework. At the category level, "Natural Resources" was the most frequent one with 96 instances through 64 distinct measurements. Only 12% of papers included all inputs and outputs categories, therefore providing a complete coverage of the environmental dimension.

The specific metrics adopted in the reviewed papers were recorded, in order to obtain a frequency analysis. The metrics were grouped in thematic clusters to facilitate the analysis as shown in Table 2.6, with each metric being assigned to a unique cluster. Metrics were assigned to clusters through keyword analysis (Ahi and Searcy, 2013). Metrics that could not be assigned to a specific cluster through this process were allocated to a cluster by similarity of scope. As an example, “Quantity of coal used”, despite not matching through keyword analysis the “Non-renewable resources consumption” cluster, is part of it, as fossil fuels are recognised as non-renewable resources. Two reviewers performed the allocation of each metric to a specific cluster independently and reached consensus before the final allocation of a metric within a cluster, in order to minimise interpretation biases. The most frequent cluster in the sample is “Energy use”, with 37 instances through 13 distinct measurements. The clustering within each input and output category is discussed in detail in Section 2.5.3.

In the entire sample, 200 distinct measurements appear, with 308 occurrences in total, which equals exactly 4 environmental measurements considered on average in each paper. The ratio between the number of occurrences and the number of distinct metrics shows a very low repetition of metrics throughout the sample, in line with the observation of Ahi and Searcy (2015) in the wider context of SSCM. Metrics are often named differently despite conveying the same measurement (e.g. “Water consumption”, “Water usage”, “Total water use”) or differ in being absolute (“Water use”) or relative (“Water use per unit of product”). Finally, some measurements are linked to targets (“Reduce the use of fresh water”).

As a clarifying example of the data presented in Table 2.6, 41 papers consider the “Energy” category, using 47 overall measurements. However, the number of distinct metrics adopted was 23, as some were repeated in the sample. The metrics referring to the energy input are grouped in four clusters, namely “Energy use”, “Renewable Energy”, “Energy Efficiency” and “Other”. For each cluster, the classification of overall and distinct measurements is repeated similarly to the higher-level category. This means that 13 distinct measurements are adopted to tackle “Energy use” with 37 overall measurements in the sample referring to this cluster.

Table 2.6: Classification of environmental measurements

Environmental input or output	Number of papers	Number of distinct/overall measurements	Measurement clusters	Number of distinct/overall measurements	Description of the cluster
Environmental input					
Natural resources	*42*	*64/96*	*Water use*	*18/33*	*Use of water*
			Use of materials	*14/21*	*Use of raw or generic materials, without specific indication on their nature*
			Non-renewable resources consumption	*10/12*	*Use of materials and resources, including fossil resources, with a clear indication of their non-renewable nature*
			Use of recycled resources	*6/11*	*Use of resources originating from reverse supply chain activities.*
			Hazardous and Harmful materials use	*7/7*	*Use of dangerous materials classified as hazardous, toxic or harmful to humans*
			Land use	*4/7*	*Use of land*
			Use of packaging	*5/5*	*Use of packaging*
Energy	*41*	*23/47*	*Energy use*	*13/37*	*Use of energy from undefined sources*
			Renewable energy	*5/5*	*Explicit use of renewable sources of energy*
			Energy efficiency	*2/2*	*Efficiency in the use of energy*
			Other	*3/3*	*Energy metrics not falling under any of the above mentioned clusters*

Environmental input or output	*Number of papers*	*Number of distinct/overall measurements*	*Measurement clusters*	*Number of distinct/overall measurements*	*Description of the cluster*
Environmental output					
Emissions to air	*58*	*48/90*	*Carbon emissions*	*11/29*	*Emissions to air of polluting agents containing carbon, including CO, CO_2 and CH_4 emissions*
			GHG emissions	*5/19*	*Aggregate consideration of emissions from all greenhouse gases*
			Generic air emissions	*9/14*	*Undefined and generic emissions of polluting agents to air*
			Other specific air emissions	*10/13*	*Emissions to air of specified polluting agents, other than carbon emissions*
			Environmental impact related measurement	*11/13*	*Emissions classified under their ultimate environmental impact rather than on the basis of the emitted substances*
			Other	*2/2*	*Emissions to air metrics not falling under any of the above mentioned clusters*
Emissions to water	*12*	*15/16*	*Liquid waste*	*6/6*	*Undefined and generic liquid waste or spillage as well as effluents of specific liquid substances other than waste water*
			Waste water	*5/6*	*Waste water effluents*
			Environmental impact related measurement	*3/3*	*Emissions classified under their ultimate environmental impact rather than on the basis of the emitted substances*
			Other	*1/1*	*Emissions to water metrics not falling under any of the above mentioned clusters*

Environmental input or output	***Number of papers***	***Number of distinct/overall measurements***	***Measurement clusters***	***Number of distinct/overall measurements***	***Description of the cluster***
Environmental output (continues)					
Emissions to land	*24*	*50/59*	*Solid waste produced*	*16/22*	*Undefined and generic solid waste as well as emissions of specific solid substances to land*
			Suitability for reverse chain (3Rs)	*15/17*	*Potential and/or effective use for recycling, reusing or remanufacturing activities of waste as well as any solid waste diverted from landfill*
			Hazardous and Harmful waste	*13/14*	*Solid waste, including toxic waste, requiring particular treatment due to the potential harm to humans*
			Other	*6/6*	*Emissions to land metrics not falling under any of the above mentioned clusters*
TOTAL		*200/308*			

2.5.3.2 Environmental inputs and outputs

Overall, 65% of the papers consider the environmental inputs: no significant preference was identified between the two inputs categories, as 42 papers consider resource consumption, whereas 41 incorporate energy use or consumption. Most addressed clusters include “Water use” for the natural resources category, whereas “Energy use” dominates the energy category. The majority of measurements adopted imply a negative correlation with the environmental impacts: an increase in input consumption leads to a worse environmental performance. The only exception is represented by renewable inputs, which are considered beneficial to the reduction of the pressure on the ecosystems. Such thematic clusters include “Use of recycled resources” and “Renewable energy”.

83% of the papers consider environmental outputs of the supply chain. Unlike the environmental inputs case, scholars are mostly interested in one specific category, namely emissions to air, considered in 74% of the articles. On the other hand, emissions to land and water received less attention with 31% and 15% respectively. Most observed clusters include “Carbon emissions” in the emissions to air category, “Liquid waste” in the emissions to water category and “Solid waste produced” in the emissions to land category.

A number of reasons justify the identified extensive consideration of environmental inputs within the supply chain. Firstly, there is a need to consider resource consumption at a macro level, as “current levels of global production and consumption are using 50% more natural resources and services than ecosystems regenerate” (O’Rourke, 2014) and natural resource scarcity at the global level may even threaten the existence of certain supply chains (Bell et al., 2013). Secondly, it is impossible to reduce environmental outputs just by providing “end-of-pipe” solutions, but there is a need to reduce inputs proactively to achieve this result (De Soete et al., 2013; McIntyre et al., 1998). Although limiting the problem to an overall quantitative analysis without considering the mix and characteristics of inputs and outputs, Ritthof et al. (2002) reinforce this argument by stating that the pressure on the environment is automatically decreased if inputs are reduced, as they will inevitably become an output of the system at a certain point. Finally, reducing inputs is particularly attractive for organisations for economic reasons too, as they represent a cost. Therefore, such a reduction provides win-win opportunities involving both economic and environmental dimensions.

On the other hand, it is more common to find trade-off rather than win-win situations with the economic dimension in the case of environmental outputs: examples include Zhang et al. (2014), Boukherroub et al. (2014) and Mellor et al. (2002). Therefore, companies are less interested to evaluate their performance in terms of environmental outputs, when the monetary outcome is less tangible. Benefits arise in the longer term thanks to environmentally driven innovation and improved brand and image value, but are rarely visible in the short term (APICS, 2012; Chin et al., 2014; Frota Neto et al., 2008). Emissions to air are an exception to the output category as they are the single most addressed category in the sample considering both inputs and outputs. This interest could be attributed to regulatory schemes aiming to control carbon emissions introduced for different sectors in various geographical areas (Bouchery et al., 2012; Vasan et al., 2014; Zakeri et al., 2015).

2.5.3.3 Contingency analysis of environmental categories

A contingency analysis of environmental categories was performed to identify association patterns between categories and pairs of categories whose combined observed frequency is higher or lower than the product of their single probabilities would suggest (Gold et al., 2010). The contingency analysis is performed through a chi-square test and calculated by the Phi-coefficient (φ), which identifies the strengths of these patterns. While these patterns do not reveal causality and necessarily provide semantic argumentation, they provide statistical evidence that has to be justified (Gold et al., 2010; Sauer and Seuring, 2017). The contingency analysis was applied at the level of environmental categories, as the expected frequency of each pair needs to be bigger than five, a condition not achievable with a more detailed level of granularity (Fleiss, 1981).

Table 2.7: Contingency results of environmental categories

Environmental categories pair		Expected frequency	Observed frequency	Chi-square significance	Phi coefficient
Energy	Emissions to land	12.8	22	0.000	0.518
Natural resources	Energy	22.4	32	0.000	0.504
Natural resources	Emissions to land	13.1	21	0.000	0.445
Natural resources	Emissions to water	6.5	12	0.001	0.392
Natural resources	Emissions to air	31.6	26	0.003	0.341
Energy	Emissions to air	30.9	26	0.010	0.295

As shown in Table 2.7, three pairs show a Phi-coefficient above 0.4, which is considered the threshold of a strong association between the two categories, whereas three additional pairs fall in the range 0.2-0.4, which indicates moderate association (Cohen, 1969). Four pairs show a higher observed frequency than expected, showing a reinforcing association whereas the “natural resources – emissions to air” and “energy-emissions to air” pairs show a lower observed frequency than expected. While a justification for these pairs is found in the willingness of some authors to avoid double counting (Bojarski et al., 2009; Michelsen et al., 2006), this result stresses a less frequent application of "Emissions to air" in combination with other environmental categories. Indeed, "Emissions to air" are applied in isolation in 24 papers accounting for 31% of the entire sample. Therefore, it can be concluded that emissions to air are often treated as a proxy of the overall environmental impact. Regulatory schemes played a significant role in this pattern. Moreover, focus on emissions by policy makers was prominent compared to other environmental impacts due to their direct effect on global warming (Kostin et al., 2012; Pattara et al., 2012). This triggered the interest of academics to address managerial choices affecting environmental sustainability under different regulatory schemes, as in Bouchery et al. (2012), Caro et al. (2013), Fahimnia et al. (2015), and Zakeri et al. (2015).

On the other hand, "energy - emissions to land", "natural resources - energy" and "natural resources - emissions to land" pairs have strong associations. Since waste-related clusters are dominant within the "emissions to land" category, it can be inferred that these associations identify strong relationship between those environmental categories that cause economic expenditure across the supply chain. As these categories are typically addressed simultaneously, they can be labelled as efficiency oriented, since the environmental performance improvement benefits the economic performance as well.

2.5.4 Supply chain aspects: who is measured

The second aspect evaluated in the systematic review is the supply chain dimension of GSCM performance assessment methods, answering to REVQ2, in order to identify the extent of the supply chain effectively measured with respect to the environmental performance (Section 2.5.4.1). Section 2.5.4.2 further explores the supply chain dimension to identify whether a cradle-to-gate or cradle-to-grave approach has been adopted along with the type of supply chain being assessed.

2.5.4.1 Supply chain extent

Previous reviews on SSCM recognised that most environmental performance measurements for supply chains targeted a single organisation and its supply chain policies, rather than the supply chain (Brandenburg et al., 2014). However, the actual extent of the supply chain covered by the current environmental measurement methods is an unexplored topic in the literature.

In this review, a tier of the supply chain is defined by each set of individual organisations, part of the supply chain, whose core activity is different from transportation activities only, that are separated from the focal company by the same number of dyadic links. Vertically integrated supply chains with a number of activities taking place within the boundaries of a single firm are considered in this analysis as a single tier, even if activities, such as production and assembly, take place in different geographical areas. The rationale behind this approach is that, despite the increased complexity of the operations, the decisions remain within the single organisation, eliminating challenges and barriers arising when multiple companies are involved.

The extent of chains covered by environmental measurement is presented in Figure 2.12. The bars length represents the extent of the supply chain assessed, with the green part on the left representing the upstream network and the yellow part on the right representing the downstream network in respect to the focal firm. If more than three tiers either upstream or downstream are assessed, the method is considered suitable to evaluate the entire upstream/downstream network respectively. The width of each bar signifies the number of papers covering that specific combination of supply chain extent and corresponds to the respective circled number.

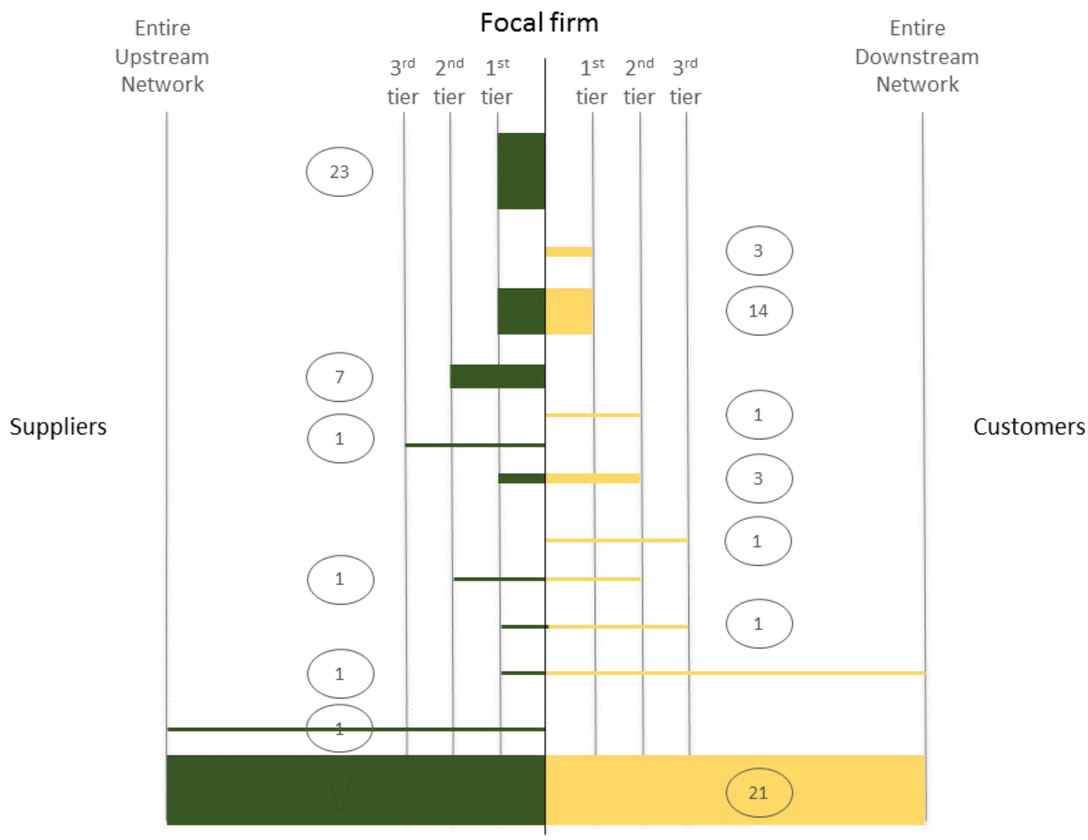

Figure 2.12: Classification of methods based on the supply chain extent

Overall, 40 papers, accounting for 51% of the sample, do not go beyond the 1st tier of the supply chain, upstream or downstream. The extent of the supply chain covered by environmental measurements is still limited in over half of the cases to direct suppliers or customers only. This reflects a broader weakness of most companies in effectively mapping their supply chains (Acquaye et al., 2014). This appears particular severe for the upstream supply chain (Egilmez et al., 2014; O'Rourke, 2014). This narrow approach is unable to evaluate accurately not only traditional economic aspects but environmental sustainability as well: the extended supply chain needs to be fully assessed to obtain a complete sustainability profile (Miemczyk et al., 2012) as the supply chain impact stretches "to 2nd and 3rd tier suppliers, and potentially beyond" (Ashby, 2014). The reviewed body of research still shows limitations in considering the environmental performance of the extended supply chain. Only 21 papers, accounting for 27% of the sample, consider the entire upstream and downstream network, providing a full coverage of the supply chain. Papers falling outside this category thus face challenges in estimating the true environmental impact of the supply chain.

Despite over half of the articles (53%) targeting both upstream and downstream chains to obtain a comprehensive evaluation (Brent and Visser, 2005), the upstream network is more frequently addressed: 94% of papers (73) include at least one upstream chain tier, whereas downstream chain is considered by 59% of papers (46). This can originate from the fact that customers' reputation is influenced by the environmental reputation of their suppliers, whereas suppliers are not affected by the reputation of their customers (Kovács, 2008). Major scandals originating from inappropriate code of conduct of suppliers impacted several organisations, pushing them to assess the sustainability performance of their suppliers including both environmental and social aspects (Gimenez and Tachizawa, 2012). On the other hand, organisations have limited influence on the behaviour of the downstream part of the chain (Mentzer et al., 2001). Moreover, focal firms are usually positioned downstream along the chain, closer to the final customer than to the raw material extraction stage (Gimenez and Tachizawa, 2012). This can justify the lower number of papers addressing the downstream network, as it naturally limits the available number of tiers downstream compared to the number of tiers upstream.

2.5.4.2 Cradle-to-gate and cradle-to-grave approaches

The second analysis regarding the supply chain dimension of the GSCM performance assessment methods considered the type of supply chain addressed by methods included in the review combined with the cradle-to-gate or cradle-to-grave approach adopted (Table 2.8).

Three types of supply chains are considered: the traditional approach of forward supply chain, considering the material and information flow from raw materials to the end customer (Handfield and Nichols, 1999; Stevens, 1989), the reverse chain, originating from the customers in the opposite direction (Hing Kai Chan, 2007) and the closed-loop supply chain, which is the combination of forward and reverse chains (Liu et al., 2011). Evaluated methods were found to target forward supply chains in 81% of the cases. Remaining papers address closed-loop supply chains, with the exceptions of Nikolaou et al. (2013) and Krikke (2011), who consider specifically a reverse chain. The limited consideration of the environmental performance of reverse supply chains indicates limited interest for these chains when considered in isolation, whereas their inclusion in a closed-loop perspective together with the related forward chain looks more appealing to assess the overall benefit to the environment. Finally, Dotoli et al. (2006), Pålsson et al. (2013) and Trappey et al. (2012) consider both forward and closed-loop supply chains in their work, thus the total values in Table 2.8 exceed the number of papers included in the review.

Table 2.8: Type of supply chain

	Cradle-to-Gate	Cradle-to-Grave	Total
Forward	52	14	**66**
Closed-loop	2	11	**13**
Reverse	2	0	**2**
Total	**56**	**25**	**81**

A cradle-to-gate approach considers all supply chain stages from raw material extraction up to the finished product (Ritthof et al., 2002). A cradle-to-grave scenario extends this view by adopting a lifecycle perspective, considering also the product usage phase and end-of-life management. Therefore, all stages from raw materials extraction up to product disposal or recycling are considered (Vasan et al., 2014). When the product undergoes recycling, this approach is referred by some authors as cradle-to-cradle, as original materials re-enter a forward supply chain (Bloemhof et al., 2015). Cradle-to-gate scenarios naturally neglect part of the environmental impacts underestimating the overall environmental impact caused by products, especially in sectors where the direct impacts (Chatzinikolaou and Ventikos, 2015) and indirect impacts (Cichorowski et al., 2015) during the usage phase can have the most significant contribution to the overall environmental impact.

Despite Elkington (2004) identifying over a decade ago a progressive change in the behaviour of companies towards an inclusive consideration of lifecycle stages following the point of sale, the identified methods rarely consider the product usage phase and end-of-life management in the performance measurement. This is particularly evident when forward supply chains are considered, where only 21% of the methods consider a cradle-to-grave scenario. The limited control of companies on the usage and end-of-life management stages as well as the difficulty in effectively measuring environmental performance during those stages can be considered among the main reasons limiting the adoption of cradle-to-grave approaches (Michelsen et al., 2006).

Data from Table 2.8 show a strong association between forward supply chain and cradle-to-gate approach as well as between closed-loop supply chain and cradle-to-grave approach. This indicates that the supply chain evaluation is mostly focused on the pre-usage stages unless a lifecycle perspective is adopted. Issues about product responsibility in the usage phase are often neglected from the analysis of forward supply chains as well as the end-of-life treatments evaluation due to uncertainties about different end-of-life options according to geographical locations (Michelsen et al., 2006). This could be also justified from the operations management focus of the literature, with usage environmental performance typically being also related to the product design literature. On the other hand, the lifecycle perspective is a common feature of closed-loop supply chains and cradle-to-grave approach. Recent regulations, such as the EU Waste Electrical and Electronic Equipment (WEEE) directive are trying to incorporate this extended perspective into regulatory schemes. A challenge still stands though for researchers to further incorporate the lifecycle perspective within effective supply chain environmental performance measurement tools.

2.5.5 Methodological approaches: how is it measured

Answering to REVQ3, the third aspect evaluated in the systematic review are the methods adopted to assess the GSCM performance, as well as the relationship between the used methods and the supply chain extent covered by the measurement.

Papers were analysed based on the methodology they adopt to assess the environmental performance of supply chains, by classifying them according to the categories identified by Brandenburg et al. (2014), who evaluated quantitative models for supply chains under various perspectives. A number of additions to the classification scheme were required as some papers could not be accurately allocated to an existing category. The adopted classification scheme is presented in Figure 2.13, whereas

Table 2.9 shows the model types and modelling techniques analysis.

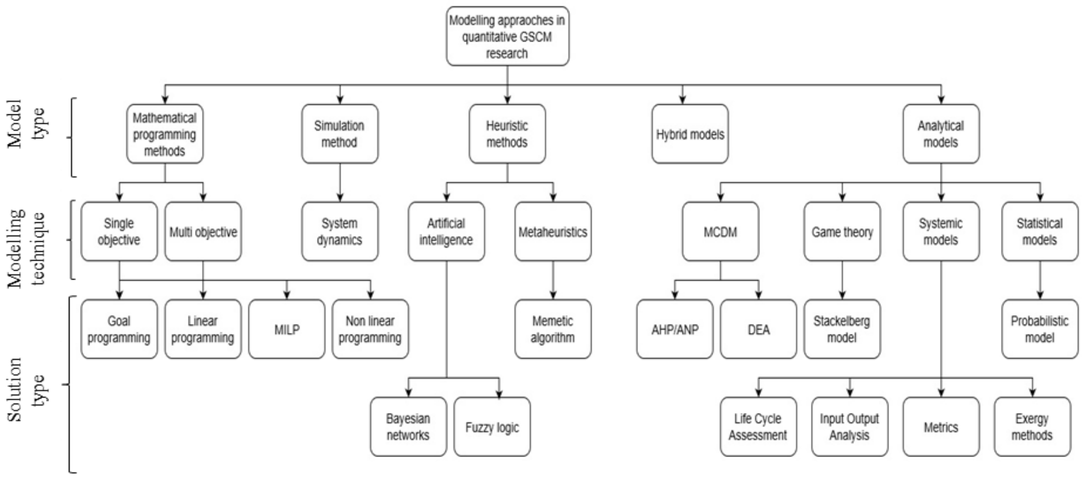

Figure 2.13: Categories to evaluate quantitative methodological approaches for GSCM performance measurement (adapted from Brandenburg et al., 2014)

Table 2.9: Classification of quantitative methodological approaches for GSCM performance measurement

Model type		Modelling technique		Solution approach	
Mathematical programming	21	Single objective	2	Goal programming	1
		Multi objective	20	Linear programming	2
				MILP	11
				Non-linear programming	7
Simulation	1	System dynamics	1		
Heuristic	8	Artificial intelligence	7	Bayesian networks	1
				Fuzzy logic	6
		Meta-heuristic	1	Memetic algorithm	1
Analytical	35	Game theory	2	Stackelberg model	1
				Unspecified	1
		MCDM	4	AHP/ANP	2
				DEA	2
		Statistical model	1	Probabilistic model	1
		Systemic model	25	LCA	4
				Input / Output Analysis	3
				Metrics	13
				Exergy methods	5
		Multiple	3	AHP and Metrics	3
Hybrid	13	Other	13	Other	13

Analytical models are the dominant model type with 35 occurrences in the sample. Within analytical models, systemic models are the most adopted modelling technique, followed by multi criteria decision-making (MCDM). The combination of both modelling techniques is common, with MCDM used to weight criteria based on opinion of stakeholders and decision makers in order to link the PMS to the supply chain strategy, while metrics are used to evaluate the actual environmental performance. Mathematical programming methods follow with 21 occurrences. The adopted modelling technique is always multi-objective in this case linking environmental and economic objectives, with the single exception of Ren et al. (2015). Additionally, Dotoli et al. (2006) adopt both single and multi-objective modelling techniques. Heuristic methods are represented in 8 papers, whereas Adhitya et al. (2011) are the only authors adopting a simulation method, using system dynamics to evaluate the environmental performance of a diaper's supply chain. Finally, a common approach is using hybrid or multiple models within the same paper: this has been recognised as a way to overcome limitations of single methods (Saunders et al., 2008). Various combinations are frequently identified in the sample: the use of heuristic methods, especially fuzzy logic, is often combined with analytical models or mathematical programming methods to include uncertainty in the model, replicating more accurately conditions faced by organisations in their operations.

Relationship between supply chain extent and methodology

The relationship between the supply chain extent covered and the methodology adopted is explored, to analyse whether specific methodologies are more suitable to assess the environmental performance of particular supply chain configurations.
The supply chain extent configurations analysed earlier are clustered in four groups:

1. Dyad: either supplier-focal firm or focal firm-customer configuration
2. Triad: supplier-focal firm-customer
3. Other: configurations involving suppliers or customers beyond the 1st tier from the focal firm, but not including the entire network
4. Extended supply chain: entire upstream and downstream network;

Identifying relationships was not meaningful for simulation methods as only Adhitya et al. (2011) adopt such model type in the entire sample. Therefore, the analysis considered only the four remaining model types. Table 2.10 shows the occurrences of each model type against the supply chain extent configurations.

Table 2.10: Relationship between model type and supply chain extent

	Dyad	Triad	Other	Extended	Total
Mathematical programming	7	3	6	5	21
Heuristic methods	7	0	1	0	8
Hybrid methods	5	4	2	2	13
Analytical models	7	7	7	14	35
Total	**26**	**14**	**16**	**21**	**77**

Mathematical programming methods prove to be similarly adaptable to different supply chain configurations, with a peak for short dyadic supply chains. Modelling of the supply chain is a key feature of this model type and the inclusion of multiple model variables increases the complexity of the mathematical formulation even with a limited number of tiers analysed, therefore typically addressing a limited extent of the supply chain. Hybrid methods are also applied for different supply chain configurations, with occurrences dropping when the extent of supply chain expands. Heuristic methods are used almost exclusively to address dyads: Jamshidi et al. (2012) are the only exception, trying to extend the evaluation of the supply chain beyond the direct suppliers. The involvement of decision makers in this type of models, with a limited adoption of primary or secondary data, limits the applicability to more extended supply chain configurations.

On the other hand, analytical models, being the dominant model type in the entire sample with 45% of overall models, are used in every supply chain configuration but show higher occurrences as the extent of the supply chain increases. Only 20% of analytical models target dyads, below the average of other model types, whereas 40% tackle extended supply chains, a significantly higher occurrence compared to other model types (Figure 2.14).

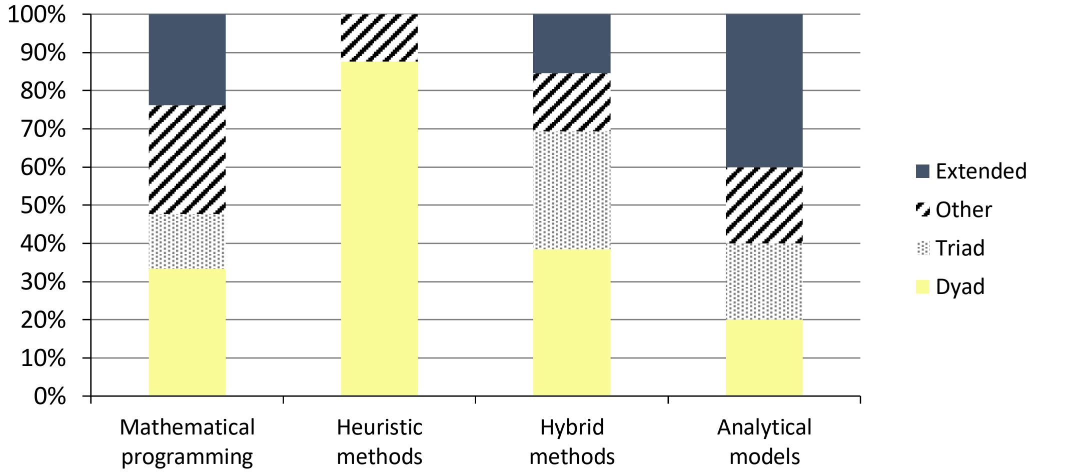

Figure 2.14: Supply chain extent covered by model type

Mirroring the analysis and using the supply chain extent as a focal point (Figure 2.15), only the extended supply chain configuration has a clear direction in terms of model type use: 67% of papers with this configuration adopt analytical models. This result supports the further development of research in the area of environmental performance assessment of extended supply chains, indicating systemic models or MCDM as the most frequently used modelling techniques for this supply chain configuration.

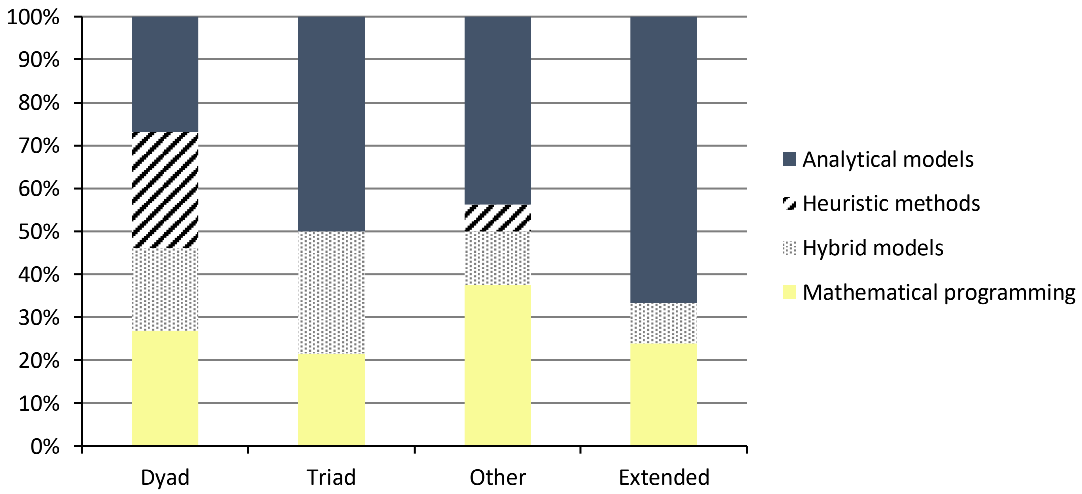

Figure 2.15: Model types by supply chain extent

In order to examine the statistical significance of the above results, Cramer's V measure of association between model types and supply chain extent was utilised (Kateri, 2014), which is a Chi-square-based test (χ^2), specifically tailored for tables with dimensions higher than 2x2 and is calculated according to equation 2.1 (Liebtrau, 1983):

$$V = \sqrt{\frac{\varphi^2}{t}} \tag{2.1}$$

Where φ is the square root of χ^2 divided by the number of total occurrences, and t is the minimum between the number of rows minus one and the number of columns minus one. Since a 4x4 square table is considered here, t equals 3. Based on Cohen's (1988) guidelines to interpret the Cramer's V results, for t=3, a small effect is associated to the value of 0.06, medium effect to 0.17 and large effect to 0.29. In the table under investigation Cramer's V is equal to 0.278. The test shows an approximate significance of 0.037, the results thus being statistically significant at the 5% level. Therefore, the contingency analysis indicates a significant effect relationship between the variables examined verifying a strong association between model types and supply chain extent.

2.5.6 Scope of the work: why is it measured

This section introduces the final perspective of analysis, which is the primary scope of the papers, that is, the primary purpose to assess the environmental performance in the reviewed papers, thus answering to REVQ4. Based on the above, three categories of scope were identified:

- Supply chain assessment (40 papers): the aim of these articles is to evaluate the performance of the supply chain from an environmental dimension only, or a combination with the economic and/or social sustainability dimension.
- Supplier selection and evaluation (14 papers): the focus of these papers is on the process of evaluating and selecting suppliers, taking into account environmental criteria along with traditional criteria such as cost, quality and service level.
- Supply chain performance optimisation and supply chain design or re-design (24 papers): the purpose of these papers is to optimise the performance of the supply chain by considering multiple objectives. This involves decisions such as capacity assignments, flow allocation and mode of transportations in either greenfield or existing supply chains. The final outputs include an environmental assessment of the supply chain either by proposing an optimal solution based on the objective functions and constraints or an evaluation of multiple scenarios leaving the final choice to decision makers.

Figure 2.16 shows the relationship between the model type and the scope of the methods. Three strong associations are identified between the dimensions under analysis, showing a consensus among scholars in model types used to fit each scope. Mathematical programming is mostly used to optimise the performance of the supply chain or to design and plan the supply chain (in 86% of the cases), whereas 75% of papers with this scope adopt this method. Heuristic methods are primarily used to select and evaluate suppliers, with the only exception of Jamshidi et al. (2012). Despite representing just one tenth of the entire sample, papers adopting heuristic methods build up 50% of papers aiming to select and evaluate suppliers. Analytical models are mainly adopted for the assessment of the performance of the supply chain (in 89% of instances). Finally, hybrid models are applied with different scopes, reflecting the variety of methods adopted in this category.

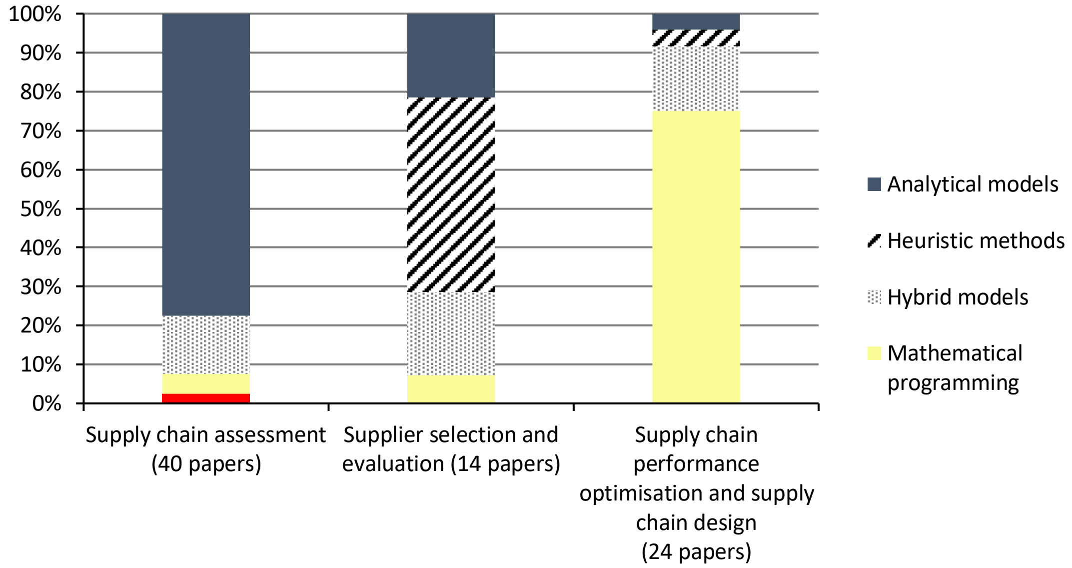

Figure 2.16: Relationship between model type and scope of the methods

Although Figure 2.16 is visually self-explanatory in terms of methodological directions depending on the scope of the paper, a contingency analysis was performed to support the findings with a quantitative output by calculating Cramer's V. Once again, the single paper adopting simulation model type was excluded for this analysis as it would affect the statistical validity of the test. Value of *t* is 2 in this case, therefore a large effect of association between variables is found for Cramer's V value above 0.35 (Cohen, 1988). Cramer's V was equal to 0.699 with a level of significance of 0.000, confirming a very strong association between model type and the scope of methods.

2.5.7 Systematic review summary

Sections 2.5.3 throughout 2.5.6 introduced the detailed results of the literature review analysis. These are condensed in a high-level perspective in this section, by introducing a synthesis of the evaluated dimensions in Section 2.5.7.1 and a summary of the answers to the review questions in Section 2.5.7.2, leading to the identification of the gaps in the current research.

2.5.7.1 Synthesis of evaluated dimensions

On top of the methodological feature, each scope includes unique characteristics, as depicted in Table 2.11, that are evaluated in this section trying to convey a consistent synthesis of all dimensions considered in this review.

Supply chain design and performance optimisation papers provide a limited coverage of the supply chain. The majority of papers is limited to short supply chains, other than extended networks, and typically includes bi-objective optimisation including economic and environmental dimensions of sustainability. One of the key points of these papers is the detailed modelling of the supply chain, which limits the extent of supply chain coverable by the performance measurement. Additionally, the environmental dimension shows a high prevalence in this type of papers: all papers, apart from Krikke (2010) and Manzardo et al., (2014) consider emissions to air, whereas other environmental inputs and outputs receive very limited attention. Natural resources and energy categories follow being represented in only 26% of the sample. As a result, supply chain design and performance optimisation papers generally tend to underestimate the overall environmental impact of the supply chain having an excessively narrow focus both in terms of supply chain extent and of environmental impacts. An additional drawback is the limited evidence of adoption of primary data in these models, posing questions about their effective applicability in a real context. However, the dominant mathematical programming methods adopted are helpful in terms of operational improvement and support for decision making, by identifying optimal or near-optimal configurations of the supply chain in relation to the objective functions and thus providing a concrete problem solving support to practitioners. The determination of the physical structure of the supply chain as well as the flow of materials connecting the various tiers are also stressed by these methods enhancing the general visibility and traceability of the supply chain under analysis.

Supplier selection and evaluation papers are limited to the 1st tier upstream in the chain and therefore only a dyad is involved in the measurement process. On the other hand, these methods balance the limited extent coverage with a wide range of environmental aspects, often including emissions to water, which are widely neglected in the literature, as pointed out in Section 2.5.3.1. Heuristic methods are the most prevalent model type for this scope, followed by analytical models and hybrid models. The measurement rarely includes primary data coming from the suppliers but rather translates the opinion of decision makers into quantitative values. On the one hand, this facilitates the integration of such tools coherently within the organisational strategy; on the other hand it leaves the evaluation in the hands of experts leading to increased uncertainty of results due to biased opinions and a degree of subjectivity (Shokravi and Kurnia, 2014; Tsoulfas and Pappis, 2008). Generally, these methods are helpful in providing support for decision-making, either by providing a ranking of suppliers, like in Sarkis and Dhavale (2015), or a scoring of the suppliers as well, like in Kannan et al. (2015), offering an in-depth knowledge about the performance of the suppliers.

Finally, papers focusing on assessment of the supply chain adopt analytical models as the preferred model type. As Section 2.5.5 showed, the choice of analytical models proves to be more frequently applied to extended supply chain and this finding is confirmed by analysing the reviewed papers based on their scope. Papers on 'assessment of the supply chain' have a more specific focus to the measurement of the environmental performance of the supply chain, whereas the other two identified scope categories include this step as functional to other managerial decisions such as the supply network design, capacity and flow assignments and supplier selection and evaluation. Because of the combination between the methodological choices and the more specific focus, the supply chain extent covered by these papers is typically expanding beyond the 1st tier of the supply chain and showing applicability to extended supply chains in 40% of the instances. However, the extensive inclusion of supply chain tiers covered by performance measurements from 'assessment of the supply chain' papers is accompanied by a narrower focus in terms of environmental inputs and outputs considered: attention is typically paid to environmental inputs and emissions to air only.

Table 2.11: Summary of the features of papers based on their primary scope

Paper scope	**Environmental aspects**	**Extent of the supply chain**	**Dominant methodology**
Supply chain design and performance optimisation	Limited scope Focus on air emissions	Not suitable for extended supply chains Various other supply chain configurations addressed	Mathematical programming
Supplier selection and evaluation	Complete evaluation of environmental inputs and outputs	Dyad supplier-focal firm	Heuristic methods dominant Hybrid models and systemic models also adopted
Assessment of the supply chain	Focus on resource consumption, energy and emissions to air	Multiple configurations of the supply chain measured: good applicability to extended supply chains	Analytical models

A trade-off can thus be identified between the extent of the supply chain and the range of the environmental aspects considered. Papers standing at extreme positions with regards to the supply chain extent and the environmental aspects considered show that a compromise was made between these choices. ‘Supplier evaluation and selection’ methods perform best in the environmental aspects but are very limited in terms of supply chain extent, whereas ‘assessment of the supply chain’ methods offer the best applicability to extended supply chains but do not consider adequately multiple environmental aspects.

2.5.7.2 Summary of literature review research questions and research gaps

Each research question led to a number of key findings, which supported the definition of six initial research gaps. Moreover, additional insights were obtained from the combined evaluation of review questions and identified research gaps.

REVQ1: What environmental performance metrics are adopted at the supply chain level?

A large variety of quantitative environmental measurements with very limited consistency was identified in the literature. Even though limiting the scope to environmental and quantitative measurements only, this finding confirms the analysis of Ahi and Searcy (2015) in the broader SSCM field. The growing body of literature on this topic is still at a divergent stage and a progressive standardisation in the future will be required to adopt similar units of reference. The extreme variety in the metrics adopted limits the applicability of developed methods for benchmarking applications. Environmental metrics are applied “to compare trends over time, to compare results with targets and to benchmark a company against others” (Gerbens-Leenes et al., 2003). While the first two objectives are achieved by the existing literature as consistency is achieved within the boundaries of each work, the last is currently missing due to the lack of standardisation in the metrics adopted and the lack of external reference values to compare results, thus making environmental measurements self-referential to specific studies and supply chains. Scholars often addressed the same environmental categories but adopted heterogeneous metrics, leading to the definition of research gap 1.1, which suggests future research:

Gap 1.1: To increase the standardisation of metrics in GSCM performance assessment to improve the comparability of studies

Moreover, a progressive merging of the perspectives from academia and industry is needed to further enhance the environmental metrics standardisation and studies comparability. The existing literature showed a very limited evidence of consideration of the metrics from the practitioners’ community such as Global Reporting Initiative, SCOR model, Environmental European Agency or ISO 14000 series. Few exceptions include Mintcheva (2005), Nikolaou et al. (2013), Salvado et al. (2015) and Varsei et al., (2014). While scholars can foster the development of standardised environmental metrics in the future, their application in operating contexts is largely dependent on the pressure companies are facing to adopt them. Regulatory bodies and third party organisations can effectively contribute towards the standardisation, whereas it is unlikely that this contribution will come from single supply chains as each is driven by different objectives. As a result, research gap 1.2 is phrased as:

Gap 1.2: To integrate environmental metrics from the academic and practitioners' community in order to facilitate the development of standardised GSCM metrics

The review also identified that a holistic evaluation of the environmental performance is still rare, with scholars focusing on limited sets of indicators that address specific environmental categories. Two patterns of environmental categories were identified thanks to contingency analysis. The 'efficiency oriented measurements' tackling environmental aspects that generate monetary expenditure and the 'regulatory oriented measurements', which are largely based on the emissions to air. In the first case, interest for sustainable performance of supply chains is still led by the economic performance looking for win-win situations with the environmental performance, while in the latter case the regulatory schemes introduced in certain sectors and geographical areas triggered the interest of academics. Researchers will need to merge in future models these perspectives in order not only to obtain a holistic evaluation of the environmental performance but also to avoid a narrow approach to optimisation of the performance. Only the simultaneous consideration of all categories can lead to the identification of trade-offs between different environmental aspects and to a holistic improvement of the system examined, thus leading to research gaps 1.3 and 1.4.

Gap 1.3: To address simultaneously 'efficiency oriented measurements' and 'regulatory oriented measurements'

Gap 1.4: To achieve a holistic evaluation of the environmental performance of supply chains

REVQ2: What extent of the supply chain, both upstream and downstream from the focal firm, are environmental performance measurement methods and related metrics addressing?

The findings show that attention is still limited to the 1st tier beyond the focal firm in the majority of cases, whereas the evaluation of extended supply chains is still at a developing stage. This finding highlights the need for improved supply chain traceability and visibility by the main players in the chain or the development of appropriate indirect mechanisms to reach sub-suppliers in multi-tier supply chains, to achieve a supply chain-wide evaluation of the environmental performance. The drawback of focusing on a limited supply chain extent appears particularly severe in the current competitive environment where global supply chains with multiple tiers are the norm (Kovács, 2008; Mena et al., 2013), as poor environmental performance of a single tier may cause an overall environmentally unsustainable behaviour of the entire supply chain (Miemczyk et al., 2012). The current dominant approach is paying attention only to direct business partners, demonstrating that GSCM is still far from being accomplished. The shift from green supplier selection to GSCM is still to be completed, at least for quantitative performance measurement of green supply chains; environmentally sustainable supply chains cannot be achieved by working only with first-tier suppliers (Ashby, 2014; Genovese et al., 2013). Research on quantitative models to measure supply chain environmental performance is still lagging behind in successfully reaching multi-tier and extended supply chain contexts. Identifying mechanisms to overcome the existing limited supply chain visibility and reach sub-suppliers located further upstream is a key challenge for researchers. An expansion of the supply chain extent covered by GSCM performance measurement methods is required to achieve an effective supply chain-wide assessment and to avoid a potential underestimation of the true supply chain environmental impact, leading to gap 2.1, phrased as:

Gap 2.1: To expand GSCM performance assessment methods beyond 1st tier suppliers and customers to achieve effective multi-tier GSCM

Moreover, the downstream network is currently overlooked compared to the upstream network due to the limited liability of companies for the behaviour of their customers (Kovács, 2008). Measuring the environmental performance of usage and end-of-life management lifecycle stages looks critical, especially due to the complexity of accessing data (Michelsen et al., 2006). A key challenge for future research will be to develop methods to collect and share environmental data about product lifecycle stages that are beyond the control of any organisation in order to move from the dominant cradle-to-gate to the cradle-to-grave approach, leading to gap 2.2.

Gap 2.2: To address the downstream supply chain environmental sustainability performance, particularly the usage and end-of-life management lifecycle stages

REVQ3: What are the quantitative methods adopted to measure the environmental performance of supply chains?

The analysis shows the dominance of two model types: mathematical programming and analytical models. Regarding the relationship between the type of method and the extent of supply chain covered, analytical models were identified by contingency analysis as the most frequently used to address extended supply chains, looking as the most promising method for future researchers to expand the supply chain extent coverage.

REVQ4: What is the main purpose of the environmental performance assessment?

Three main purposes to assess the environmental were identified: supplier selection and evaluation, supply chain performance optimisation and supply chain design or re-design and supply chain assessment in the strict sense.

The paper scope and model types relationship exploration identified several strong associations: mathematical programming is primarily adopted for the design and optimisation of green supply chains, heuristic methods for green supplier selection and evaluation, and analytical models for the assessment of the supply chain performance. Considering the novelty of the research field, it is likely that the body of research will develop in three major streams in the future, based on a different purpose of the research and on consistent differences in the definition and boundaries of the supply chain. The analysis also revealed that papers focusing on the assessment of the supply chain show an excellent applicability to extended supply chains. On the other hand, supplier selection and evaluation papers proved to provide the most extensive coverage in terms of environmental aspects considered, for both environmental inputs and outputs.

2.6 Research problem

The combined evaluation of REVQ1 and REVQ2 led to the identification of the research gap addressed in this research, which is a combination of gap 1.4 and gap 2.1. Currently, a trade-off between the scope of environmental performance and the extent of supply chain effectively measured exists. No paper was identified in the systematic literature review, which considers the extended supply chain while addressing and measuring all environmental aspects, according to the environmental categories defined in Section 2.5.3. The closest papers to this criterion are Koh et al. (2012), Michelsen et al. (2006) and Varsei et al. (2014), including four environmental categories while addressing extended supply chains and Adhitya et al., (2011), considering one upstream and two downstream tiers while still addressing all environmental categories.

Figure 2.17 summarises the evolution of the literature. Supply chain performance measurement traditionally incorporated economic metrics along with other well-established key performance indicators such as time and quality (Beske-Janssen et al., 2015). The inclusion of environmental metrics followed as organisations recognised the importance of sustainability and of measuring non-financial aspects (Shen et al., 2013). However, environmental measurements were initially narrow in terms of scope, focusing on specific environmental categories while addressing a limited extent of the supply chain. Research further developed in two directions (solid arrows in Figure 2.17): either broadening the scope of environmental performance evaluation coverage or extending the supply chain extent coverage. However, no work was identified to progress sufficiently along both dimensions (dotted arrows in Figure 2.17), leading to the formulation of the research gap in GSCM performance assessment methods literature as:

The lack of GSCM performance assessment methods expanding simultaneously the comprehensiveness in terms of both environmental aspects considered and supply chain extent

The lack of a method progressing along both dimension ultimately calls for the development of a method achieving a more comprehensive evaluation of the environmental performance of a supply chain, which avoids a potential underestimation of the true environmental impact due to too narrow approach in terms of environmental performance or extent of supply chain.

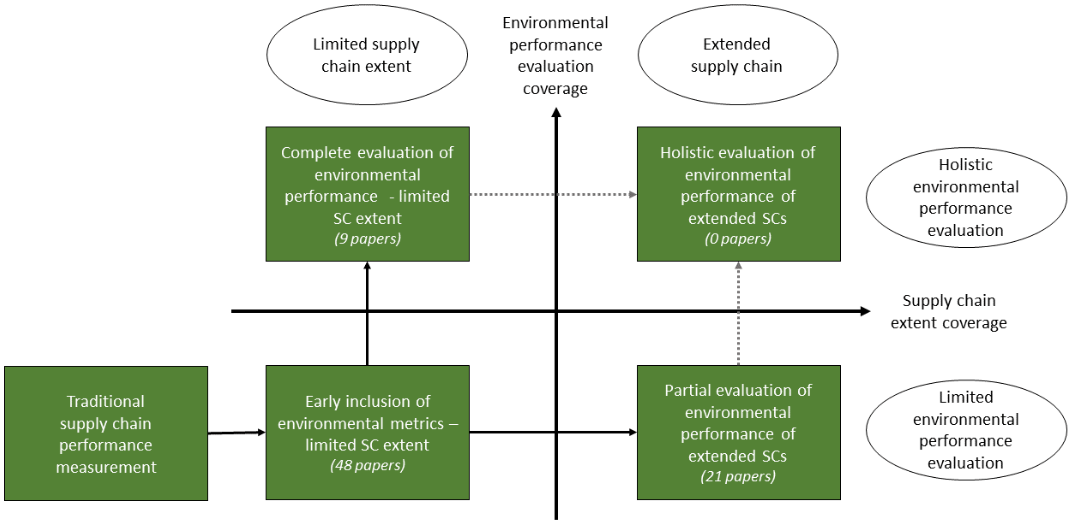

Figure 2.17: Framework on the development of the GSCM performance assessment research field

The gap was specifically identified for extended supply chains, which include "suppliers of the immediate supplier and customers of the immediate customer, all involved in the upstream and/or downstream flows of products, services, finances, and/or information" (Mentzer et al., 2001). However, organisations are held responsible for the unsustainable behaviour of their upstream suppliers (Gimenez and Tachizawa, 2012; Hartmann and Moeller, 2014), whereas they have limited influence and are not accountable for the behaviour of the downstream part of the chain (Mentzer et al., 2001). As a result, coherently with the issues faced by focal companies, this research focuses specifically on the development of a method to assess the environmental sustainability performance of upstream multi-tier supply chains - in what follows, multi-tier supply chains- to address the extended supply chain issue.

As the aim of every literature review process is not limited to the mapping of existing literature but entails also the specification of "a research question to develop the existing body of knowledge further" (Tranfield et al., 2003), the final outcome of the review process was the definition of the research question:

> *How can the environmental sustainability performance of multi-tier supply chains be quantitatively assessed?*

The research question, which guided the following phases of this research, was then re-phrased in an action-oriented sentence, representing the aim of this research, which is to *facilitate quantitative assessment of the environmental sustainability performance of multi-tier supply chains*. The aim was then further elaborated into five research objectives, as detailed in Section 1.2.

2.7 Summary

This chapter reviewed the research on green supply chain management performance assessment. The introduction to sustainability (Section 2.1) identified key definitions to the concept, illustrating the 3BL concept and the differences among strong and weak sustainability, detailing the rationale to position this research within the weak sustainability perspective. The main sources of pressure for organisations to include sustainability concerns within their operations were also identified, namely the pressure arising from regulatory bodies, customers and wider societal stakeholders. This pressure initially targeted single organisations and later expanded to the wider supply chain, determining the emergence of sustainable supply chain management (Section 2.2) and green supply chain management (Section 2.3). A summary of GSCM activities, GSCM practices and drivers to adopt GSCM is also provided in Section 2.3. Sub-sections 2.3.4 and 2.3.5 focused specifically on multi-tier GSCM, illustrating the four key approaches to manage sub-supplier in multi-tier GSCM: ‘Don’t bother’, ‘Direct’, ‘Indirect’ and ‘Work with third party’. Section 2.4 reviewed the performance assessment literature, with a particular focus on supply chain performance assessment and sustainability performance assessment. The increased complexity due to the involvement of multiple organisations was recognised as the main challenge for SCM performance assessment, having various implications on the assessment process, such as lack of trust and lack of standardised data along the chain, whereas the multi-dimensional nature of sustainability determines additional challenges in the sustainability assessment process. The funnel approach adopted in the literature review culminated in Section 2.5, which constitutes the core of this chapter, illustrating the systematic literature review at the intersection of GSCM and performance assessment. Four main aspects were investigated in the systematic literature review, namely the environmental aspects measured, the supply chain extent covered, the methodological approaches adopted and the main purpose of methods to assess the environmental performance of supply chains. Six initial gaps were identified as a result of the investigation guided from individual review questions. The combined evaluation of the analysed aspects, led to the finalisation of the research gap informing this research, which is “*the lack of GSCM performance assessment methods expanding simultaneously the comprehensiveness in terms of both environmental aspects considered and supply chain extent*”. The main gap in the current research supported the definition of the research problem and the framing of the research question guiding this research as “*How can the environmental sustainability performance of multi-tier supply chains be quantitatively assessed?”* (Section 2.6). Having identified the gap in the literature and having defined the research question guiding this research, Chapter 3 details the research approach followed to conduct this research.

3 Research approach

Research is "a careful, systematic, patient study and investigation in some field of knowledge", which is undertaken to expand the body of knowledge by establishing facts and principles (Kumar, 2011). Every research process needs to meet certain requirements to be qualified as such: it must be rigorous, systematic, empirical, critical, valid and verifiable (Kumar, 2011). In order to meet these criteria, the approach followed throughout the research needs to be formalised. Research approaches are "plans and the procedures for research that span the steps from broad assumptions to detailed methods of data collection, analysis, and interpretation" (Creswell, 2014).

Researchers face several decisions to deploy the research approach. The philosophical assumptions brought by the researcher to the study are at the basis of the pyramid (Creswell, 2014). These assumptions inform the methodological decisions and the specific methods and techniques adopted to collect, analyse and interpret data (Creswell, 2014). The outcome of these decisions determines the procedures of inquiry of the researcher, which is the research design (Creswell, 2014), as highlighted in the research approach framework depicted in Figure 3.1.

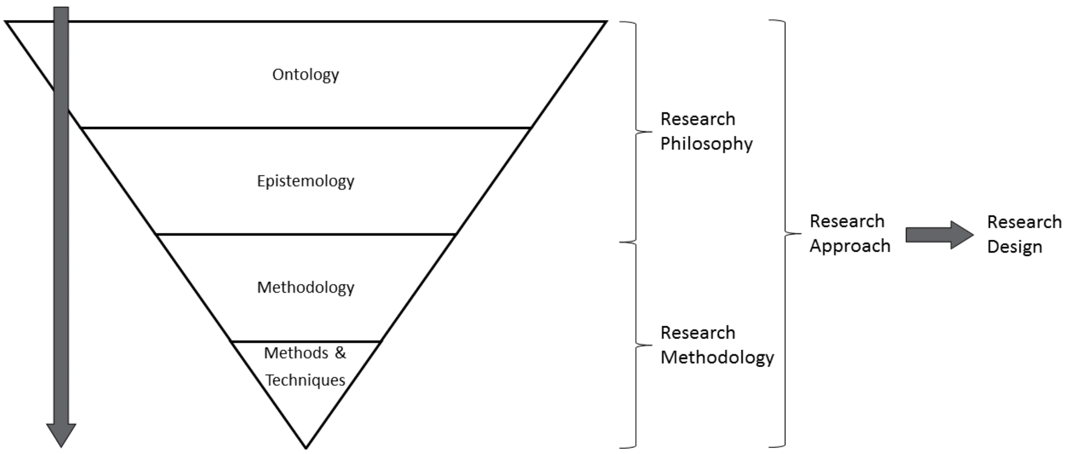

Figure 3.1: Research approach framework (based on Easterby-Smith et al., 2012)

The approach adopted in this research is illustrated in this chapter. First, an introductory section discussing the positioning of this research according to the perspectives identified in the classification scheme by Kumar (2011) opens this chapter in Section 3.1. Section 3.2 discusses about research philosophy and it is further broken down into sub-sections dedicated to ontology and epistemology. This section provides a brief overview of the dominant research philosophy positions and outlines the assumptions about the nature of reality and of knowledge adopted in this research. These assumptions are informing the research methodology, which is outlined in Section 3.3. This section is also divided into sub-sections, illustrating the methodological decisions and the methods and techniques adopted. Finally, dissemination of the research is discussed in Section 3.4 followed by a literal and graphical description of the research design in Section 3.5. A summary of the research approach section ends this chapter (Section 3.6).

3.1 Research Classification

Every piece of research can be classified according to three perspectives (Kumar, 2011):

- Applications of the findings of the research study: if findings do not have a practical relevance and are only functional to the advancement of academic theory and the body of knowledge, research is defined as *pure research* (Easterby-Smith et al., 2012). On the other hand, if practical issues are addressed, the research is depicted as *applied research* (Easterby-Smith et al., 2012; Kumar, 2011);
- Objectives of the study: four non-mutually exclusive viewpoints exist for this perspective, which are descriptive, correlational, explanatory and exploratory (Kumar, 2011; Saunders et al., 2008). *Descriptive* studies aim to "describe systematically a situation, problem, phenomenon, service or programme" (Kumar, 2011), whereas *correlational* studies aim to identify the existence of any type of association between two or more aspects of a situation (Kumar, 2011). *Explanatory* studies also deal with two aspects of a situation or phenomenon, but are mostly interested in seeking the causal relationship between them (Kumar, 2011; Saunders et al., 2008). Finally, *exploratory* studies look at areas where little research has been performed, trying to obtain new insights over the topic or question the feasibility of further studies in the area (Kumar, 2011; Saunders et al., 2008);
- Enquiry mode: based upon the decisions regarding the use of the findings and the objectives of the study, a *structured* or *unstructured* enquiry mode may be selected (Kumar, 2011). The former, which is often associated to *quantitative* data collection and analysis techniques, requires a predetermination of the research process and design, whereas the latter, often labelled as *qualitative*, is emergent and flexible in the process (Creswell, 2014; Kumar, 2011).

Based on the perspectives identified by Kumar (2011), the classification of this research is as follows:

- Findings of the research study are practically *applied* to address a practical emerging issue, which is the need of companies to assess the environmental performance of their supply chain. Findings of the research are applied in multiple case studies to link theoretical advancement to practical applications.
- The objectives of the study may be labelled as a combination of descriptive and exploratory. The combination of these viewpoints is common: the descriptive objective may act as a forerunner or an extension to the exploratory objective (Saunders et al., 2008). In this research, the exploratory objective is conducted through a search of the literature, which is one of the three ways to perform exploratory research according to Saunders et al.(2008). This is complemented by a

descriptive element, which is the modelling of supply chain environmental performance.

- Enquiry mode is *structured* and predominantly *quantitative*. A predetermined, rigorous and systematic enquiry mode is followed throughout the research project, which is largely dominated by the adoption of quantitative methods and techniques, despite qualitative methods being occasionally adopted in the research process. Moreover, the structured enquiry mode adopted in this research is pursued through a clear definition of the research approach, as outlined in Figure 3.1, and of the research design, which is described in Section 3.5. Further details on the enquiry mode are illustrated in Section 3.3.

3.2 Research Philosophy

Research philosophy "relates to the development of knowledge and the nature of that knowledge" (Saunders et al., 2008). Every piece of research contains certain philosophical assumptions that the researcher brings to the study (Saunders et al., 2008). These assumptions influence the overall way the researcher addresses the research process and need to be formalised (Saunders et al., 2008). The philosophical assumptions guiding the research are summarised in this work by the term 'worldview', which is "a basic set of beliefs that guide action" (Guba, 1990). Two major matters determine the worldview in research philosophy: ontology and epistemology (Saunders et al., 2008). Section 3.2.1 and Section 3.2.2 describe the key concepts relating to these matters and illustrate the philosophical assumptions underlying this research.

3.2.1 Ontology

Ontology determines the philosophical assumptions about the nature of reality and about the nature of "knowable" (Easterby-Smith et al., 2012; Guba, 1990). Ontologies can be classified according to their different positioning in respect of truth and facts (Easterby-Smith et al., 2012). Three ontological positions are typically outlined in the literature (Guba, 1990):

- Realism: according to this ontological stance, reality can be assumed as an external concrete structure (Easterby-Smith et al., 2012; Morgan and Smircich, 1980). Reality is considered driven by natural laws and mechanism (Guba, 1990). According to realism, a single truth exists and it is accessible (Creswell, 2014; Easterby-Smith et al., 2012). The realism ontological positioning is sometimes labelled as objectivism, claiming that "social entities exist independent of social actors" (Saunders et al., 2008).
- Critical realism: this ontological stance, also known as internal realism, moves beyond the realist ontology, distinguishing between the laws of physics and nature and the accessibility to the knowledge of these laws by researchers (Easterby-Smith et al., 2012). According to this ontology, truth exists but is not absolute, whereas a single reality exists but cannot be fully accessed (Creswell, 2014;

Easterby-Smith et al., 2012; Guba, 1990). Scientific laws are accepted and an objectivist position is held, similarly to realism.

- Relativism: according to this ontological stance, reality is a projection of human imagination and its content and form are dependent on the perceptions of individuals (Guba, 1990; Morgan and Smircich, 1980). The relativism ontological positioning is sometimes labelled as subjectivism, stating that "social phenomena are created from the perceptions and consequent actions of social actors" (Saunders et al., 2008). Relativism could be moved to even more extreme positions according to Easterby-Smith et al. (2012) if nominalism is embraced and the truth is completely neglected while considering facts as simple human creations.

The technology and engineering research traditionally adopts a realism perspective, in order to assess the credibility of numerical results and to support decision making (Roy and Oberkampf, 2011). However, this research moves beyond the strict engineering tradition, by investigating the nature of environmental sustainability and supply chain management. As a result, this research is interdisciplinary in nature and draws from multiple disciplines, such as operations management and environmental sciences, being evenly influenced by each of them.

Some aspects of the traditional engineering approach are preserved, such as the nature of reality, which is considered objective. Environmental sustainability is considered to be driven by natural laws and operating according to physical laws in this research. Nevertheless, an absolute truth or a single reality over its nature are not possible to be determined, as the interpretation of its meaning varies for different individuals (Hay, 2015). Supply chains are also considered to behave according to physical laws, as they "have been assumed as inter-organisational forms that have ontological identities independent of the social entities, relations and practices through which they have been generated" (Adamides et al., 2012). If supply chains are treated independently from the people, who create and manage them, they can then be evaluated according to performance criteria (Adamides et al., 2012).

In the light of the above considerations, this research adopts a critical realism ontological position to guide the research: reality exists 'out there' independently from human minds, natural and physical laws as well as objectivism are embraced, but truth is not considered absolute as human beings experience reality through imperfect senses (Guba, 1990; Saunders et al., 2008).

3.2.2 Epistemology

Epistemology deals with a general set of assumptions about "ways of inquiring into the nature of the physical and social worlds" (Easterby-Smith et al., 2012), which is the relationship between the inquirer and the known or "knowable" (Guba, 1990). Epistemological positions span between positivism and constructionism views, depending on assumptions such as the role of the observer and of human interests as well as the features of explanations and concepts (Easterby-Smith et al., 2012). Moreover the positions differ in terms of axiology, which refers to the judgements about value, as positivists advocate for value-free and unbiased research, whereas constructionists support a value-laden and unbiased research (Clarke, 2005; Saunders et al., 2008). Based on differences in these assumptions as well as in the underlying ontological assumptions, these two dominant epistemological positions can be further broken down in more categories. As a result, four epistemological positions are obtained in the literature (Guba, 1990), which are complemented by the pragmatism position. This fifth position blends different epistemological positions and underlying philosophical assumptions to best answer the research questions (Creswell, 2014; Saunders et al., 2008). A brief overview of the epistemological positions follows:

- Positivism: also labelled as strong positivism (Easterby-Smith et al., 2012), is the traditional epistemological stance of natural scientists, who proceed through hypothesis formulation and testing in their research (Saunders et al., 2008). The underlying ontological assumption is realism. A strong objective and value-free way of inquiring into the nature of the world is adopted by positivism (Easterby-Smith et al., 2012; Guba, 1990; Saunders et al., 2008), as only observable and measureable facts are considered able to generate knowledge (Easterby-Smith et al., 2012; Saunders et al., 2008). Concepts need to be clearly defined in order to be observed and measured (Easterby-Smith et al., 2012). Positivism also embraces determinism, in which cause and effect relationship is accepted and reductionism, which is the breaking down of complex problems to the simplest unit of analysis (Creswell, 2014; Easterby-Smith et al., 2012). Finally, a quantitative enquiry mode is typically preferred (Easterby-Smith et al., 2012; Saunders et al., 2008).
- Post-positivism: this epistemological position moves beyond strong positivism by refusing the notion of absolute truth as an ontological background and thus shifting from realism to critical realism (Creswell, 2014; Easterby-Smith et al., 2012). As a result, a modified objectivist way of inquiring into the nature of the world is adopted as "objectivity remains a regulatory ideal but it can only be approximated" due to the impossibility of separating completely the inquirer from what is inquired (Guba, 1990). Post-positivism also moves beyond positivism tradition by adopting qualitative modes of enquiry along with quantitative ones in the research and tries to establish a more enduring truth (Popper, 1959). However, post-positivism maintains some features of the positivist tradition. The value-free and neutral way of inquiring into the nature of the world is retained, as well as determinism and reductionism (Creswell, 2014; Guba, 1990).
- Critical theory: this epistemological stance, also labelled as transformative (Creswell, 2014), adopts critical realism as the underlying ontological stance, similarly to post-positivism. However critical theorists strongly reject objectivism and embrace subjectivism (Guba, 1990). Values mediate the inquiry and the research abandons its neutrality to become values-oriented and politically-oriented (Creswell, 2014; Guba, 1990).

- Constructionism: this epistemological stance, in contrast to post-positivism and critical theory, does not try to move beyond positivism by fixing some positions and assumptions, but offers a completely alternative epistemology (Guba, 1990). Indeed, the underlying ontological assumption is not connected to realism, but is relativism (Easterby-Smith et al., 2012; Guba, 1990). As a consequence, human interests and values become the main drivers of science and knowledge and the inquirer is not detached from what is being inquired (Easterby-Smith et al., 2012). Moreover, explanations are meant to augment the general understanding of the situation and thus cannot be reached through reductionism, but include the complexity of whole situations (Easterby-Smith et al., 2012). Finally, a qualitative enquiry mode is typically preferred, although quantitative modes may be adopted (Creswell, 2014; Easterby-Smith et al., 2012).
- Pragmatism: this position avoids the debate over the ways of inquiring the nature of the world and the underlying ontological positions, by adopting research questions as the only lodestar (Saunders et al., 2008). As a consequence, different epistemologies, and even ontologies, may be adopted if functional to answer the research questions (Creswell, 2014; Saunders et al., 2008). Even the axiology, which is the "researcher's judgement about value" may vary (Saunders et al., 2008). As a result, pragmatism naturally adopts a mix of quantitative and qualitative enquiry modes (Saunders et al., 2008).

Having embraced objectivism as part of the underlying ontology, this research naturally falls within the positivism and post-positivism spectrum in terms of epistemology. While still recognising that reality is external from the researcher, several pieces of work in the sciences proved that results "arise from the interaction of inquirer and inquired into" and knowledge can be acquired objectively without completely separating the inquirer from what is inquired (Guba, 1990). Moreover, it has to be acknowledged that every piece of research is a human construction and, as such, is to some extent naturally influenced by values as even a "value-free perspective suggests the existence of a certain value position" (Guba, 1990; Saunders et al., 2008). As a result, a fully objective and unbiased way of inquiring is deemed impossible to achieve. Therefore, a milder form of objectivism is adopted in this research, considering "objectivity as a regulatory ideal" in the way of inquiring into the nature of the world rather than an immutable certainty (Guba, 1990). This ideal is pursued by adopting a way of inquiring as much neutral and value-free as possible (Creswell, 2014; Guba, 1990). Driven by the regulatory ideal of objectivity, structured and measureable data which are not affected by the researcher worldview are predominantly adopted in this research, matching the position of natural scientists and of several operations management specialists (Saunders et al., 2008).

In the light of above considerations and coherently with the critical realism ontological stance, this research finds its natural epistemological positioning within post-positivism.

3.3 Research methodology

Research methodology is about the acts of an inquirer to find out knowledge (Guba, 1990). This involves the determination of a reasoning methodology, which is illustrated in Section 3.3.1 and the selection of appropriate methods to answer the research question guiding this research and to address the research objectives.

The research methodology is deployed through a combination of methods and techniques, which are used to inquire into a specific situation (Easterby-Smith et al., 2012). Methods are focused and systematic ways of working throughout the research process, whereas techniques further narrow the focus, offering step by step procedures and precise actions (Adams, 2015). Sala et al. (2015) further specify the research methodology within sustainability assessment science as "a collection of individual characterisation methods, which together address the different environmental, economic and social issues and the associated effect/ impact". The research methods and techniques adopted in this research as well as the theoretical justification for their selection are illustrated in Section 3.3.2.

3.3.1 Methodological approach

The methodological choice is a fundamental decision in the research process (Saunders et al., 2008). Researchers face two possibilities: the deductive or the inductive methodology. The former implies that "a clear theoretical position is developed prior to the collection of data", whereas the latter "is based on the principle of developing theory after the data have been collected" (Saunders et al., 2008). Deductive reasoning is usually associated to positivist and post-positivist epistemological stances, whereas inductive positions are mostly adopted by constructionists (Adamides et al., 2012; Meredith et al., 1989). This research is no exception to this association and being developed from a post-positivist epistemological stance, it adopts a deductive flow of logic. Accordingly, it adopts the literature to frame the research questions and has some preliminary assumptions informing the research (Creswell, 2014; Saunders et al., 2008). As a consequence, this research moves from the general, which is the wider field of green supply chain management, to the particular, which is represented by the theoretical method developed to assess the supply chain environmental performance and its application in multiple case studies. Saunders et al. (2008) reports that a theoretical or conceptual framework is usually developed at an initial stage of the research and is later tested using data when deductive methodology is adopted, a strategy followed by this research as well.

Saunders et al. (2008) further identified five distinctive features of deductive methodology, which can all be observed in the methodology adopted in this research:

- Testing: following the scientific research methodology, a rigorous test of a theory or a hypothesis is required. The developed method to assess the environmental performance of multi-tier supply chains is tested in this research.

- Structured methodology: reliability and replicability of the research should be ensured, to guarantee as much as possible the transparency in the treatment of raw data and that similar observations would have been made by other observers. This is particularly evident in this research in the choice of a systematic methodology to review the literature, as outlined in Section 3.3.2.1.
- Operationalisation: concepts need to be put into practice "in a way that enables facts to be measured quantitatively"; the operationalisation of the method is sought in this research through multiple case studies technique with quantitative outcomes, as outlined in Section 3.3.2.5.
- Reductionism: problems are broken down at the smallest possible level of granularity to achieve a better understanding. Reductionism is sought in this research by breaking down the overall environmental performance of the supply chain into the environmental performance of each organisation part of the supply chain and by investigating the environmental performance through multiple specific environmental indicators to reduce the granularity level.
- Generalisation: it is how "findings may be equally applicable to other research settings, such as other organisations". It is often labelled as external validity. Generalisation is sought in this research by applying the developed method in multiple supply chains with different organisational contexts.

3.3.2 Research methods and techniques

This research adopted multiple methods to answer the research question and address the research objectives, using both qualitative and quantitative data collection and data analysis techniques. Therefore, it can be considered as a study adopting mixed methods (Saunders et al., 2008). Within the mixed-methods choice, this research specifically adopted mixed-method research. This means that, despite both qualitative and quantitative worldviews being adopted at the research method stage, data analysis is strictly separated, with quantitative data analysed quantitatively and qualitative data analysed qualitatively. This is in contrast to the mixed-model research, which adopts a mixed approach in the data analysis (Saunders et al., 2008). The research choices decision tree is depicted in Figure 3.2.

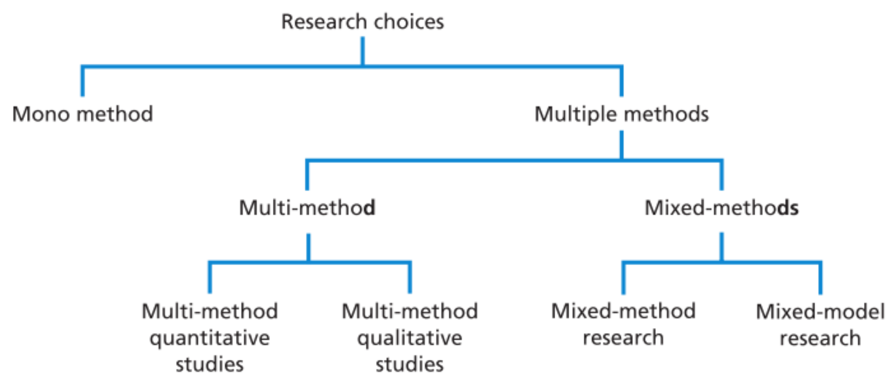

Figure 3.2: Research choices (Saunders et al., 2008)

Saunders et al. (2008) also stress that mixed-method research usually shows a dominance of either quantitative or qualitative techniques. This applied to this research too, as quantitative techniques are dominant and qualitative techniques are supporting the overall research process. Moreover, the adoption of multiple methods within mixed-method research is usually linked to triangulation of data sources as “a mean for seeking convergence across qualitative and quantitative methods”, increasing the reliability and validity of the research (Creswell, 2014). This research achieved multiple triangulation, as data and methodological (both within-method and between-method) triangulation were adopted (Wang and Duffy, 2009), as outlined in the following part of this section.

Five research methods and techniques were adopted throughout the research project: systematic literature review; conceptual and mathematical modelling; semi-structured interviews; numerical example; multiple case studies. The implementation of the research methods and techniques as well as the data collection and analysis procedure followed a sequential procedure, a typical approach in mixed-method research (Creswell, 2014; Saunders et al., 2008), as depicted in Figure 3.3. Each method was functional to inform the subsequent stage of the research and the relative method adopted. Nevertheless, additional inputs to the conceptual and mathematical modelling arouse while adopting subsequent research methods and techniques and, as a result, some feedback loops emerged throughout the research process. The continuous refinement to both the conceptual and the mathematical model is shown in Figure 3.3, illustrating the outputs of each research method and technique in the form of different versions of both models.

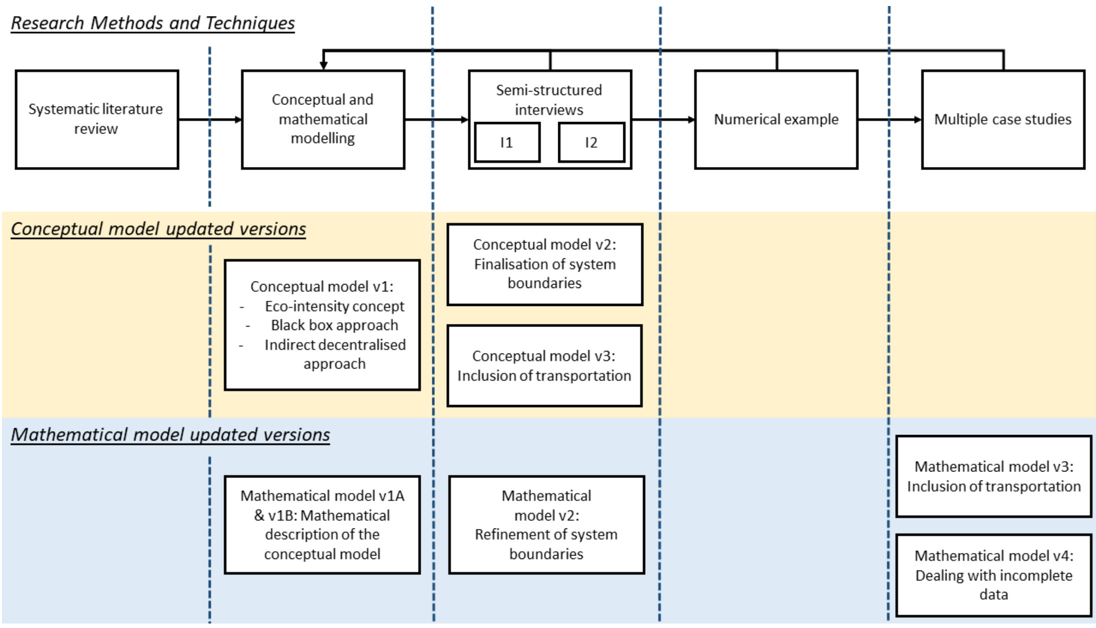

Figure 3.3: Temporal visualisation of iterative models’ development

The five research methods and techniques were functional to answer the research question guiding this research, outlined in Section 1.1. Three of them were spefically adopted to address objective 4 (O4) in order to corroborate findings thanks to between-method triangulation, which is the adoption of “different methods with the same object of study”

(Wang and Duffy, 2009). A summary of research methods and techniques adopted in this research to address the research objectives is illustrated in Table 3.1, whereas more details about each method and technique are illustrated in Sections 3.3.2.1 to 3.3.2.5.

Table 3.1: Summary of research methods and techniques adopted to answer the research question

Research objective		**Research methods and techniques**
O1	Identify quantitative methods developed to assess the environmental performance of supply chains and evaluate their key features	Systematic literature review
O2	Understand the key mechanisms regulating sub-supplier management and multi-tier supply chains, with a particular focus on GSCM	State-of-the art literature review
O3	Construct a method to quantitatively determine the environmental sustainability performance of multi-tier supply chains	Conceptual and mathematical modelling
O4	Apply the method to operating supply chains	Multiple case studies
O5	Evaluate the utility, accuracy and applicability of the method	Semi-structured interviews Numerical example Multiple case studies

3.3.2.1 Systematic and state-of-the-art literature review

A systematic literature review adopts an "explicit and reproducible design for identifying, evaluating, and interpreting the existing body of recorded documents" (Fink, 1998). A systematic process was adopted in this research as it allows a transparent and structured approach to investigate the body of knowledge in a specific field. Systematic literature reviews are widely accepted as a standardised approach to analyse published materials in the field of management, as they are recognised to minimise bias in the selection of papers and offer the opportunity to replicate the research (Tranfield et al., 2003).

The systematic literature review method was adopted to investigate the core topic of interest in the literature, which is green supply chain performance assessment, and to identify the gaps in the literature, which informed and guided the following stages of this work. The systematic literature review method was also functional to address objective 1 (O1): "Identify quantitative methods developed to assess the environmental performance of supply chains and evaluate their key features". As illustrated in Section 2.5.1, for each paper included in the systematic literature review sample the following data were recorded: environmental performance (environmental inputs and outputs considered; distinct metrics adopted), supply chain features (number of tiers upstream and downstream of the focal firm involved in the environmental performance measurement; type of supply chain; cradle-to-gate or cradle-to-grave approach), methodology (model type, modelling technique and solution type), scope of the work.

The systematic literature review is complemented by an overview of the wider topics of: sustainability; sustainable and green supply chain management; performance measurement. The literature search for these topics followed a snowball approach, since its main purpose was to provide context for this work. Finally, a state-of-the-art literature review was conducted in the field of multi-tier sustainable supply chain management, as state-of-the-art reviews "tend to address more current matters in contrast to other combined retrospective and current approaches" (Grant and Booth, 2009), addressing the current state of knowledge in emerging fields, such as multi-tier SCM. The state-of-the-art review was performed in order to address objective 2 (O2): "Understand the key mechanisms regulating sub-supplier management and multi-tier supply chains, with a particular focus on GSCM".

3.3.2.2 Conceptual and mathematical modelling

The systematic literature review findings informed about the gaps in the literature and urged the development of a method to assess the environmental performance of multi-tier supply chains. In the area of sustainability assessment science, a method "is a set of models, tools and indicators that enable the calculation of the values of indicators for a certain impact category" (Sala et al., 2015). Coherently with this definition, the method was built through a set of two models in this research: a conceptual model for the assessment of the eco-intensity performance and a mathematical model to quantitatively operationalise the conceptual model, allowing testing in the real world.

Therefore, modelling is the research method adopted to address objective 3 (O3): "Construct a method to quantitatively determine the environmental sustainability performance of multi-tier supply chains". Modelling is defined as the act of making models (Oxford University Press, 2018a), which are the outcomes of this method. A model is "a representation of a physical system or process intended to enhance our ability to understand, predict, or control its behavior" (Neelamkavil, 1987). In this research, the developed models are primarily aimed to understand the environmental performance status of the system, which is the supply chain. It is therefore claimed that conceptual and mathematical modelling for the purposes of this research are descriptive and explanatory in nature (Saunders et al., 2008).

According to Oberkampf and Roy (2010), the specification of the existing physical system of interest and its surroundings is the starting point of the modelling process. This is followed by the conceptual modelling phase and finally by the mathematical modelling phase, which aims to develop "analytical statements based on the conceptual model formulated in the previous phase" (Oberkampf and Roy, 2010a). Informed from Oberkampf and Roy (2010), this research adopted a similar process.

3.3.2.3 Semi-structured interviews

Interviews were one of the three methods adopted in the model evaluation stage in order to address objective 5 (O5): "Evaluate the utility, accuracy and applicability of the method". More specifically, semi-structured interviews were adopted to evaluate the utility of the developed method, which is the usefulness and fitness for purpose of the conceptual model part of the method. The interviews were also functional to evaluate the adequacy for the domain of intended application according to the opinion of experts. Finally, they provided an overview the status of SSCM from an industrial perspective in order to understand the positioning of the model within the current needs of the industry.

Semi-structured interviews are a research technique, which is a subset of the interview research method, aiming to collect data through language (Easterby-Smith et al., 2012; Hay, 2015). Semi-structured are non-standardised and open-ended interviews, which allow interviewees "to expand on what they consider to be important and to frame those issues in their terms" (Barnes, 2001; Saunders et al., 2008). Semi-structured interviews cover a number of themes and questions, allowing a flexible delivery which may change from interview to interview: questions may be omitted or added based on the flow of the conversation and their order may also vary (Easterby-Smith et al., 2012; Saunders et al., 2008). Advantages of semi-structured interviews include the natural flow of communication, the possibility to refer back to most important questions if the answer remains unclear as well as the possibility for respondents to expand on the aspects they believe to be important (Barnes, 2001; Freeman and Chen, 2015; Kovács, 2008). Moreover, they manage to get access to "accurate inclusive accounts that are based on personal experience" (Burgess, 1982).

This research adopted both one-to-one and one-to-many interviews (Saunders et al., 2008). A participant interview typology was adopted in this research, as the interviewer had a leading role in the interviews while interviewees mostly answered the questions of the researcher (Saunders et al., 2008). In contrast to the informant interview typology, participant interview enables the researcher to have an increased control over the interview and to cover all themes and questions identified in the interview preparation, an aspect which was considered beneficial towards the purpose interviews fulfilled which is the conceptual model qualification (Saunders et al., 2008).

Overall, four experts from the Sustainability Team from Scottish Enterprise (SE) were interviewed for this research across two interviews, namely a one-to-one interview and a one-to-many interview. Interviewees were selected on the basis of their expertise in the field of sustainability and cross-industry experience. Additional details on the profile of interviewees and the conducted interviews are reported in Section 5.2.1. In accordance with the mixed-method research illustrated in Section 3.3.2, data emerging from the interviews was analysed qualitatively.

3.3.2.4 Numerical example

Numerical example was the second technique adopted in the model evaluation stage in order to address objective 5 (O5): “Evaluate the utility, accuracy and applicability of the method”. More specifically, numerical example was adopted to verify and evaluate the accuracy of the mathematical model. Numerical examples are a common choice to illustrate models and evaluate them when primary data are not available (Sundarakani et al., 2010).

Randomly generated values or secondary data can be adopted for the purpose. While both options are actually feasible for illustrating the model, the advantage of secondary data is that they are real data, which are retrieved from archival sources and thus can be more functional to the purpose. Secondary data are “data that have been collected for some other purpose” (Saunders et al., 2008). This research adopts multiple source of secondary data, as quantitative data for the numerical example are retrieved both from databases available online and publications available in the literature. Easterby-Smith et al. (2012) claim that a key task for researchers is to identify the value of secondary sources to identify “how close the study objectives are to those that influenced the original collection of the data”. The online databases that were consulted are aimed to publicly report economic and environmental data and can be labelled as survey-based secondary data (Saunders et al., 2008). The journal publication adopted as a source of secondary data is focused on reporting the water consumption performance of a supply chain. Therefore, it could be here claimed that the data originally collected fit the study objectives in terms of scope and are suitable to be adopted in the numerical example.

3.3.2.5 Multiple case studies

Multiple case studies were the last technique adopted in the model evaluation stage in order to address objective 4 (O4) and objective 5 (O5), which are “Apply the method to operating supply chains” and “Evaluate the utility, accuracy and applicability of the method” respectively. Multiple case studies were adopted to complete the method evaluation by validating the method in operating contexts with primary data sourced from actual practice and evaluating the applicability of the method. Moreover, multiple case studies allowed bridging back the link between the mathematical model and reality, demonstrating that the aspects of interest of the reality are adequately represented in the method. Finally, the feedback from the supply chain managers offered additional information on the usefulness of results and applicability of the method to obtain an assessment of the supply chain environmental performance in an operating context.

Multiple case study technique is a subset of the case study method and requires that at least two cases are studied (Saunders et al., 2008). Case study method is a method, which can be embraced by different epistemological positions (Easterby-Smith et al., 2012). The design of the study, the size of the sample, the type of analysis as well as the ultimate theoretical outcome depend on the epistemological stance (Easterby-Smith et al., 2012). The adoption of case study method for validation purposes combined with a size of the sample larger than one is coherent with the positivist and post-positivist epistemology according to Yin (2003).

Yin (2003) also adds that it is generally preferable to use multiple case studies and this is even more valid when the case study method is used to generalise findings (Saunders et al., 2008). In this research, the use of multiple case studies technique aims to demonstrate the applicability of the method in various supply chains, which differ in terms of industrial sector, size of the focal company and manufacturing production strategy as well as in terms of structure and geographical scope. Hence, the technique aims to generalise the applicability of the method in different operating contexts. Two case studies were carried out in this research. They involved first the application of the method in operating supply chains, which was followed by an evaluation of the results and outputs through a comparison with anoter case (case study 1) and with information available at the focal company (case study 2) as well as by an evaluation of the applicability of the method based on enablers for multi-tier GSCM, which was achieved through semi-structured interview for both case studies. Additional details on the case studies design and context is presented in Section 5.4.1.

The adoption of multiple case studies also determines that the case study method is adopted in different occasions, obtaining a within-method triangulation, and that multiple data sources are adopted, thus achieving a triangulation of data sources and enhancing the justification of the findings (Creswell, 2014; Wang and Duffy, 2009). This is particularly important at the stage of validation, as researchers are required to "retrieve data from a number of different sources with similar foci for the purpose of validation" (Wang and Duffy, 2009).

Finally, the selection of multiple case studies technique fits the post-positivist orientation of this research (Easterby-Smith et al., 2012) as well as the cross-case analysis, which is dominant in this research compared to within-case analysis. The external validity of the research is sought through the use of replication logic according to the multiple case study research design (Yin, 2003).

3.4 Dissemination

The research led to the development of research outputs at each stage of the research project. Research outputs need to be appropriately recorded and communicated in order to provide access to the wider research community and to contribute to the expansion of the body of knowledge (Blessing and Chakrabarti, 2009; Kumar, 2011). Moreover, in the light of the post-positivism epistemology, a consistent positioning of the research outputs within the scholarly tradition of the field is considered an adequate way to seek objectivity of the research thanks to the judgement of peers in the critical community (Guba, 1990).
Research outputs are:

- Journal article: a paper published on an international peer-reviewed journal;
    1) "Environmental performance measurement for green supply chains: a systematic analysis and review of quantitative methods" (2018), published in the International Journal of Physical Distribution & Logistics Management, Vol. 48, Issue 8, pp. 765-793. The findings of the systematic literature review at the intersection of GSCM and performance measurement are presented;
    2) "An innovative eco-intensity based method for assessing extended supply chain environmental sustainability" (2018), published online on the International Journal of Production Economics. The method, with a focus on the mathematical model, as well as the numerical example adopted for the verification stage are presented;
    3) "An integrative approach to assess environmental and economic sustainability in a multi-tier supply chain: a case study", accepted for publication in Production Planning and Control. The findings of case study 2 are presented.
- Conference paper: a paper presented at an international peer-reviewed conference;
    1) "Measuring the eco-intensity of the supply chain: a novel approach", presented at the 4th International EurOMA Sustainable Operations and Supply Chains Forum, Milan, Italy, 27th – 28th February 2017: presentation of the conceptual model and introduction to the mathematical model;
    2) "Benchmarking the environmental performance of supply chains through eco-intensity", presented at the 24th EurOMA Conference, Edinburgh, Scotland, United Kingdom, 1st – 5th July 2017: refinement of the conceptual and mathematical model along with a simplified numerical example with secondary data to showcase the potential for applicability of the method;
    3) "Measuring eco-intensity in a multi-tier food supply chain: a case study", presented at the 5th International EurOMA Sustainable Operations and Supply Chains Forum, Kassel, Germany, 5th – 6th March 2018: presentation of case study 1 and initial discussion about the applicability of the method in an operating context.
- Conference presentation: a presentation given at an international conference;

1) “Mapping and Evaluation of Approaches for Supply Chain Environmental Sustainability Performance”, presented at the 27th European Conference on Operational Research, Glasgow, Scotland, United Kingdom, 12th – 15th July 2015: preliminary findings of the literature review on the topic of SSCM;
2) “Quantitative assessment of supply chain environmental performance, with a focus on benchmarking”, presented at the ISIR Workshop on Sustainable Logistics and Supply Chain Management, Lyon, France, 7th – 9th October 2015: expansion of the findings of the literature review on the topic of SSCM, with a more detailed focus on quantitative methods and potential for benchmarking;
3) “From a literature review to an innovative model to assess environmental performance for supply chains”, presented at the 1st EWG on Sustainable Supply Chains, Aachen, Germany, 1st – 2nd July 2016: findings of the systematic literature review on GSCM performance assessment methods coupled with preliminary ideas to bridge the gaps identified in the literature;

- Supply chain report: technical report addressed to the relevant decision makers of the companies part of the supply chains that were involved in the case studies. Reports were documented in the form of presentations;
- Thesis: “a detailed account of a piece of research undertaken for the purpose of obtaining a research degree” (Blessing and Chakrabarti, 2009). This document is the most comprehensive output of the research as a result.

3.5 Research design

The research approach, research philosophy and research methodology were outlined throughout Sections 3.2 and 3.3, providing the basis to introduce a summarised picture of the overall structure of the research, which is the research design. Figure 3.4 depicts the research design highlighting the main research phases, research sub-phases, research methods and techniques, as well as the data sources and the documental outputs. Seven research phases are identified from Figure 3.4 and are linked to specific chapters of this work:

1. State-of-the-art review: the review mapped the existing body of literature in the field of green supply chain performance assessment adopting a funnel approach moving from the wider topics of sustainability and SSCM to GSCM and GSCM performance assessment progressively narrowing the scope. Moreover, specific attention is paid to the mapping of multi-tier GSCM literature as well as of eco-efficiency and eco-intensity literature (Chapter 2).
2. Research problem: the issue at the basis of the research enquiry (Kumar, 2011) is outlined in a dedicated section at the end of Chapter 2 and is informed by the gaps identified in the literature through the literature review process.
3. Aim and objectives: based on the outcomes of research phase 2, the research aim and objectives were defined (Chapter 0). The research aim is “a brief statement of

the purpose of the research project" (Saunders et al., 2008), whereas the research objectives are intermediate goals that require to be achieved to complete the research process (Kumar, 2011). Research objectives are usually based on research questions, but are worded adopting action-oriented vocabulary rather than interrogative form (Kumar, 2011).

4. Method development: based on the gaps identified in the literature and reflecting the aim and objectives highlighted in research phase 3, a method to assess the environmental sustainability performance of multi-tier supply chains was developed. The method includes a conceptual model and a mathematical model (Chapter 4).
5. Method evaluation: the utility, accuracy and applicability of the models building the method were evaluated through a three steps process. Model qualification aimed at evaluating the usefulness and fitness for purpose, i.e. the utility, of the conceptual model through semi-structured interviews. Model verification aimed to check that mathematical model implementation accurately represents the conceptual description of the model. This was performed through a numerical example. Finally, validation aimed to establish the degree the method accurately represents the real world from the perspective of the intended uses of the model (USDoD, 1994) and to evaluate the conceptual and mathematical model applicability through multiple case studies (Chapter 5). The description and results of the case studies are presented in a separate section (Chapter 6).
6. Discussion: reflections over the research findings, methods and approach are discussed (Chapter 7). A summarised excerpt of the research concludes the work, including its novelty and contribution to the knowledge, as well as implications for practitioners and policy makers and directions for future research (Chapter 8).
7. Consolidation: research findings were documented throughout the research process with different media. Formal documents, which are helpful to support the dissemination of the research were presented in Section 3.4, whereas a variety of informal documents, both in a digital and hardcopy formats were used to record the research progress over time. Finally, this thesis consolidates the entire research project work in a single and formal piece of writing.

3.6 Summary

This chapter presented the research approach adopted in this work. First, the research was positioned according to the classification by Kumar (2011) in Section 3.1: this research can be thus described as applied research and having a combination of descriptive and exploratory objectives. The adopted enquiry mode is structured and predominantly quantitative.

Second, the main philosophical and methodological choices of this research were explicated in Section 3.2 and Section 3.3 following the research approach framework by Easterby-Smith et al. (2012). Being informed by multiple disciplines, this research blends the traditional engineering perspective with the social sciences one and thus adopts a critical realism ontological position. Guided by this ontological stance, this research embraces post-positivism as its epistemology. Moving to the methodological aspects of this research, a deductive methodological approach was selected, which results in five distinctive features of this research: testing, structured methodology, operationalisation, reductionism and generalisation. Five research methods and techniques were adopted to answer the research question: literature review, systematic and non-systematic; conceptual and mathematical modelling; semi-structured interviews; numerical example; multiple case studies. The last three methods and techniques were all adopted to address objective 4 (O4), thus obtaining a triangulated methodology.

The research was disseminated through three journal articles, three conference papers and three conference presentations within the academic community, whereas supply chain reports were delivered to the practitioners of the organisations involved in the case studies, as explicated in Section 3.4. Finally, the research design, presented both in literal and graphical form, was illustrated in Section 3.5, summarising the main research phases, the research methods and techniques, the source of data as well as the main disseminated outputs of the research.

In the next chapter (Chapter 4), the method to assess the environmental sustainability performance of multi-tier supply chains is introduced based on the gap identified in the literature.

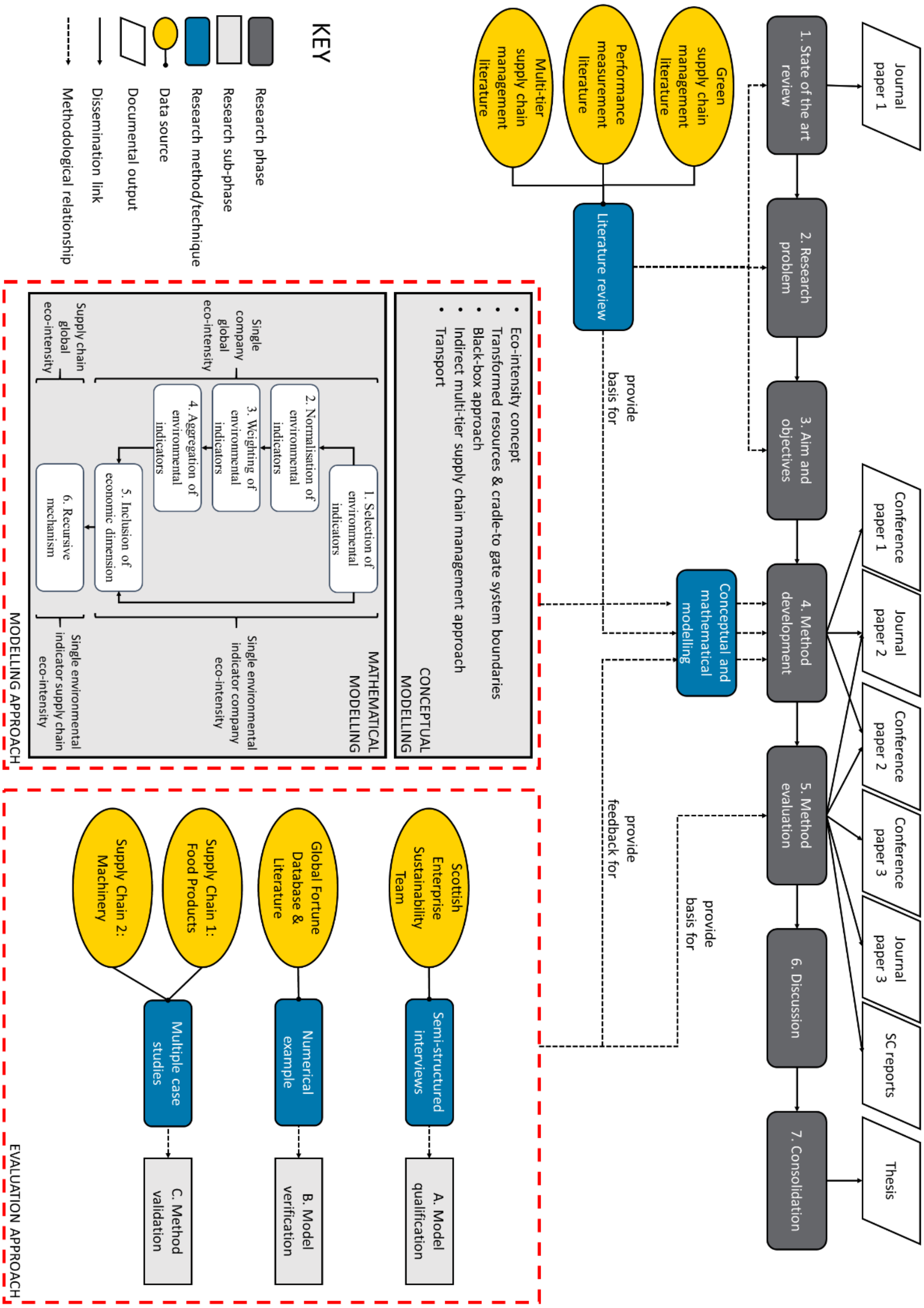

Figure 3.4: Research Design

4 Method description

The literature review findings informed about the gaps in the existing literature (Chapter 2) and urged the development of a method to assess the environmental sustainability performance of multi-tier supply chains. This research aims to develop such a method in order to address the lack of methods that simultaneously:

- Assess multi-tier supply chains environmental sustainability performance;
- Provide a comprehensive evaluation of environmental aspects;
- Use primary data sourced from actual practice to assess the environmental performance;
- Respect the multiple organisation and non-collaborative nature of the majority of real-life supply chains.

To achieve this purpose, the method was developed, contributing towards objective 3 (O3), which is to "construct a method to quantitatively determine the environmental sustainability performance of multi-tier supply chains".

In the area of sustainability assessment science, a method "is a set of models, tools and indicators that enable the calculation of the values of indicators for a certain impact category" (Sala et al., 2015). The method developed in this research is built by a set of two models, namely a conceptual model and a mathematical model. Models are "a simplified representation or abstraction of reality" (Brandenburg et al., 2014), which are built through assumptions, conceptualizations, abstractions, and mathematical formulations (Roy and Oberkampf, 2011). Figure 4.1 provides an overview of the method, identifying the two constituting models building the method as well as the outputs of the method. The conceptual model is developed abstracting from the existing physical system of interest and its surroundings (Oberkampf and Roy, 2010a), while the mathematical model quantitatively operationalise the conceptual model, allowing testing in the real world, by developing "analytical statements based on the conceptual model formulated in the previous phase" (Oberkampf and Roy, 2010a).

The method developed to assess the environmental sustainability performance of multi-tier supply chains is illustrated in this chapter. Section 4.1 outlines the conceptual model underpinning the method, while Section 4.2 presents the mathematical model stemming from the underlying conceptual model, including all relevant equations. Section 4.1 is broken down into several sub-sections, each of whom is dedicated to a pillar of the conceptual model. Section 4.2 is also divided in multiple sub-sections, however it follows a narrative approach progressively building the mathematical model and illustrating the necessary steps to calculate the various outputs of the method, which are outlined in Section 4.3. Finally, a summary of the chapter is provided in Section 4.4.

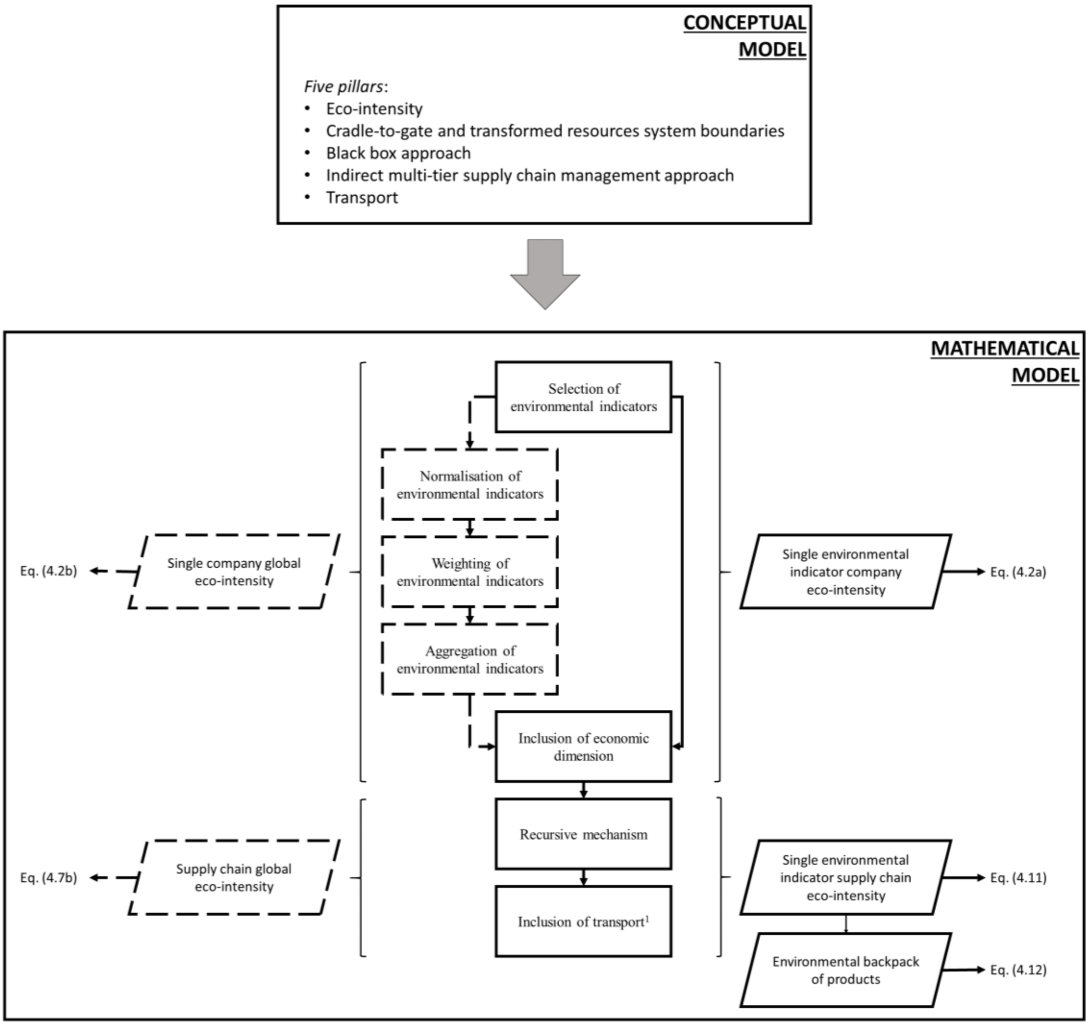

Figure 4.1: Overview of the method[1]

4.1 Conceptual model

Conceptualising and understanding the system under analysis is the most critical task in any modelling effort, as it affects following stages such as mathematical modelling, verification and validation (Oberkampf and Roy, 2010a). Two activities are necessary at the conceptual modelling stage:

- Specification of the physical system of interest and its surroundings: a clear separation needs to be drawn between the system, which can be defined as a "construct or collection of different elements that together produces results not obtainable by the elements alone" (Sokolowski and Banks, 2010) and its surroundings, which are "all entities and influences that are physically or conceptually separate from the system" (Oberkampf and Roy, 2010a). The separation between the system and its surroundings "depends on the purpose of

[1] Inclusion of transport stage is performed only for a limited set of environmental indicators, as further detailed in sections 4.1.5 and 4.2.7

the analysis" (Oberkampf and Roy, 2010a), as only elements functional to the purpose of the analysis need to be included. The purpose of this research is the assessment of the environmental performance of multi-tier supply chains. As such, the system needs to be conceptualised with respect to two main dimensions, which are the specification of the environmental performance (and its surroundings) and the specification of the supply chain (and its surroundings). The former is a purely conceptual distinction, which specifies how the environmental performance is interpreted in this research. The specification of the environmental performance and its surroundings is discussed in Section 4.1.1. The latter contains both elements of physical distinction, associated to the material flow of products, and of conceptual distinction, as a supply chain is a human-made system. The specification of the supply chain and its surroundings is extensively discussed in Section 4.1.2.

- Determination of the environments of interest: the environment of interest is the "external condition or situation in which the system can be exposed to; specifically: normal, abnormal or hostile conditions" (Oberkampf and Roy, 2010a). In this research the environment of interest is assumed to be normal, meaning that "the system is typically expected to operate or function and achieve its performance goals" (Oberkampf and Roy, 2010a).

Moving from these activities, the conceptual model for the assessment of the environmental sustainability performance of multi-tier supply chains is introduced in this section. The conceptual model is built upon five pillars, which are individually illustrated in the following sub-sections. Each pillar contributes to conceptualise a specific aspect, as shown in Figure 4.2.

Conceptual model pillar	**Conceptualised aspect**
Eco-intensity *(Section 4.1.1)*	Environmental impact
Cradle-to-gate and transformed resources system boundaries *(Section 4.1.2)*	Supply chain structure and dynamics
Black box approach *(Section 4.1.3)*	
Indirect multi-tier supply chain management approach *(Section 4.1.4)*	
Transport *(Section 4.1.5)*	

Figure 4.2: Conceptual model pillars

The final version of the conceptual model is presented here, however the model underwent two refinement loops as part of the method evaluation process, leading to three version of the conceptual model as explicated in Chapter 3 and summarised in Figure 4.3. The first version (v1) of the model included three pillars: eco-intensity, black box approach and indirect multi-tier supply chain management approach. The system boundaries were already considered as a critical aspect in this initial version, however multiple options were left open at this stage of development. Following semi-structured interview I2, the system boundaries were finalised, leading to version 2 (v2) of the conceptual model. Finally, transport was included in the conceptual model at a later stage, originating from insights arisen also during semi-structured interview I2. This led to the third version of the conceptual model (v3), which is the final version illustrated throughout the following sub-sections.

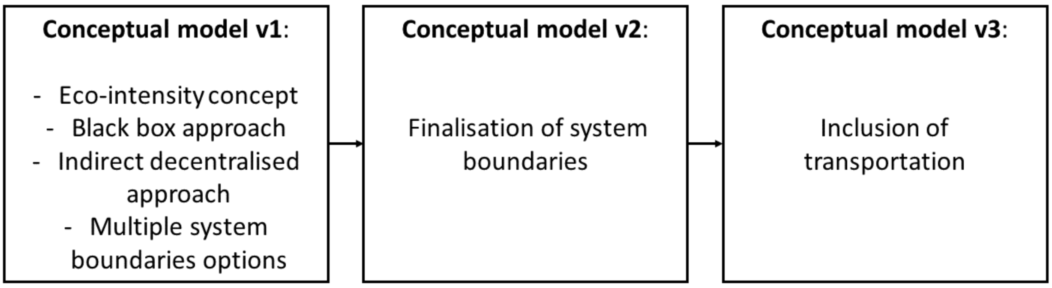

Figure 4.3: Iterative development of conceptual model

4.1.1 Eco-intensity

The eco-intensity conceptualises the environmental dimension of analysis in this research, detailing how the environmental impact is conceptually modelled in the method. Eco-intensity is defined as the “environmental impact per unit of production value” (Huppes and Ishikawa, 2005), thus being the environmental impact divided by the economic benefit generated by an economic activity (Schmidt and Schwegler, 2008). As such, eco-intensity is a relative indicator, as the absolute environmental figures are referenced to another variable, which is the value of production in this case (Jasch, 2000; Vasileiou, 2002). As Section 2.4.2.2 detailed, eco-intensity, alike relative indicators adopting different reference parameters, better supports comparability of results and decision making process compared to absolute indicators (Michelsen et al., 2006; Shokravi and Kurnia, 2014).

The economic dimension of sustainability is used in this work to relate the environmental performance to a single reference unit through the eco-intensity concept. Monetary unit was selected as the reference unit for the environmental dimension for two reason. First, it is applicable to any profit oriented company belonging to any manufacturing industry, thus having an extended range of applicability, differently from reference units that are linked to the physical properties of the products under analysis (Schaltegger et al., 2008). Second, it avoids subjective assumptions regarding its definition – e.g. in the case of functional unit –

that limit the benchmarking potential of the indicators (Michelsen et al., 2006; Schmidt and Schwegler, 2008), as discussed in Section 2.4.2.1.

Among the various options to express relative indicators using monetary reference units (Section 2.4.2), this research adopts value of production as the economic reference unit as it is better suited for the supply chain environment on the grounds of data confidentiality, compared to alternative economic reference units, thus not undermining the competitive advantage of organisations (Brandenburg, 2015; Caro et al., 2013). This choice is further justified in Section 4.2.7. The decision to have environmental impact at the numerator is guided from the easier applicability to a supply chain context of eco-intensity compared to eco-efficiency from a mathematical perspective (Schmidt and Schwegler, 2008) .

Several environmental indicators are adopted in this research at the numerator of the eco-intensity indicators, based on the outcomes of the literature review, tackling different environmental aspects having an impact on the environment and including both environmental inputs and outputs. An aggregated indicator of the environmental performance is also adopted to synthetize information about the environmental performance of organisations and supply chains. The details about the environmental indicators are discussed in Section 4.2.1. A single indicator is adopted at the denominator, which is the value of production. This is further refined as the turnover at the organisation level and the part of turnover generated by each product at the product level, as it will be illustrated mathematically in sections 4.2.5 and 4.2.6.

In conclusion, eco-intensity specifies how environmental performance is conceptualised in the method at a high level. The quantitative nature of eco-intensity naturally excludes qualitative environmental indicators, coherently with the predominantly quantitative mode of enquiry of this research. However, the selection of the actual environmental indicators, which will be detailed in section 4.2.1, is ultimately specifying which environmental aspects are taken into consideration and are part of the model. Environmental aspects not considered within the set of indicators are outside of the system specifications and thus constitute the surroundings of the system under analysis.

4.1.2 System boundaries

On top of the environmental dimension, the system needs to be conceptualised along the second dimension of analysis, which is the supply chain. Being the underlying physical system of interest, the supply chain requires to be modelled in the method and the first step towards the modelling is the definition of its system boundaries.

The definition of the system boundaries is a necessary activity of any conceptual model as it determines the system of interest, which is modelled, and its surroundings, which are not modelled as part of the system (Oberkampf and Roy, 2010a). Moreover, the definition of the system boundaries is also a necessary step to assess the performance of any system and to provide comparability of results (Wiedmann et al., 2009). Therefore, the demarcation line between the system of interest and its surroundings needs to be clearly defined.

The system boundaries are defined coherently with the definition of supply chain, which can be described as “all activities associated with the flow and transformation of goods from the raw materials stage (extraction), through to the end user, as well as the associated information flows” (Handfield and Nichols, 1999). Coherently with this supply chain definition, the method is developed for forward supply chains.

The supply chain system boundaries are defined in this work according to two main principles, the cradle-to-gate approach and the transformed resources approach, which shape the system boundaries as illustrated in Figure 4.4. Organisations and activities outside of the red dotted line in Figure 4.4 are not part of the system under analysis and thus constitute the surroundings of the system.

4.1.2.1 Cradle-to-gate approach

Cradle-to-gate approach, which includes all activities of the supply chain from raw material extraction (cradle) up to the point where the finished product leaves the organisation (gate), determines the base boundaries of the supply chain (Mele et al., 2011; Nasir et al., 2017; Vasan et al., 2014). The upstream boundary is the raw material extraction stage coherently with the cradle-to-gate approach. The cradle-to-gate approach also defines specifically the downstream boundary of the supply chain, which is reached when the product crosses the gate between the most downstream player of the supply chain and the final customer or consumer to whom the product is sold. This player could be typically identified as a retailer or a distributor in a business-to-consumer context, whereas it could be the manufacturer in a business-to-business context. The boundaries of the supply chains are thus including the material flow from the raw material stage down to the gate between the most downstream tier on the chain and the final user. The material flow moves downstream from the raw materials to the focal firm and the user and is associated to a monetary flow in the opposite direction as customers pay to receive the materials or semi-finished products from their suppliers.

Adopting a cradle-to-gate approach means that the usage and end-of-life management phases of product lifecycle are omitted. Being the method designed for a generic supply chain, inclusion of the usage and end-of-life management lifecycle stages would introduce significant uncertainties in the collection of primary data (Michelsen et al., 2006). Both usage patterns and end-of-life management practices of products are often beyond the control of any player in the supply chain, being affected directly by practices of the customers and local authorities. Including them in the method would limit its applicability and its usefulness for organisational decision-making.

4.1.2.2 Transformed resources side-boundary

Transformed resources approach, found in Slack et al. (2013), determines the side boundaries of the supply chain. Slack et al. (2013) defines two types of resources:

- Transformed resources are resources that will be treated, transformed or converted during the production processes and are sourced from “product-related suppliers” (Kovács, 2008; Slack et al., 2013).
- Transforming resources: are resources that facilitate the processes, including the facilities, the equipment and the machineries necessary to transform the products and involve the supporting members of the supply chain (Kovács, 2008; Slack et al., 2013).

The side boundaries of the supply chain in this work are strictly defined according to the transformed resources of the transformation model. The supply chain of the transforming resources is not included within the system boundaries, as these products have already reached the usage phase and their impacts refer to a different supply chain. The direct environmental impact of transforming resources, such as equipment and machinery, is included only with respect to their usage in the production processes taking place along the supply chain as part of the direct impact of each company enclosed within the supply chain boundaries. This means that companies adopting more energy intensive machineries are penalised by having a bigger energy eco-intensity indicator at the company level, but there is no penalty for companies adopting machineries whose manufacturing supply chain is environmentally unsustainable, as the machineries’ supply chain is outside system boundaries and part of a different supply chain analysis.

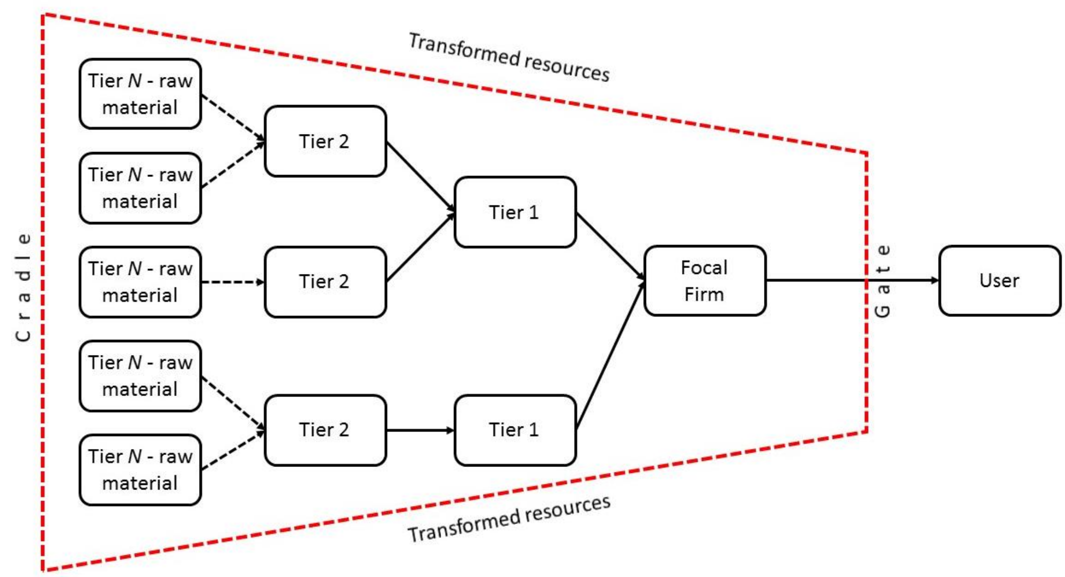

Figure 4.4: System boundaries

Finally, the last defined boundary of the supply chain could be considered the level of detail of the investigation within the external system boundaries, which is the level of granularity reached within the defined system. This is defined according to the black box approach, which will be discussed in the following section (4.1.3).

4.1.3 Black box approach

The second conceptualised aspect related to the supply chain aspect is the definition of the level of granularity within the supply chain, which is the system under analysis (Low et al., 2015). Each system can be indeed decomposed into sub-systems that can be divided into further sub-systems until an elementary sub-system is reached (Simon, 1962). The relevant sub-systems need to be captured by the model, until the decomposition reaches and models the elementary sub-systems (Low et al., 2015; Simon, 1962). The decision over the elementary sub-system is determined when the complexity is understood and sub-systems do not require to be further reduced (Simon, 1962). The definition of the elementary sub-system formalises the degree to which reductionism is applied within the system.

The system under analysis in this research is the supply chain, whose system boundaries where defined in Section 4.1.2. As every system, a supply chain is made up by interconnected elements or sub-systems that deploy different functions (Koh et al., 2012). In this specific system, the sub-systems are the "connected and interdependent organisations" part of the supply chain, which are considered in this research as the elementary sub-system of analysis (Christopher, 2011; Koh et al., 2012).

The behaviour of any system and sub-system can be described according to two broad categories of models: explanatory models and empirical models (Oberkampf and Roy, 2010a). The former type of model requires a great amount of information about the processes happening inside the system as well as repeated observations of the system across a timespan (Oberkampf and Roy, 2010a). On the other hand, empirical models do not require any information about the processes occurring within the system, as this "is considered to be a black box and the only issue is the global relationship between the inputs and the outputs of the system" (Oberkampf and Roy, 2010a).

Economic modelling has extensively treated organisations as black boxes (Sokolowski and Banks, 2010). Moreover, this approach has been extensively adopted in the supply chain literature to model companies part of the supply chain (Corsano and Montagna, 2011) and is also an established approach in the sustainability literature, which largely treated organisations as black boxes (Linnenluecke et al., 2009; Lozano, 2015, 2012b). Consistently with the existing literature and owing to the reduced amount of information required by empirical black-box models compared to explanatory models, which can facilitate the applicability of the model in operational contexts, this research embraces black box approach to model organisations part of the supply chain. Internal dynamics of each organisation remain outside of the scope of the study, as an exact representation of reality within organisational boundaries is not needed for the higher-level purpose of assessing the environmental performance of the supply chain. Therefore, interest lies only in the inputs and outputs of organisations, without requiring the detail of information of explanatory models, and in line with the descriptive nature of this research, as illustrated in Chapter 3. The black box approach is applied to each elementary sub-system, which is each organisation part of the supply chain whose core activity is different from transport activities.

Moreover, every individual organisation belongs to a tier within the supply chain. Vertically integrated supply chains with a number of activities taking place within the boundaries of a single firm are considered in this analysis as a single tier, even if activities occur in different geographical areas. The rationale behind this approach is that the decisions remain within the single organisation, eliminating challenges and barriers arising when multiple organisations are involved. Transport activities are treated outside of the black box approach, as it will be detailed in section 4.1.5.

For each company part of the supply chain, a certain number of environmental and economic inputs and outputs taken into account, which are detailed throughout Section 4.2. Data are thus to be collected at the company level for each player of the supply chain, as Section 4.2.1 and Section 4.2.5 further detail.

4.1.4 Indirect multi-tier supply chain management approach

The third conceptualised aspect related to the supply chain aspect is how each company interfaces with its suppliers and sub-suppliers, which is conceptually modelled in this research through the indirect multi-tier supply chain management approach.

The indirect approach in a multi-tier supply chain takes place when the focal company establishes a contact with sub-suppliers indirectly through another supplier (Tachizawa and Wong, 2014), as detailed in Section 2.3.5. It is here selected as the approach to reach sub-suppliers in the multi-tier environmental performance assessment method on the basis of its superior feasibility for focal companies based on the actual structure and dynamics of the majority of supply chain.

Managing the extended supply chain directly is a complex task for the majority of focal firms due to the limited visibility and control they have on their sub-suppliers (Acquaye et al., 2014; Wilhelm et al., 2016a). Several surveys highlighted that companies have limited knowledge about the structure of their upstream multi-tier supply chain with majority of supply chain executives admitting that the visibility of their supply chain is limited to 1st tier suppliers (Acquaye et al., 2014; Egilmez et al., 2014; O'Rourke, 2014). Moreover, focal companies have a low level of control on sub-suppliers due to "lack of contractual relationships to sub-suppliers, few opportunities to put direct pressure on sub-suppliers, or lack of transparency concerning sub- suppliers' involvement in a focal firm's supply chains" (Grimm et al., 2014).

While some contextual variables, such as the balance of power and the level of mutual dependency may affect the degree of control of the focal company over its multi-tier supply chain (Cox et al., 2007; Dou et al., 2017; Grimm et al., 2018; Lee et al., 2014; Mena et al., 2013; Scott and Westbrook, 1991; Tachizawa and Wong, 2014; Wilhelm et al., 2016b), typical supply chains remain built up by interconnected autonomous entities (Mena et al., 2013), making a direct approach substantially unfeasible. This is even reinforced in contemporary long and global supply chains (Mena et al., 2013), calling for the need of a collaboration between different supply chain tiers (Koh et al., 2012; Mueller et al., 2009).

The supply chain management thus requires a decentralised indirect approach, where responsibilities are shared between different players, namely the organisations belonging to different tiers of the supply chain (Jabbour et al., 2018), leading to the indirect SCM approach. Within this shared responsibility governance mechanism, a pivotal role is played by suppliers at any level of the supply chain in disseminating sustainability in their upstream supply chain (Wilhelm et al., 2016a), a perspective that is adopted in this work as one of the pillar of the conceptual model.

This governance mechanism is further detailed in this work into an information-sharing mechanism, which is an essential element within indirect multi-tier supply chain management approach (Tachizawa and Wong, 2014). The information-sharing mechanism works along two directions, going upstream and downstream, as illustrated in Figure 4.5. The former concerns the pressure focal firms pass to their direct suppliers to spread sustainability requirements also to lower-tier suppliers in order to obtain relevant information about their environmental sustainability performance (Tachizawa and Wong, 2014). This pressure is formalised through a standard, stemming from the focal company, to be adopted by the upstream supply chain to gather sustainability-related information (Tachizawa and Wong, 2014). The standard to assess the environmental performance thus becomes a mechanism of coordination of the upstream supply chain (Tachizawa and Wong, 2014). On the other hand, the downstream information-sharing mechanism involves the actual forwarding of the requested requirements downstream to the focal company. These information-sharing mechanisms require some standardisation to allow direct suppliers to obtain sustainability information from focal firm's indirect suppliers (Ciliberti et al., 2009), which is sought in this research by simplifying the data collection process thanks to the black box approach (Section 4.1.3) and a limited set of environmental data to be collected. Finally, the adoption of standardised data collection spreadsheets for all entities building the supply chain also contributes towards the information-sharing mechanism.

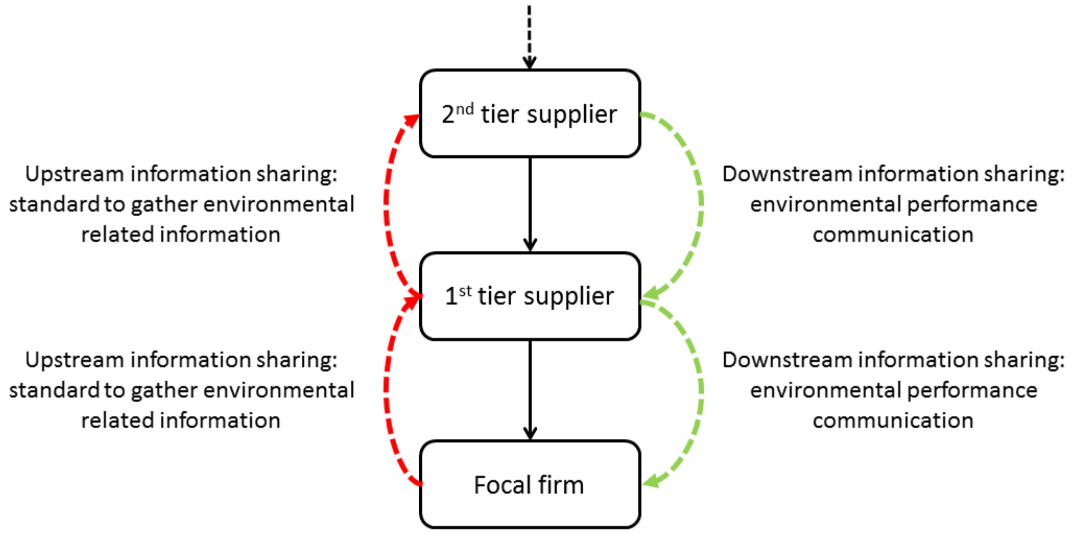

Figure 4.5: Indirect multi-tier supply chain information sharing mechanism

4.1.5 Transport

The fourth and final conceptualised aspect related to supply chain aspect is the transport, which is the mean of conveying goods from place to place by means of different transportation modes (Kannegiesser et al., 2015; Oxford University Press, 2018b). As such, transport is a key element of every supply chain, providing the link between supply chain tiers, where products are being transformed. Moreover, transport is a key factor for the success of GSCM, given its environmental impact (Azadi et al., 2015).

Transport is treated with a specific approach within the conceptual model, not being treated according to the black box approach. Products being transported are only spatially transformed, being moved from place to place, but do not undergo any further transformation in their physical nature. As a result, transport is not treated as a separate tier within the conceptual model, because there are no transformed resources entering the supply chain at the transport stage. Instead, merely transforming resources characterise the transport activity. However, the environmental impact of the spatial transformation cannot be neglected in a GSCM perspective (Azadi et al., 2015) and needs to be incorporated within the method.

Being the spatial transformation the only transformation taking place during transport activities, the transport is conceptually modelled only with respect of this aspect, capturing the point of origin, which is the geographical location of the supplier in each dyadic transport link, and the point of destination, which is the geographical location of the customer in each dyadic transport link, along with the characteristics of this spatial transformation. These are the mode of transport selected to move the goods and the quantity of goods moved as the environmental impact of transport "depend on ton-miles and the mode of transportation" (Bouchery et al., 2012; Kannegiesser and Günther, 2013;

Sundarakani et al., 2010). These pieces of information are specific to the product supply chain and its geographical design along with the supply chain strategical choices. On the other hand, no information is required about the overall environmental performance of the transport provider as a whole as all variables involved are dependent on the supply chain tiers' decisions and not on the internal structure of the logistics provider.

Summarising, the specific service nature of transport activities, along with the fact that only spatial transformation occurs in the transport, justifies the different conceptual modelling of the transport, which follows a product-specific logic instead of the dominant logic introduced through the black box approach. This conceptual modelling of transport will be operationalised in the following mathematical model section, and specifically in sub-section 4.2.7.

4.2 Mathematical model

The mathematical model aims to develop "analytical statements based on the conceptual model formulated in the previous phase" (Oberkampf and Roy, 2010a) by transforming conceptualizations and abstractions generated in the conceptual model into mathematical formulations. As such, a mathematical model is "a collection of mathematical constructions that represent the essential aspects of a system in a usable form" (Prudhomme, 2015). Therefore, the mathematical formulations are functional to generate the method outputs and to operationalise the method for use within operative supply chains.

The mathematical model follows two streams, which are leading to two different outputs of the model: supply chain eco-intensity for each specific environmental indicator e and supply chain global eco-intensity. While the majority of the methodological steps are performed in the same way for both streams, the normalisation, weighting and aggregation steps are only performed to calculate the supply chain global eco-intensity, whereas they are bypassed in the stream leading to the calculation of the supply chain eco-intensity for each specific environmental indicator, as Figure 4.6 illustrates. Finally, the inclusion of transport stage is performed only for a limited set of environmental indicators as section 4.2.7 details.

The final version of the mathematical model is presented here, however the model underwent three iterative development loops, leading to four versions of the mathematical model as explicated in Chapter 3 and summarised in Figure 4.7. The first version (v1) of the model translated the principles of the conceptual model into mathematical formulations, identifying the basic equations at the company level and identifying several options for the recursive mechanism formulation. Following the decision over the system boundaries in I2, the recursive mechanism was finalised and the skeleton of the mathematical model completed (v2). Transport was later included in the third version of the mathematical model (v3) following insights from I2. Finally, version four (v4) is an addition to the model which emerged from CS2. While not adding any relevant equation to the mathematical model, it details how to cope with incomplete environmental data along the supply chain, defining how to process data in these instances, as well as refining the functioning of the recursive mechanism with outsourcing organisations, by de-coupling the material flow from the financial flow.

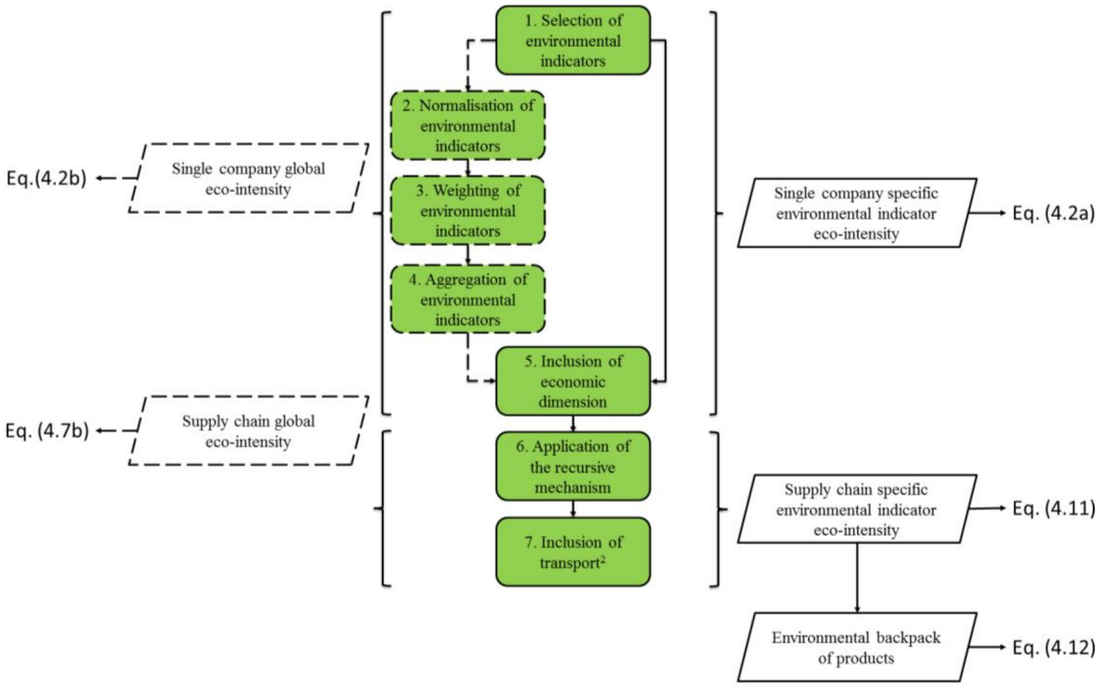

Figure 4.6: Mathematical model methodological steps

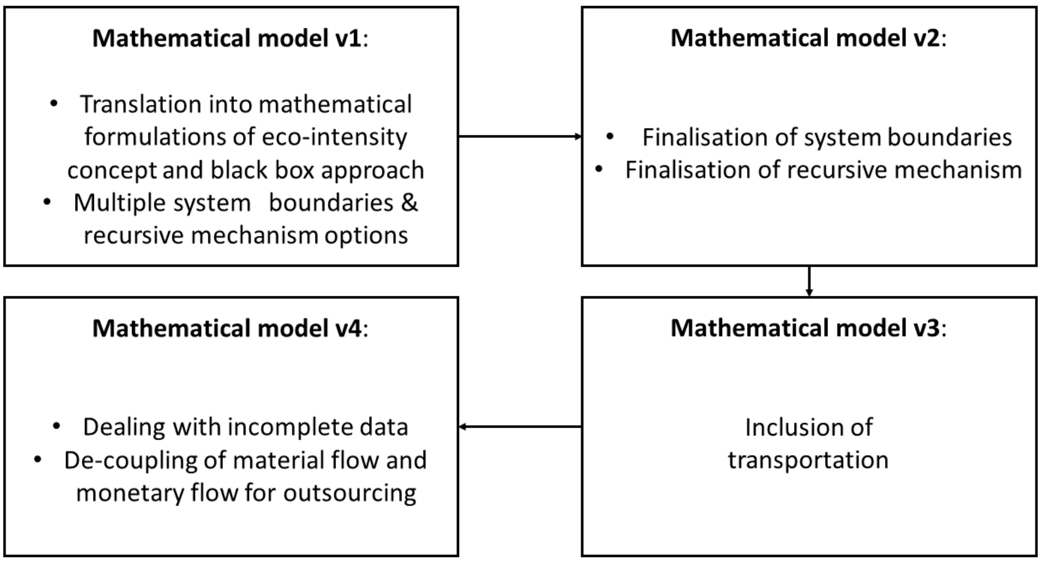

Figure 4.7: Iterative development of mathematical model

The mathematical model is explicated throughout the following sub-sections that mirror the steps identified in Figure 4.6 and are largely based on the work entitled “An innovative eco-intensity based method for assessing extended supply chain environmental sustainability” (2018), published online on the International Journal of Production Economics (Tuni and Rentizelas, 2018). The mathematical model is illustrated starting from the selection of environmental indicators in Section 4.2.1. The normalisation, weighting and aggregation of indicators are discussed in Sections 4.2.2, 4.2.3 and 4.2.4, while the economic dimension is integrated into the model in Section 4.2.5. Finally, the recursive mechanism is applied in Section 4.2.6 and the transport is addressed in Section 4.2.7, completing the mathematical model. A summary of the core equations concludes the presentation of the mathematical model (Section 4.2.8).

4.2.1 Selection of environmental indicators

The systematic literature review at the intersection of performance measurement and GSCM informed the method development stage with respect to the most frequent environmental aspects that are covered in the literature, as outlined in Section 2.5.3. Based on the measurement clusters identified at the literature review stage and performing a second loop of keyword analysis (Ahi and Searcy, 2013), seven key environmental aspects were identified as the most frequently addressed in the literature and adopted as a reference for the development of the indicators. The identified aspects mirror the identified categories for inputs by Kravanja and Čuček (2013) and outputs by Brent and Visser (2005).

The identified environmental aspects required to be applicable to any manufacturing industry and not sector-specific in order to allow assessing the environmental performance of any supply chain. The seven environmental aspects, which are displayed in Figure 4.8, offer a balanced accounting of inputs withdrawn from the natural system and outputs environmental impacts in order to reflect the limited capability of a thermodynamically closed system like planet Earth to supply resources and absorb pollution (Ayres and Kneese, 1969; Dimian et al., 2014; Kravanja and Čuček, 2013).

A balanced assessment of inputs’ and outputs’ environmental impacts is also required in a future perspective to improve environmental sustainability performance. Adopting only end-of-pipe solutions to reduce environmental outputs only is not sufficient, but a proactive approach aiming to reduce the inputs is also necessary to diminish the pressure on the natural capital (De Soete et al., 2013; McIntyre et al., 1998; Ritthof et al., 2002). As a result, the selected environmental indicators in this work cover both environmental inputs to supply chain operations as well as environmental outputs arising from production activities of the supply chain.

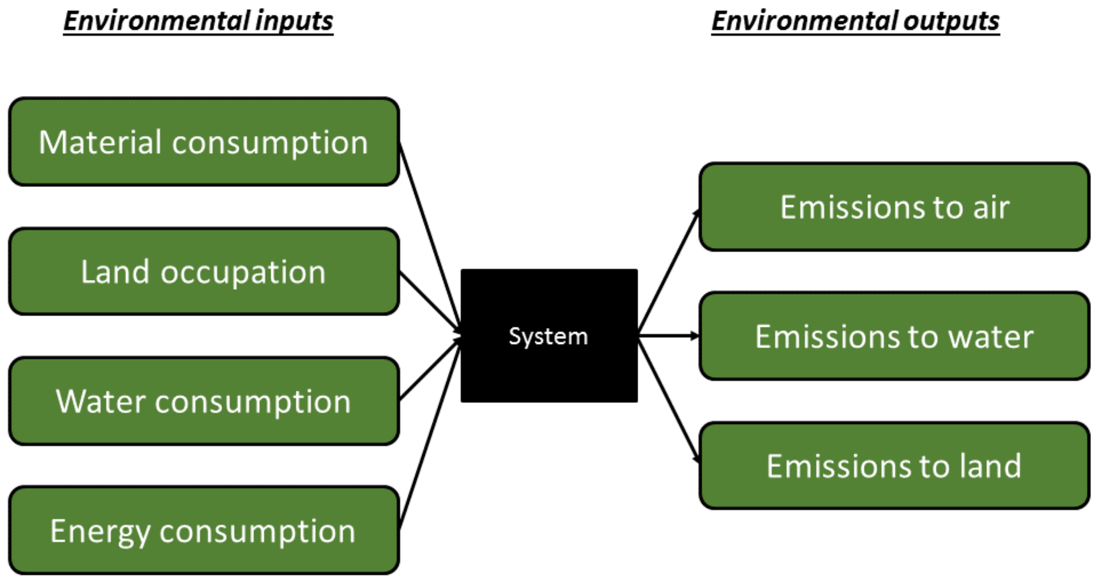

Figure 4.8: Environmental aspects

Environmental indicators are calculated at the company level on a yearly basis, coherently with the black box approach identified in Section 4.1.3. For each environmental aspect, a single high-level indicator is determined to keep the size of indicators manageable, as Table 4.1 shows. However, certain environmental indicators are the result of the aggregation of environmental sub-indicators as detailed in Section 4.2.1.2. The hierarchy of indicators and sub-indicators contributing towards each high-level indicator is illustrated in Figure 4.9. A recommended unit of measurement is associated to each environmental impact input or output in order to facilitate the information sharing mechanism along the supply chain, by having homogenously measured environmental impacts between different organisations. The recommended unit of measurement also aims to provide a basis for future applications of the method and therefore facilitate benchmarking of different supply chains. An alternative unit of measurement is provided for some categories, such as “Material consumption” and “Solid waste”, which can both be expressed by weight-based indicators or by volume-based indicators.

However, the method is flexible in its applicability and allows managers and stakeholders to introduce additional environmental indicators to address the needs of specific supply chains if required. The selected environmental categories and associated indicators were chosen to provide a common reference base and to facilitate benchmarking of products. While preferable to be adopted, they are no by means restrictive, offering a potential to expand the coverage of environmental aspects by the method. The suggested set of environmental indicators to be adopted in the method is presented in Section 4.2.1.1.

Table 4.1: Recommended environmental impacts

Environmental aspects		Environmental indicators	Recommended unit of measurement	Alternative unit of measurement
Inputs	Use of materials	Materials consumption	[kg]	[m^3]
	Land use	Land occupation	[m^2]	
	Water use	Water consumption	[m^3]	[l]
	Energy use	Energy consumption	[kWh]	[MJ]
Outputs	Emissions to air	GHG emissions	[kg CO_2 e]	
	Emissions to water	Water waste	[m^3]	[l]
	Emissions to land	Solid waste	[kg]	[m^3]

4.2.1.1 Definition of the environmental indicators

The environmental sub-indicators were selected based on the outcome of the systematic literature, largely mirroring the measurement clusters listed in Table 2.6. A single sub-indicator was derived for clusters appearing with higher frequency in Table 2.6, adapting existing indicators available in the literature. Only absolute environmental indicators were selected, as the inclusion of economic dimension, illustrated in Section 4.2.5, generates the relative eco-intensity indicators. The hierarchy of environmental indicators and connected sub-indicators is displayed in Figure 4.9.

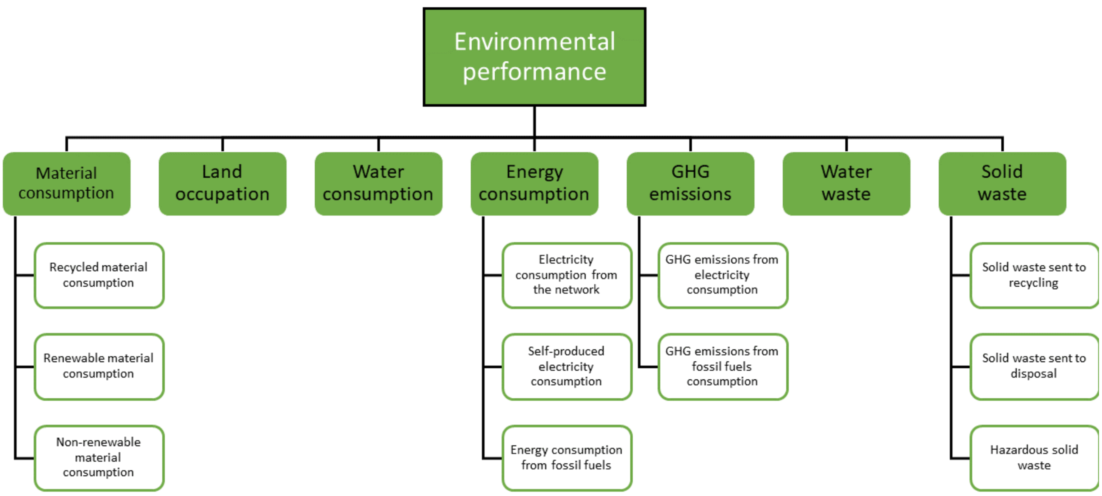

Figure 4.9: Hierarchy of environmental indicators

Material consumption

Every manufacturing activity requires raw materials as inputs to deliver the final product to the customer. Material consumption depletes the natural capital as it causes a withdrawal of finite resources (UNEP, 2010; Wackernagel, 1994). The environmental impact associated to material consumption is determined in terms of total amount of materials required (Ritthof et al., 2002). However, qualitative characteristics of different materials are also taken into account as the environmental impact associated to the materials consumption differs based on the type of inputs. Three types of materials were identified, based on the outcomes of the systematic literature review:

- Non-renewable materials: also known as abiotic materials, are those resources that are not regenerated by themselves (UNEP, 2010). These resources include mineral raw materials, fossil energy carriers and materials arising from soil excavation (Ritthof et al., 2002; UNEP, 2010). Consumption of non-renewable materials is considered the most environmentally impactful use of materials, as the stock of non-renewable materials is finite and is not regenerated (Despeisse et al., 2012a; UNEP, 2010).
- Renewable materials: also known as biotic materials, are those resources that are regenerated by themselves (UNEP, 2010). These resources include plant biomass from cultivated areas and biomass from uncultivated areas, including as well as fauna (Ritthof et al., 2002; UNEP, 2010). Consumption of renewable materials is considered having an intermediate environmental impact, as these resources can be regenerated over a relatively short amount of time but are still contributing to the depletion of natural resources (Despeisse et al., 2012a; UNEP, 2010)
- Recycled materials: these resources are the outcome of 3Rs activities and are later inserted again into a forward supply chain. Recycled materials, either biotic or abiotic, are considered having the least environmental impact as they are not withdrawn from the natural environment and thus do not contribute to the overall depletion of the natural capital (Despeisse et al., 2012a; European Commission et al., 2014; Graedel and Howard-Grenville, 2005; Tsoulfas and Pappis, 2006).

As a result, “Material consumption” environmental indicator includes three sub-indicators: “Recycled materials consumption”, “Renewable materials consumption” and “Non-renewable materials consumption”. The aggregation of these sub-indicators into the “Material consumption” indicator is discussed in Section 4.2.1.2.

Land occupation

Land occupation is considered as a specific indicator separated from other natural resources as one of the only two natural resources that cannot be substituted by any other, the other being water (Goedkoop et al., 2009). Environmental impact of land occupation is due to two factors (Holma et al., 2013). First, land occupation may determine a reduction of the amount of productive arable land, which is a limited resource necessary to guarantee human survival. Second, land occupation affects biodiversity and soil quality (Holma et al., 2013). A single indicator named “Land occupation” tackles this environmental aspect without further sub-indicators.

Water consumption

Water is considered as a specific indicator separated from other natural resources, as one of the only two natural resources that cannot be substituted by any other, the other being land (Goedkoop et al., 2009). Water is a necessary resource for human survival and was identified as a resource increasingly under risk of scarcity due to growing world population and constant economic growth (Schornagel et al., 2012; UNEP, 2010). Moreover, excessive water consumption can cause specific damages to local ecosystems and biodiversity (Brown and Matlock, 2011). Finally, water is a key transforming resource for various economic activities, despite not necessarily being part of their final product (UNEP, 2010). The systematic literature review also confirmed that water consumption is treated aside from other natural resources, a perspective that is embraced by this method too. A single indicator named “Water consumption” tackles this environmental aspect without further sub-indicators.

Energy consumption

Alike other environmental inputs, energy is a finite resource on planet Earth (UNEP, 2010). Energy is a key input for every industrial activity and its production process is a major contribution to the overall effect of human activities on the environment (Defra, 2006; Graedel and Howard-Grenville, 2005). Energy consumption generates mainly indirect environmental impacts, which however organisations are not able to influence such impacts other than by reducing their energy consumption and/or improving their energy efficiency (Defra, 2006). As such, and in accordance with the outcomes of the systematic literature review, energy is treated as a separate environmental input (European Commission et al., 2014). Three sub-indicators build the “Energy consumption” environmental indicator: “Electricity consumption from the network”, “Self-produced electricity consumption” and “Energy consumption from fossil fuels”. The aggregation of these sub-indicators into the “Energy consumption” indicator is discussed in Section 4.2.1.2.

GHG emissions

Emissions to air environmental aspect is assessed through the “GHG emissions” environmental indicator. Greenhouse gas emissions are considered the major cause of global warming and climate change (Trappey et al., 2012; Vasan et al., 2014). The three major greenhouse gases are (Defra, 2006): carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O). Conversion coefficients are applied to convert all emissions to a single unit of measurement, which is the tonnes of CO_2 equivalent. Two sub-indicators build the “GHG emissions” environmental indicator: “GHG emissions from fossil fuels”, being the preponderant part of Scope 1 emissions, and “GHG emissions from electricity consumption from the network”, usually labelled as Scope 2 emissions (Kremer et al., 2016). Scope 3 emissions are not included in the indicator, as supply chain dimension is captured through the recursive mechanism, which is illustrated in Section 4.2.6. The aggregation of the sub-indicators into the “GHG emissions” indicator is discussed in Section 4.2.1.2.

Waste water

The systematic literature review identified a limited number of environmental metrics within the “Emissions to water” environmental aspect, with even a lower standardisation among the presented metrics. Emissions to water environmental aspect is therefore assessed through the more generic “Waste water” environmental indicator. Waste water identifies water that requires to be treated before being discharged due to its pollutant content (Gao and You, 2015; Jiang et al., 2014). A single indicator named “Waste water” tackles this environmental aspect without further sub-indicators.

Solid waste

Emissions to land environmental aspect is assessed through the “Solid waste” environmental indicator, in accordance with the outcomes of the systematic literature review. Solid waste contributes to climate change as well as to the release of polluting substances into the land (Eurostat, 2010; Goedkoop et al., 2009). The environmental impact associated to solid waste determined in terms of total amount of waste generated, with an increase in the amount of waste generated associated to a negative environmental impact (Slack et al., 2013; Tseng, 2011). However, qualitative characteristics of waste are also to be taken into account as the environmental impact associated to solid waste differs based on the type of waste and its destination (Defra, 2006; Slack et al., 2013). Three types of solid waste were identified, based on the outcomes of the systematic literature review:

- Solid waste sent to recycling: amount of solid waste sent to recycle, remanufacture or reuse, thus entering a reverse supply chain. Recycling of solid waste is considered the most environmentally sustainable option for the end-of-life management of products (Büyüközkan and Çifçi, 2012; Defra, 2006), as it allows to give a secondary use to products and materials in a circular economy perspective, reducing the amount of virgin materials withdrawn from the natural environment (Ellram et al., 2008; Lai et al., 2008; Tsoulfas and Pappis, 2006).
- Solid waste sent to landfill: amount of solid waste sent to landfill. Disposing waste to the landfill is an EOL option to be adopted only for non-recyclable and non-recoverable waste, due to its significant contribution to climate change, release of polluting substances into the soil, causing its progressive degradation (European Environment Agency, 2016; Eurostat, 2010).
- Hazardous solid waste: amount of hazardous solid waste produced according to existing country-based regulations which oblige organisations to appropriately collect and handle this type of waste (European Commission et al., 2014; Eurostat, 2010). Hazardous waste contains substances that may be irritant, inflammable or harmful to human health, other living organisms or the environment (European Commission et al., 2014; Eurostat, 2010). Hazardous waste includes radioactive and toxic waste (European Commission et al., 2014; Frischknecht and Büsser Knöpfel, 2013). Hazardous waste is considered the least environmentally sustainable type of waste due to its high potential harm for society and ecosystems (Graedel and Howard-Grenville, 2005).

As a result, “Solid waste” environmental indicator includes three sub-indicators: “Solid waste sent to recycling”, “Solid waste sent to landfill” and “Hazardous solid waste”. The aggregation of these sub-indicators into the “Solid waste” indicator is discussed in Section 4.2.1.2.

4.2.1.2 Aggregation of sub-indicators within the same environmental category

The method is designed around seven environmental categories, namely four environmental inputs and three environmental outputs, in order to keep the outputs of the method within a manageable size that can effectively support decision-making. However, four environmental indicators are the result of the aggregation of sub-indicators, as highlighted in Figure 4.9: “Materials consumption”, “Energy consumption”, “GHG emissions” and “Solid waste”. Two aggregation techniques are adopted to generate the environmental indicators, as summarised in Table 4.2:

- Linear summation: data from sub-indicators is linearly added to generate the higher-level indicator (Vasileiou, 2002). This aggregation technique is applied to all four environmental indicators containing sub-indicators.
- Weighted summation: this aggregation technique is applied only to “Materials consumption” and “Solid waste” environmental indicators, as the environmental sub-indicators differ on the basis of their environmental impact (Graedel and Howard-Grenville, 2005), as discussed in Section 4.2.1.1. An ordinal evaluation of the sub-indicators based on a three-level sets is adopted (Graedel and Howard-Grenville, 2005), which is used to generate the weights assigned to the sub-indicators (Graedel and Howard-Grenville, 2005).

Both aggregation techniques are adopted for “Materials consumption” and “Solid waste”, as linear and weighted aggregation techniques convey different information. Environmental impact can be reduced either by reducing the absolute quantities of material consumed and waste generated, thus referring to the unweighted indicator, or by substitution effect, switching from a more environmentally impactful input or output to a more environmentally sustainable option, thus referring to the weighted indicator.

Table 4.2: Aggregation techniques for environmental sub-indicators

Environmental indicator	Linear summation	Weighted summation
Materials consumption	✓	✓
Energy consumption	✓	
GHG emissions	✓	
Solid waste	✓	✓

Materials consumption

The “Materials consumption” indicator includes three sub-indicators: “Recycled material consumption”, “Renewable material consumption” and “Non-renewable material consumption”. The sub-indicators differ qualitatively in terms of environmental impact; therefore, two aggregated indicators are calculated. The “Materials consumption – unweighted” linearly sums the three sub-indicators, without distinguishing the nature of the materials used. On the other hand, “Materials consumption – weighted” takes into account the different environmental impact associated to different types of materials consumption, thus assigning a different weight value to each indicator. The weights assigned to the environmental sub-indicators, displayed in Table 4.3, are based on their respective environmental impacts, as discussed in Section 4.2.1.1, and their ordinal evaluation according to the approach illustrated by Graedel and Howard-Grenville (2005).

Energy consumption

The “Energy consumption” environmental category includes three sub-indicators: “Electricity consumption from the network”, “Self-produced electricity consumption” and “Energy consumption from fossil fuels”. The sub-indicators do not differ qualitatively in terms of environmental impact, thus they are aggregated by linear summation.

Emissions to air

The “Emissions to air” environmental category includes two sub-indicators: “GHG emissions from electricity consumption” and “GHG emissions from fossil fuel consumption”. The sub-indicators do not differ qualitatively in terms of environmental impact, thus they are aggregated by linear summation.

Solid waste

The “Solid waste” environmental category includes three sub-indicators: “Solid waste sent to recycling”, “Solid waste sent to disposal” and “Hazardous solid waste”. Alike the case of use of materials, the sub-indicators differ qualitatively in terms of environmental impact, therefore two aggregated indicators are calculated. The “Solid waste – unweighted” linearly sums the three sub-indicators, without distinguishing the nature of the waste produced. On the other hand, “Solid waste – weighted” takes into account the different environmental impact associated to different types of waste, thus assigning a different weight to each indicator. The weights assigned to the environmental sub-indicators, displayed in Table 4.3, are based on their respective environmental impacts, as discussed in Section 4.2.1.1, and their ordinal evaluation according to the approach by Graedel and Howard-Grenville (2005).

Table 4.3: Weighting for the aggregation of environmental sub-indicators

Weight	Material consumption	Solid waste
1	Recycled material consumption	Solid waste sent to recycling
2	Renewable material consumption	Solid waste sent to landfill
3	Non-renewable material consumption	Hazardous solid waste

4.2.2 Normalisation of environmental indicators

Figure 4.6 highlighted two streams for the methodological development of the mathematical model, which are generating different outputs of the method. Following the identification of the environmental indicators, the dotted stream to the left of the figure identifies normalisation, weighting and aggregation of environmental indicators as subsequent steps to obtain global eco-intensity indicators. On the other hand, these steps are bypassed in the stream to the right of the figure, to obtain single environmental eco-intensity indicators at the company level and at the supply chain level.

Normalisation, weighting and aggregation are the three steps required to extract composite index (Angelakoglou and Gaidajis, 2015). Normalisation is a necessary preliminary step to obtain a single comparable scale for indicators expressed in different units of measurement (Angelakoglou and Gaidajis, 2015; Dos Santos and Brandi, 2015; Jonsdottir et al., 2005; Kostin et al., 2015; Kravanja and Čuček, 2013; OECD, 2009; Tokos et al., 2012). Normalisation is achieved by dividing each indicator by a normalisation factor (Tugnoli et al., 2008). Normalisation techniques can be clustered into internal normalisation techniques and external normalisation techniques based on the type of normalisation factor in use (Tugnoli et al., 2008). Internal normalisation adopts a value derived from an alternative or a combination of available alternatives as the normalisation factor, whereas external normalisation adopts generic reference values as normalisation factors, which are independent from the specific alternatives available (Tugnoli et al., 2008).

Internal normalisation compares different alternatives, scenarios or decision-marking units. Alternatively, internal normalisation compares performance of the same unit of analysis across time. Internal normalisation adopts a range of normalisation factors, including:

- Sum of indicators (Kannan et al., 2013; Mahdiloo et al., 2015; Sarkis, 1998; Tsoulfas and Pappis, 2008)
- Mean of indicators (Egilmez et al., 2014; Sarkis and Dhavale, 2015)
- Maximum value of indicators (Bloemhof-Ruwaard et al., 1996; Büyüközkan and Ifi, 2012; Chithambaranathan et al., 2015; Clarke-Sather et al., 2011; Frota Neto et al., 2008; Govindan et al., 2013; Hashemi et al., 2015; Jamshidi et al., 2012; Kannan et al., 2013; Kostin et al., 2012; Liou et al., 2015; Sabio et al., 2012; Wu et al., 2014; Zhang et al., 2014)
- Based on max-min techniques (Bai et al., 2012; Bai and Sarkis, 2014; Curzons et al., 2007; Dou et al., 2014; Kostin et al., 2015, 2012; Nikolaou et al., 2013; Salvado et al., 2015; Tseng et al., 2013; Tseng and Chiu, 2013; Wu et al., 2014)
- Based on Canberra Z-score technique (Dos Santos and Brandi, 2015).

However, such normalisation factors are self-referential as they only manage to achieve a comparison among the organisations part of a specific system, i.e. supply chain, and do not allow “for an assessment of relative significance” (Heijungs et al., 2007). External normalisation aims to overcome this shortcoming, typically by adopting normalisation factors, which are independent from the system under analysis. Examples of such normalisation factors are the geographic impact area for each indicator and/or the amount of population living in a certain geographic area (Clift, 2003; Heijungs et al., 2007; Kravanja and Čuček, 2013; Tugnoli et al., 2008). In order to provide an assessment of relative significance and allow consistent benchmarking application of the global eco-intensity indicators, external normalisation is selected as normalisation technique in this research. However, despite providing a more significant picture of the actual behaviour of any system, external normalisation requires accurate and reliable data to be carried out and this may ultimately limit its application (Bloemhof-Ruwaard et al., 1996). This research suffered from this constraint too, as robust external normalisation factors to be merged into the method could not be identified for all environmental indicators presented in Section 4.2.1. As a result, the identification of such normalisation factors and the implementation of the normalisation technique is left as a direction for future research, as further illustrated in Chapter 7 and Chapter 8 .

4.2.3 Weighting of environmental indicators

Weighting is adopted to determine the relative importance of environmental indicators. Wang et al. (2009) identified four weighting techniques: equal weighting, subjective weighting, objective weighting and combination weighting. All these weighting techniques are categorised as rank-order weighting methods, with the only exception of equal weighting. As a result, they require a set of alternatives to generate a ranked order among them, a condition that is not met in this research. Therefore, in line with the decision of external normalisation over internal normalisation presented in Section 4.2.2, rank-order weighting techniques are not considered viable to be incorporated into the method.

Alternatively, subjective weighting in the form of experts’ opinion have been integrated in certain multi-criteria decision methods even in the absence of a set of alternatives, as in Brent and Visser (2005) or in Manzardo et al. (2014). However, subjective judgements limit the value of indicators as they are prone to be biased (Shokravi and Kurnia, 2014; Tsoulfas and Pappis, 2008). On the other hand, equal weighting does not introduce biases in the generation of aggregated indicators and it has been demonstrated that it generates for decision makers “results nearly as good” as those obtained through more elaborated weighting techniques while requiring no input (Wang et al., 2009), and is therefore selected as weighting technique within this method.

4.2.4 Aggregation of environmental indicators

Aggregation is the last step required to obtain a composite index, i.e. global eco-intensity indicators in this research. Wang et al. (2009) identified three aggregation techniques, which are voting techniques and mathematical aggregation techniques, with the latter category further divided into hard aggregation techniques and soft aggregation techniques.

However, both voting technique and soft aggregation technique require certain input from decision makers, thus introducing a certain degree of subjectivity (Shokravi and Kurnia, 2014; Tsoulfas and Pappis, 2008). Therefore, hard aggregation technique is selected as the appropriate technique to enhance the objectivity and comparability of results. As equal weighting is applied (Section 4.2.3), the normalised eco-intensity indicators are aggregated according to linear aggregation (Salvado et al., 2015).

4.2.5 Inclusion of economic dimension

The eco-intensity concept requires to divide the environmental impacts with the economic benefit generated by the economic activity, and specifically with the value of production (Huppes and Ishikawa, 2005), thus introducing the economic dimension of sustainability within the method.

Contrary to the multiple indicators adopted to capture the environmental dimension of sustainability, the value of production is the only economic indicator adopted in the mathematical model. The value of production is formalised by the yearly turnover of a company, which is defined in this research as the sum of sales revenues generated by the sale of products, without considering any other source of income, as it typically appears at the top of the income statement of organisations. Turnover of the *i-th* company can be calculated through equation 4.1:

$$T_i = \sum_k Q_{ik} P_{ik} = \sum_k T_{ik} \tag{4.1}$$

Where k are the different products sold by company i. Each product is sold at a unitary price P_{ik} in a quantity equal to Q_{ik}. The product of P_{ik} times Q_{ik} is equal to T_{ik}, which is the quota of the overall turnover T_i generated by each product k. Therefore, the turnover can be also expressed as the sum of economic outputs generated by each product k, which is the company turnover generated by each product expressed in monetary units T_{ik}.

Despite the turnover not providing a full picture of the economic performance of an organisation, this indicator suits the supply chain environment. The turnover is typically publicly available and does not pose questions about data confidentiality, especially in the case of non-collaborative supply chains, which represent the biggest share of operating supply chains (Parker and Kapuscinski, 2011; Schmidt and Schwegler, 2008). Costs or net present value, which are found as alternative economic indicators in the supply chain literature, require confidential data to be shared with other players in the chain, potentially affecting the competitive advantage of companies (Brandenburg, 2015; Caro et al., 2013).

The first two outputs of the method are obtained at this stage: the single company eco-intensity for each specific environmental indicator e (EI_{ei}) and the single company global eco-intensity (EI_i). The single company eco-intensity EI_{ei} for each individual environmental indicator e outlined in Section 4.2.1 can be calculated according to equation 4.2a, by simply dividing the environmental performance at the company level EP_{ei} by the turnover of the company T_i. Multiple eco-intensity indicators are thus generated for each company depending on the environmental impacts considered in the analysis.

$$EI_{ei} = \frac{EP_{ei}}{T_i} \tag{4.2a}$$

Equation 4.2a shows the organisation-wide eco-intensity values, which provide an indication on the performance of each company i for each specific environmental indicator e, without including any environmental impact arising in the supply chain. Similarly, the single company global eco-intensity EI_i can be calculated from Equation 4.2b, by dividing the aggregated environmental performance at the company level EP_i by the turnover of the company T_i. A single global eco-intensity score is generated for each organisation.

$$EI_i = \frac{EP_i}{T_i} \tag{4.2b}$$

4.2.6 Application of the recursive mechanism

The recursive mechanism enabling to move from the single company level to the supply chain level is illustrated in this section. Each organisation needs to add the environmental performance and economic output of its upstream suppliers to its internal eco-intensity to calculate the cumulative eco-intensity up to that point in the supply chain. Each company thus requires to obtain relevant eco-intensity indicators upstream from its direct suppliers only, which themselves need to access their own direct suppliers to calculate their eco-intensity indicators, with the process being completed once the raw material extraction stage is reached, following the red dotted line in Figure 4.10. At the same time, each company is also passing its eco-intensity information to its customer, enabling the eco-intensity indicator to move downstream along with the material flow, moving from one tier of the supply chain to the next one, until the system boundary is reached, following the green dotted line in Figure 4.10. When the last player in the chain before the gate is reached and its internal eco-intensity added to the indirect impacts generated by the upstream supply chain, the application of the recursive mechanism is complete. The following subsections gradually build the mathematical formulation of the model developed, which is applied in the same way both to calculate the supply chain eco-intensity for each specific environmental indicator and the supply chain global eco-intensity.

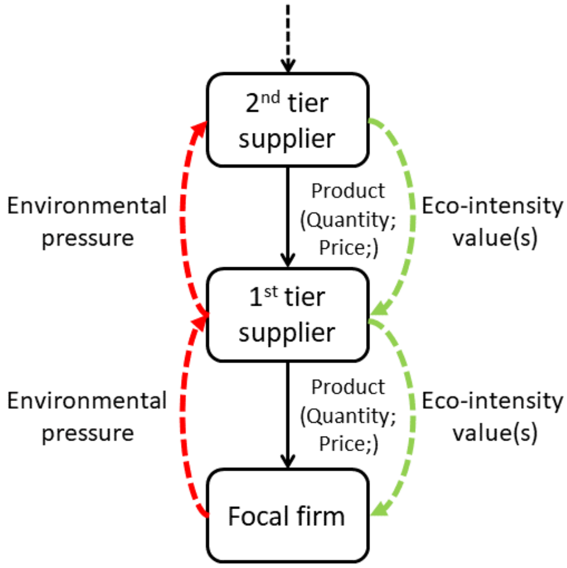

Figure 4.10: Recursive mechanism

4.2.6.1 Numerator: environmental impact

Moving from the single company level to the supply chain level, the environmental performance needs to encompass not only the internal environmental performance of each organisation but also the environmental performance of the whole upstream supply chain up to that tier. However, each company produces several products and belongs to a different supply chain for each of its products. Therefore, each organisation is part of several supply chains based on its product mix.
The internal environmental performance at the company level needs to be first allocated to the various product supply chains the company is part of (Ahi and Searcy, 2014). The allocation is based, consistently with the eco-intensity concept, on the economic output generated by each product k, which is the company turnover generated by each product expressed in monetary units T_{ik}, as shown in equations 4.3a and 4.3b, leading to EP_{eik} and EP_{ik}, depending whether specific environmental indicators e or the aggregated environmental performance of an organisation are considered:

$$EP_{eik} = \frac{T_{ik}}{T_i} EP_{ei} \tag{4.3a}$$

$$EP_{ik} = \frac{T_{ik}}{T_i} EP_i \tag{4.3b}$$

The environmental impact of the upstream supply chain needs to be then added to this value. The share of the environmental impact of suppliers that is passed on to the customers follows the same principle, being proportional to the share of turnover of supplier j generated by customer i thanks to deliveries of intermediate products n for output product k. This value can be easily calculated by the customer once the supplier communicates downstream its internal company wide eco-intensity values. The eco-intensity scores of supplier j is multiplied by the quantity and the price of purchases of intermediate products n for output product k, leading to equations 4.4a and 4.4b:

$$EP_{eik} = \frac{T_{ik}}{T_i} EP_{ei} + EI_{ej} \sum_{n} Q_{ijkn} P_{ijkn} \tag{4.4a}$$

$$EP_{ik} = \frac{T_{ik}}{T_i} EP_{i} + EI_{j} \sum_{n} Q_{ijkn} P_{ijkn} \tag{4.4b}$$

Where EI_{ej} is the eco-intensity of the supplier j for the environmental indicator e, EI_j is the global eco-intensity of the supplier j, Q_{ijkn} and P_{ijkn} are respectively the quantity and the price of intermediate products n shipped from supplier j to customer i for the output product k. This formulation however is valid only if supplier j is at the most upstream end of the supply chain. Otherwise, its contribution will need to include a contribution of its upstream supply tiers as well, similarly to the calculation of EP_{eik} and EP_{ik} in equations 4.4a and 4.4b. Therefore, supplier j, alike its customer i, will have eco-intensity values EI_{ejk} and EI_{jk} for each of the output products k encompassing the contribution of the upstream supply chains of all intermediate products n. This process is repeated recursively along the supply chain. Supplier j passes the product supply chain-specific eco-intensity values EI_{ejk} and EI_{jk} to the next tier, therefore the equation to calculate the numerator of the eco-intensity of company i for output product k including the contribution of supplier j and its upstream supply chain environmental impact is shown in equations 4.5a and 4.5b:

$$EP_{eik} = \frac{T_{ik}}{T_i} EP_{ei} + EI_{ejk} \sum_{n} Q_{ijkn} P_{ijkn} \tag{4.5a}$$

$$EP_{ik} = \frac{T_{ik}}{T_i} EP_{i} + EI_{jk} \sum_{n} Q_{ijkn} P_{ijkn} \tag{4.5b}$$

If company i purchases precursor products from more than one supplier j, the environmental impact of each supplier needs to be added, leading to equations 4.6a and 4.6b, which are the final formulations for the environmental numerator of the supply chain eco-intensity for each specific environmental indicator e and of the supply chain global eco-intensity respectively:

$$EP_{eik} = \frac{T_{ik}}{T_i} EP_{ei} + \sum_{j} (EI_{ejk} \sum_{n} Q_{ijkn} P_{ijkn}) \tag{4.6a}$$

$$EP_{ik} = \frac{T_{ik}}{T_i} EP_{i} + \sum_{j} (EI_{jk} \sum_{n} Q_{ijkn} P_{ijkn}) \tag{4.6b}$$

4.2.6.2 Denominator: economic output

The recursive mechanism applies to the economic denominator too. First, similarly to what happened for the environmental nominator, the economic output at the company level needs to be allocated to the product mix. Each product k generates T_{ik}, a quota of the overall turnover T_i, which is equal to the product of the quantity produced Q_{ik} times the price of a single unit P_{ik}.

Secondly, the economic benefit of the supply chain is not simply the sum of the turnover generated at each tier of the supply chain by the product output k and the precursor products n necessary to obtain k, but is reduced by the expenses made by each organisation to acquire the precursor products and transformed resources necessary to produce its output product. A number of product-specific transformed resources are indeed necessary to obtain the final product and the cost of these resources needs to be subtracted from the turnover generated by the overall volume of sales of the final product.

If we consider a simple dyadic chain, as the one pictured in Figure 4.11, where a single product is exchanged between supply chain partners and no supply chain exists upstream from supplier j, the economic output of the supply chain is the sum of the economic output from supplier j and the economic output from customer i. The former is given by the product of the quantity of product Q_{OUT-j} being delivered to the customer i times the price of an individual unit of this product, P_{OUT-j}. The latter is given by the earnings of company i, which are the product of the quantity of product Q_{OUT-i} being sold times the price of this product, P_{OUT-i}, minus the costs faced to acquire relevant supplies from supplier j which are the product of quantity of supplies Q_{IN-i} and the price of a single unit of them P_{IN-i}. However, this work assumes that the quantities Q_{OUT-j} and Q_{IN-i} are equal, as are the prices P_{OUT-j} and P_{IN-i}. Therefore, the expenses faced by customer i match the economic output obtained by supplier j, which can be omitted. The economic output of the dyadic supply chain represented in Figure 4.11 is thus the economic output generated by customer i and is equal to $T_{ik} = Q_{ik}P_{ik}$.

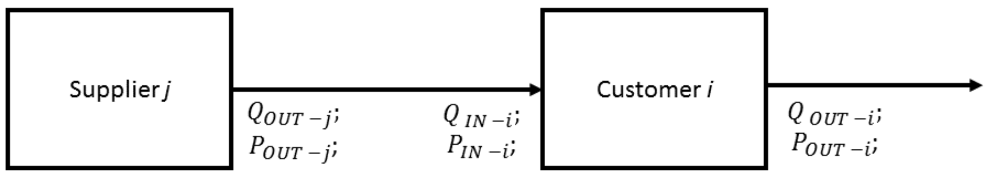

Figure 4.11: Economic dimension recursive mechanism

If this mechanism is replicated along a multi-tier supply chain, the mechanism is not affected and the ultimate economic indicator representing the economic benefit of the supply chain is the turnover generated by the product at the most downstream player considered. If the assumption about a single product delivered from supplier j to customer i is relaxed, supplier j may deliver multiple intermediate products n to customer i to be used in the same output product k. However, this does not affect the mechanism to calculate the overall economic output of the supply chain, which still corresponds to the turnover generated by the product k at the most downstream player of the supply chain i. If multiple suppliers are involved, delivering multiple intermediate products n to customer i to be used in the same final product k, the mechanism remains once again unchanged. The economic output of the supply chain still corresponds to the turnover T_{ik} generated by the most downstream company i in the supply chain thanks to product k.

4.2.6.3 Complete formulations

Once the recursive mechanism is applied throughout the entire supply chain including the direct impact of the most downstream player in the chain, two additional outputs of the method are calculated. These are the eco-intensity EI_{eik} of company i including its environmental impact from the supply chain of product k for each environmental indicator e and the global supply chain eco-intensity EI_{ik} of company i including its environmental impact from the supply chain of product k. Combining the recursive mechanisms illustrated in Sections 4.2.6.1 and 4.2.6.2, the complete formulations of the supply chain eco-intensities are detailed in Equations 4.7a and 4.7b.

$$EI_{eik} = \frac{1}{T_{ik}} [\frac{T_{ik}}{T_i} EP_{ei} + \sum_j (EI_{ejk} \sum_n Q_{ijkn} P_{ijkn})] \tag{4.7a}$$

$$EI_{ik} = \frac{1}{T_{ik}} [\frac{T_{ik}}{T_i} EP_i + \sum_j (EI_{jk} \sum_n Q_{ijkn} P_{ijkn})] \tag{4.7b}$$

Where T_{ik} is the turnover of company i generated by its output product k, T_i is the overall turnover of company i, EP_{ei} is the internal environmental performance of company i at the company level for the environmental indicator e, EP_i is the internal global performance of company i at the company level, EI_{ejk} is the eco-intensity of the 1st tier supplier j for the output product k with respect to environmental indicator e including the environmental impact of its upstream product specific supply chain, EI_{jk} is the global eco-intensity of the 1st tier supplier j for the output product k including the environmental impact of its upstream product specific supply chain. Finally, Q_{ijkn} is the quantity of intermediate product n shipped from supplier j to customer i for the output product k, whereas P_{ijkn} is its price. This equation is the most practical to be adopted in an operating supply chain context, where the information about Q_{ijkn} and P_{ijkn} are available to the customer i as part of the economic transaction associated to the purchase of the precursor products or materials from supplier j. The customer i requires to obtain from each of its 1st tier suppliers j for product k only the values of EI_{ejk} to calculate the value of EI_{eik} and the value of EI_{jk} to calculate EI_{ik}, as all remaining data is available at the company level. Two alternative versions of equation 7 are also presented in this work to simplify the illustration of the model in the numerical example. The summation of the n intermediate products can be substituted by the turnover of supplier j generated by deliveries to customer i for the output product k, labelled as T_{ijk}, leading to the formulation of equations 4.8a and 4.8b. In this case, the second summation in equations 4.7a and 4.7b disappears as all supplies from supplier j to customer i for the output product k are aggregated in a unique economic value.

$$EI_{eik} = \frac{1}{T_{ik}} \left(\frac{T_{ik}}{T_i} EP_{ei} + \sum_j EI_{ejk} T_{ijk} \right) \tag{4.8a}$$

$$EI_{ik} = \frac{1}{T_{ik}} \left(\frac{T_{ik}}{T_i} EP_i + \sum_j EI_{jk} T_{ijk} \right) \tag{4.8b}$$

The simplified expression of the recursive mechanism equation can also be presented by analysing T_{ijk} as a ratio of the overall turnover of supplier j generated by organisation i for its final product k as equations 4.9a and 4.9b show.

$$EI_{eik} = \frac{1}{T_{ik}} \left(\frac{T_{ik}}{T_i} EP_{ei} + \sum_j EI_{ejk} \frac{T_{ijk}}{T_j} T_j \right) \tag{4.9a}$$

$$EI_{ik} = \frac{1}{T_{ik}} \left(\frac{T_{ik}}{T_i} EP_i + \sum_j EI_{jk} \frac{T_{ijk}}{T_j} T_j \right) \tag{4.9b}$$

Once the calculation of EI_{eik} and EI_{ik} is completed, the mechanism can be repeated moving downstream along the supply chain: output product k of company i becomes an intermediate product n for the next downstream stage of the supply chain and thus becomes part of the environmental backpack of the upstream supply chain for the supply chain member located right downstream along the chain. The recursive mechanism is repeated moving downstream along the supply chain until the most downstream player is reached and its internal environmental performance is included, according to the system boundaries defined in Section 4.1.2. Finally, the environmental backpack EBP_{eik} associated with the entire volume of every product k produced by company i can be easily calculated starting from either equation 4.7a, 4.8a or 4.9a for each environmental indicator e. It is actually the numerator of the eco-intensity ratio, which can be expressed through any of the alternative formulation of equation 4.10:

$$EBP_{eik} = \frac{T_{ik}}{T_i} EP_{ei} + \sum_j (EI_{ejk} \sum_n Q_{ijkn} P_{ijkn}) \tag{4.10a}$$

$$EBP_{eik} = \frac{T_{ik}}{T_i} EP_{ei} + \sum_j EI_{ejk} T_{ijk} \tag{4.10b}$$

$$EBP_{eik} = \frac{T_{ik}}{T_i} EP_{ei} + \sum_j EI_{ejk} \frac{T_{ijk}}{T_j} T_j \tag{4.10c}$$

4.2.7 Inclusion of transport

Section 4.1.5 detailed the specific role of transport within the supply chain from the conceptual perspective, highlighting the key features affecting the environmental impact of the spatial transformation intermediate products undergo. These are the geographical location of organisations, the mode of transport and the weight of goods moved. Transport is merged into the mathematical model in this section considering such features, by first detailing the mathematical formulations to be added to the mathematical model with respect to energy consumption and emissions to air categories (Section 4.2.7.1) and second introducing the EcoTransIT tool adopted for the calculation of transport environmental impact (Section 4.2.7.2).

Taking into account the transformed resources system boundaries definition, transport directly impacts only energy consumption and emissions to air categories among those identified in Section 4.2.1 (Harris et al., 2011). The two categories are tackled through two indicators, which are the “Transport energy consumption” and the “Transport GHG emissions”.

4.2.7.1 Transport formulation

The values of the two transport-specific indicators are calculated for each transport link through EcoTransIT, as detailed in Section 4.2.7.2. A mono-directional transport link is assumed for each dyad, including those connecting outsourcing companies. The transport-specific indicators are then merged into the mathematical model for the calculation of the “energy consumption” and “emissions to air” categories, both in terms of supply chain eco-intensity and environmental backpack. The transport environmental impact is partially aggregated to the environmental impact of the customer in each dyadic transport link, as it is not aggregated to its internal eco-intensity performance but it is aggregated to its supply chain eco-intensity. “Transport energy consumption” and “Transport GHG emissions” are merged into the main eco-intensity indicators according to the following logic:

- Transport environmental impact does not influence the calculation of the company eco-intensity of any of the organisations involved in each dyadic transport link. This is to preserve the independent evaluation of each supply chain organisation without affecting the validity of the method.
- Transport environmental impact contributes to the calculation of the supply chain eco-intensity, only with respect to the inbound transport flows up to the tier whose internal environmental impact is last added. In the recursive formulation, this means that at the i-th supply chain tier the transport environmental impact of transport links up to the i-th are only accounted, whereas the outbound flows originating from the i-th tier are not included, as shown in Figure 4.12, where only transport links within the red line are considered. The outbound flows from the i-th tier are going to be included only when the i-th+1 downstream tier and its internal environmental impact are taken into account. This cascading logic respects the

cradle-to-gate system boundary, which does not consider the final outbound flow into the analysis, which is the transport of the final product to the final customer.

- Transport environmental impact adds up to the determination of the environmental backpack at each tier of the supply chain according to the previous remark. Therefore, in order to calculate the environmental backpack at each tier i of the supply chain, the absolute environmental impact of transport is added to the quota derived from internal environmental impact of the i-th tier and to the quota derived from the supply chain contribution.

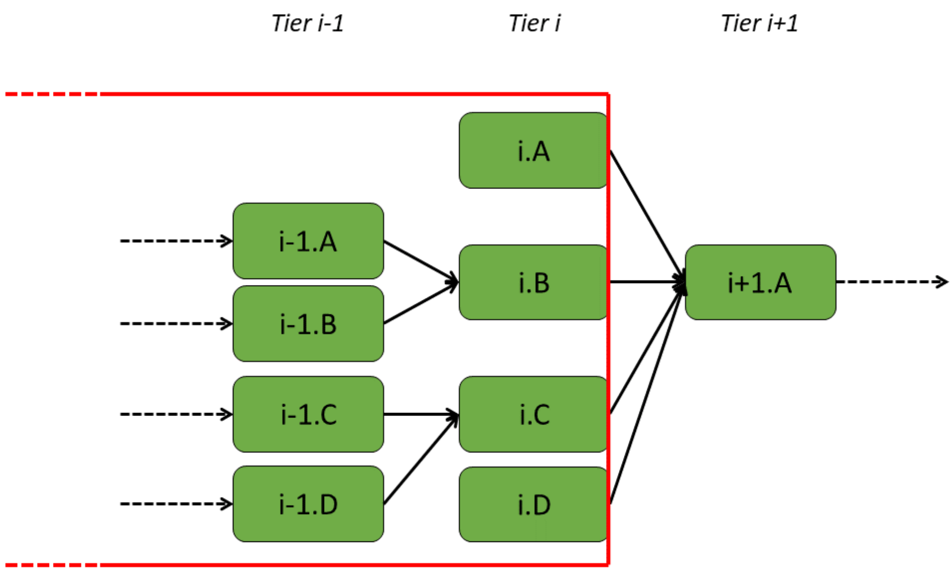

Figure 4.12: Inclusion of transport at the i-th supply chain tier

Equation 4.7a to calculate supply chain eco-intensity is therefore modified into equation 4.11a, which includes the environmental impact of transport EP_{eij}^{tr} from supplier j to customer i with respect to the environmental indicator e. The formulation is generalised in a summation as customer i is likely to source intermediate products for its final product k from multiple suppliers j. Transport impacts only energy consumption and GHG emissions, therefore equations targeting other environmental impacts are not affected by this formulation. Similarly, equations 4.11b and 4.11c develop alternative formulations of the same equation, which are based on the different notations identified in equations 4.8a and 4.9a.

$$EI_{eik} = \frac{1}{T_{ik}} [\frac{T_{ik}}{T_i} EP_{ei} + \sum_j EP_{eji}^{tr} + \sum_j (EI_{ejk} \sum_n Q_{ijkn} P_{ijkn})] \tag{4.11a}$$

$$EI_{eik} = \frac{1}{T_{ik}} (\frac{T_{ik}}{T_i} EP_{ei} + \sum_j EP_{eji}^{tr} + \sum_j EI_{ejk}\, T_{ijk}) \tag{4.11b}$$

$$EI_{eik} = \frac{1}{T_{ik}} (\frac{T_{ik}}{T_i} EP_{ei} + \sum_j EP_{eji}^{tr} + \sum_j EI_{ejk} \frac{T_{ijk}}{T_j}\, T_j) \tag{4.11c}$$

A similar rationale is followed for the calculation of the environmental backpack, which is still derived from the numerator of the eco-intensity ratios appearing in equations 4.11a, 4.11b and 4.11c, leading respectively to equations 4.12a, 4.12b and 4.12c.

$$EBP_{eik} = \frac{T_{ik}}{T_i} EP_{ei} + \sum_j EP_{eji}^{tr} + \sum_j (EI_{ejk} \sum_n Q_{ijkn} P_{ijkn}) \tag{4.12a}$$

$$EBP_{eik} = \frac{T_{ik}}{T_i} EP_{ei} + \sum_j EP_{eji}^{tr} + \sum_j EI_{ejk} T_{ijk} \tag{4.12b}$$

$$EBP_{eik} = \frac{T_{ik}}{T_i} EP_{ei} + \sum_j EP_{eji}^{tr} + \sum_j EI_{ejk} \frac{T_{ijk}}{T_j} T_j \tag{4.12c}$$

The inclusion of transport does not modify the economic denominator of the eco-intensity equations. Indeed, the recursive mechanism is not affected in its logic, as the economic value of the transport activities is assumed to be included either in the price paid from the customer i to supplier j or in the price paid to customer i from its clients. Should the supplier be responsible for the transport service, this is going to result in an extra-price charged to the customer on top of the intermediate product price in order to cover the costs the supplier incurred to provide the transport service. Alternatively, in the case customer i is responsible for the transport activity and the resulting costs, this is going to be added to the other purchasing costs the customer faced and will lead to an increase of the price of its output product k.

Therefore, equations 4.12a, 4.12b and 4.12c conclude the progressive construction of the mathematical model, whose main equations for operational use are condensed in a summary in the following section.

4.2.7.2 EcoTransIT

Both transport-specific indicators are calculated in this research through the Ecological Transport Information Tool (EcoTransIT), a freely available online tool (https://www.ecotransit.org/) to calculate environmental impact associated to transport, which was developed by the European Committee for Standardisation. EcoTransIT follows the “Methodology for calculation and declaration of energy consumption and GHG emissions of transport services (freight and passengers)” and has already been used in the GSCM literature, like in Brandenburg (2015). As a result, the only source of secondary data within the calculation of the environmental impact of the supply chain is hereby introduced. The rationale for this choice is twofold. First, transport is a relatively standardised activity that takes place in every supply chain, thus not sharing the same variance associated to activities taking place in supply chain tiers belonging to different industries. The assumptions introduced with the adoption of secondary data are therefore less prone to be inaccurate. Second, the environmental impact of transport is an established research field, with an abundant amount of reliable secondary sources to estimate the energy consumption and GHG emission with a certain degree of accuracy (Koh et al., 2012; Paksoy et al., 2011).

The EcoTransIT tool requires as inputs for the calculation of the two indicators associated to the transport the following inputs:

- Origin: geographical location of the supplier;
- Destination: geographical location of the customer;
- Freight amount: tool offers the option to provide the amount of freight either by the weight of products shipped (measured in tonnes) or by the volume of products expressed in Twenty-foot Equivalent Unit (TEU);
- Transport modes: five transport modes are offered by the tool. These are: truck, train, airplane, sea ship and barge. The option to combine multiple transport modes is also offered by the tool.

While requiring limited information inputs, the tool encapsulates the aspects supply chain organisations are able to influence in terms of transport, which are the choice of the supplier, thus its location, and the mode of transport, a decision linked to the overall strategy of the company. Organisations largely rely on external third party logistics providers for transport and are therefore not able to influence other aspects of the transport such as “the freight load or transport speed” (Brandenburg, 2015). On the other hand, the tool adequately covers the spatial transformation of the products as “emissions rates are proportional to distances traveled” (Zakeri et al., 2015). Finally, the weight of products information is also an information captured by the tool as “transport emissions are linear in the freight quantity” (Brandenburg, 2015). Therefore, EcoTransIT adopts the most common approach to estimate the environmental impact of transport being based on “factors per distance unit and/or per weight unit” for different transport modes (Soysal et al., 2014).

Once the inputs are fed to the tool, outputs are then automatically calculated. Outputs of the tool are calculated in accordance to EN 16258, the “Methodology for calculation and declaration of energy consumption and GHG emissions of transport services (freight and passengers)” develop by the European Committee for Standardization (EcoTransIT World Initiative, 2016). The tool offers three options to visualise the environmental impact with three different types of information (EcoTransIT World Initiative, 2016):

- Tank-to-wheel (TTW): it includes the environmental impact associated only with transport operation, calculating the final energy consumption and the vehicle GHG emissions.
- Well-to-tank (WTT): it includes the environmental impact associated with the upstream fuel supply chain activities, such as construction, extraction, refining, energy generation, energy production and energy distribution. It calculates the upstream energy consumption and the upstream GHG emissions.
- Well-to-wheel (WTW): it is the sum of TTW and WTT environmental impacts, calculating total energy consumption and total GHG emissions.

The environmental impacts associated both with the construction of the transport infrastructure and with the construction of vehicles are outside the scope of EcoTransIT (EcoTransIT World Initiative, 2016), consistently with the transformed resources system boundary approach. Building on the same conceptual model pillar, the tank-to-wheel (TTW) calculation is adopted in this research, as upstream activities are related to the production of fuels adopted in the transport activities. Fuel is considered a transforming resource according to the definition given in section 4.1.2.2. As such, these represent activities that are related to the fuel-specific supply chain and not to the supply chain of the product that is transported using that fuel and stand outside of the system boundaries.

A separate calculation is performed for each supply chain link, which is the transport activity taking place between any two supply chain tiers. The TTW values derived from EcoTransIT are then incorporated into the main body of the mathematical model, according to the formulations detailed in the following section.

4.2.8 Summary of the mathematical model

Once the environmental impact of the transport is also added to the mathematical model, the final formulations of the model are reached. These formulations are the basis to calculate the various outputs of the method and to operationalise the method in operative supply chains. In order to provide a summarised view of the equations developed throughout the section, the final formulations of the eco-intensity at the supply chain level are consolidated in Table 4.4, whereas those of the environmental backpack are summarised in Table 4.5. The formulations are provided with three different options to visualise the economic transaction associated to the deliveries of intermediate products n for output product k from supplier j to customer i.

Table 4.4: Summary of final formulations to calculate supply chain eco-intensity

	Eco-intensity	
	Excluding transport	Including transport
Turnover generated by products visualised as the product of the quantity and price of intermediate product n shipped from supplier j to customer i for the output product k	$EI_{eik} = \frac{1}{T_{ik}} [\frac{T_{ik}}{T_i} EP_{ei} + \sum_j (EI_{ejk} \sum_n Q_{ijkn} P_{ijkn})]$ (Eq. 4.7a)	$EI_{eik} = \frac{1}{T_{ik}} [\frac{T_{ik}}{T_i} EP_{ei} + \sum_j EP_{eji}^{tr} + \sum_j (EI_{ejk} \sum_n Q_{ijkn} P_{ijkn})]$ (Eq. 4.11a)
Turnover generated by products visualised as an absolute figure aggregating all deliveries of supplier j to customer i for the output product k	$EI_{eik} = \frac{1}{T_{ik}} (\frac{T_{ik}}{T_i} EP_{ei} + \sum_j EI_{ejk} T_{ijk})$ (Eq. 4.8a)	$EI_{eik} = \frac{1}{T_{ik}} (\frac{T_{ik}}{T_i} EP_{ei} + \sum_j EP_{eji}^{tr} + \sum_j EI_{ejk} T_{ijk})$ (Eq. 4.11b)
Turnover generated by products visualised as a ratio of the overall turnover of supplier j generated by organisation i for its final product k	$EI_{eik} = \frac{1}{T_{ik}} (\frac{T_{ik}}{T_i} EP_{ei} + \sum_j EI_{ejk} \frac{T_{ijk}}{T_j} T_j)$ (Eq. 4.9a)	$EI_{eik} = \frac{1}{T_{ik}} (\frac{T_{ik}}{T_i} EP_{ei} + \sum_j EP_{eji}^{tr} + \sum_j EI_{ejk} \frac{T_{ijk}}{T_j} T_j)$ (Eq. 4.11c)

Table 4.5: Summary of final formulations to calculate environmental backpack of products

	Environmental backpack	
	Excluding transport	Including transport
Turnover generated by products visualised as the product of the quantity and price of intermediate product n shipped from supplier j to customer i for the output product k	$EBP_{eik} = \frac{T_{ik}}{T_i} EP_{ei} + \sum_j (EI_{ejk} \sum_n Q_{ijkn} P_{ijkn})$ *(Eq. 4.10a)*	$EBP_{eik} = \frac{T_{ik}}{T_i} EP_{ei} + \sum_j EP_{eji}^{tr} + \sum_j (EI_{ejk} \sum_n Q_{ijkn} P_{ijkn})$ *(Eq. 4.12a)*
Turnover generated by products visualised as an absolute figure aggregating all deliveries of supplier j to customer i for the output product k	$EBP_{eik} = \frac{T_{ik}}{T_i} EP_{ei} + \sum_j EI_{ejk} T_{ijk}$ *(Eq. 4.10b)*	$EBP_{eik} = \frac{T_{ik}}{T_i} EP_{ei} + \sum_j EP_{eji}^{tr} + \sum_j EI_{ejk} T_{ijk}$ *(Eq. 4.12b)*
Turnover generated by products visualised as a ratio of the overall turnover of supplier j generated by organisation i for its final product k	$EBP_{eik} = \frac{T_{ik}}{T_i} EP_{ei} + \sum_j EI_{ejk} \frac{T_{ijk}}{T_j} T_j$ *(Eq. 4.10c)*	$EBP_{eik} = \frac{T_{ik}}{T_i} EP_{ei} + \sum_j EP_{eji}^{tr} + \sum_j EI_{ejk} \frac{T_{ijk}}{T_j} T_j$ *(Eq. 4.12c)*

4.3 Outputs of the method

Once the recursive mechanism is applied until the most downstream tier of the supply chain and the environmental backpack associated to the product is calculated, all outputs of the method are available. Five outputs are offered overall by the application of the method: four eco-intensity based indicators and the environmental backpack based indicators associated to the final product. The outputs provide different information about the environmental performance at the single company level and at the supply chain level and can be adopted to support various managerial decisions:

- Single company eco-intensity for each specific environmental indicator e: these values indicate the eco-intensity of each organisation with respect to each specific environmental indicator, giving detailed indications about the internal environmental performance of each company belonging to the supply chain. They do not consider any environmental impact from upstream members of the supply chain. The indicators can be used internally by the companies to set environmental targets, to perform longitudinal benchmarking as well as to support the supplier selection and evaluation processes.
- Single company global eco-intensity: the indicator provides a summarised information about the eco-intensity performance of each organisation with a synthetized value aggregating all eco-intensity indicators in a single index, which does not consider any environmental impact from upstream members of the supply chain. The applications are similar to those offered by single company eco-intensity indicators for each specific environmental aspect, however providing a higher level of information which overcomes trade-offs between different environmental aspects.
- Supply chain eco-intensity for each specific environmental indicator e: these values reveal the eco-intensity of the supply chain of a product with respect to each specific environmental indicator e, giving indications about the cradle-to-gate environmental performance of the supply chain. These offer a primary application to benchmark the environmental performance of products by considering their supply chain with respect to specific environmental aspects. Additional applications include use for external reporting of environmental performance of products as well as adoption as a reference for operational improvement towards a more sustainable supply chain behaviour. Finally, these outputs can be also used for identification of eco-intense hotspots along the supply chain, a necessary step to prioritise action (Lake et al., 2015).
- Supply chain global eco-intensity: the indicator reveals a summarised information about the eco-intensity of the supply chain of a product, offering a synthetized indication about the cradle-to-gate environmental performance of the supply chain. The applications are similar to those offered by supply chain eco-intensity indicators for each specific environmental aspect, however providing a higher level of information that overcomes trade-offs between different environmental aspects.

- Environmental backpack of products for each specific environmental indicator e: moving from the eco-intensity of the supply chain, these values quantify the environmental impact that is assigned to the produced volume of each product with respect to each specific environmental indicator, allowing to further allocate the environmental backpack on different basis for reporting purposes. For example, the CO_2 emissions per unit of product or the water consumed per kilogram of final product can be calculated.

The outputs informing about the global environmental performance of the system require the identification of appropriate normalisation technique to be finalised, which is one of the future research directions of this work as it will be presented in Chapter 7 and Chapter 8. This could potentially lead to the identification of a global environmental backpack of products, another potential future research direction of this work.

The outputs can be disaggregated along two axes, which are the supply chain extent coverage and the environmental aspects coverage. Disaggregating the outputs on the basis of the supply chain extent coverage, the outputs can be differentiated between those that are assessing the performance of a single organisation (single company eco-intensity for each specific environmental indicator e, single company global eco-intensity) and those that specifically tackle the supply chain environment and thus cover multiple organisations (supply chain eco-intensity for each specific environmental indicator e, supply chain global eco-intensity, environmental backpack of products for each specific environmental indicator e). The single company-outputs find an application as part of the traditional green supplier selection and evaluation process, whenever an organisation limits its attention to its direct suppliers. Moreover, they are adopted for organisational external reporting and for internal use, in order to provide organisations with a set of relative indicators to monitor their own environmental performance across time. On the other hand, the supply chain-outputs are specifically designed to be shared with other organisations part of the network and can be adopted by buyers for multi-tier based green supplier selection and evaluation, where each supplier is not only evaluated based on its internal performance but also on the basis of the environmental sustainability of its upstream supply chain. Moreover, outputs at the supply chain level offer a range of applications in the area of external reporting, having the potential to benchmark different products. Customers can compare the environmental performance of different products in order to make a more informed and sustainable choice, both in a B2B and in a B2C context. Moreover, environmental labelling of products is another potential application of this group of outputs, especially suitable for the B2C context.

Disaggregating the outputs on the basis of the environmental aspects coverage, the outputs can be divided among those providing information that are tackling a specific environmental indicator (single company eco-intensity for each specific environmental indicator e, supply chain eco-intensity for each specific environmental indicator e, Environmental backpack of products for each specific environmental indicator e) and those informing about the global environmental performance of the system (single company global eco-intensity, supply chain global eco-intensity), following the two streams of the mathematical model identified in Figure 4.1 and Figure 4.6. Considering single environmental indicators can help practitioners to focus on specific environmental aspects based on the decision-makers preferences, supply chain strategy or specific sector characteristics, providing accurate directions towards identification of environmental hotspots and guidance towards operational improvement. On the other hand, an aggregated environmental information can better quantify the impact of trade-offs arising when considering simultaneously multiple environmental indicators and provide a holistic evaluation of the eco-intensity of a company and of a supply chain as well as of the environmental backpack associated to products.

The disaggregation of the eco-intensity outputs of the method is summarised in the matrix in Figure 4.13, where also main practical applications of the indicators are displayed. These will be discussed in-depth in the illustration of the case studies (Chapter 6) and in the practical implications of this research in Chapter 8.

Model outputs	**Single company**	**Supply chain**	
Specific environmental indicator	Single company specific environmental indicator eco-intensity	Supply chain specific environmental indicator eco-intensity	Focused operational improvement
Global environmental performance	Single company global eco-intensity	Supply chain global eco-intensity	Trade-off between environmental aspects & holistic eco-intensity evaluation
	Supplier evaluation & selection Organisational external reporting & benchmarking	Multi-tier based supplier evaluation & selection Product supply chain external reporting & benchmarking	**Main applications**

Figure 4.13: Eco-intensity based outputs and their main applications

4.4 Summary

This research aimed to develop a method to assess the environmental sustainability performance of multi-tier supply chains, in order to address the lack of a method that simultaneously:

- Assesses multi-tier supply chains environmental sustainability performance;
- Provides a comprehensive evaluation of environmental aspects;
- Uses primary data sourced from actual practice to assess the environmental performance;

- Respects the multiple organisation nature and non-collaborative nature of the majority of real-life supply chains.

This chapter outlined the method developed in this research in order to fill this gap in the existing literature. Being the method a set of models, the method illustrated in this chapter is built by two models, namely a conceptual model and a mathematical model.

Section 4.1 defined the conceptualisation of the system under analysis by specifying the physical system of interest and its surroundings and determining the environment of interest. This was further detailed into the five pillars framing the conceptual model, which are: eco-intensity concept; cradle-to-gate and transformed resources system boundaries; black box approach; indirect multi-tier supply chain management approach; transport to link supply chain tiers. The pillars conceptualise the environmental impact, supply chain structure and dynamics, as illustrated in Figure 4.2: Conceptual model pillarsFigure 4.2.

Section 4.2 presented the mathematical model stemming from the underlying conceptual model, including all relevant equations. The mathematical model was built progressively moving from the single company formulation into the supply chain formulation, illustrating step-by-step the assumptions made to translate the concepts into the equations required to operationalise the method and calculate the main outputs obtained through the method. These are outlined in Section 4.3 along with main internal and external applications of each of them.

In the next chapter (Chapter 5), the three-stage process adopted to evaluate the utility, accuracy and applicability of the method developed in this chapter is going to be illustrated.

5 Method evaluation

The method illustrated in Chapter 4 consists of a conceptual and a mathematical model to assess the environmental sustainability performance of multi-tier supply chains. This chapter introduces the work conducted to evaluate the method.

Evaluation aims to assess “the effectiveness and the validity of the research results” (Duffy and Donnell, 1999) and is a required step in scientific research in order to achieve a more objective approach (Duffy and Donnell, 1999). Evaluation is an ascertaining process requiring a set of criteria to evaluate the research against (Duffy and Donnell, 1999). As such, evaluation can be adopted to assess the relation between a method and requirements specification, known practice or performance targets (Duffy and Donnell, 1999). This is performed in this research by evaluating the developed method against a set of three criteria:

- Utility: according to Hay (2015), utility is the “usefulness and fitness for purpose” of a model, as every model is developed with a planned intended use (Pidd, 2010), which in this case is the assessment of the environmental performance of multi-tier supply chains. In this work, the conceptual foundations of the method are evaluated with respect to the utility criterion, to determine whether the method fits the purpose to achieve the intended use in its conceptual pillars and the expected outputs of the method are useful for its potential users.
- Accuracy: as models are a simplified representation of reality, they entail various degree of accuracy, which is defined as “the quality or state of being correct or precise” (Oxford University Press, 2018c). In this thesis, both transformational accuracy and solution accuracy are evaluated. Transformational accuracy determines how accurately the mathematical model in its executable implementation represents the conceptual description of the model (Sokolowski and Banks, 2010). Solution accuracy is “the process of determining the correctness of the input data, the numerical accuracy of the solution obtained, and the correctness of the output data” (Oberkampf and Roy, 2010b) and is here verified for the mathematical model.
- Applicability: in the context of environmental models, applicability is defined as the relevance and appropriateness for the intended use (U.S. Environmental Protection Agency, 2009). In this thesis, the applicability of the method refers thus to the extent the method, which includes both the conceptual and the mathematical model, is relevant and appropriate to assess the environmental performance of different operating supply chains. The applicability to different systems, such as different supply chains, is a necessary requisite to demonstrate the generic applicability of the method (Hay, 2015).

A variety of methods can be adopted to carry out method evaluations such as case studies, experiments, industrial studies, protocol analysis and worked examples (Duffy and Donnell, 1999). This research adopts industrial studies in the form of semi-structured interviews, worked examples in the form of a numerical example and case studies as the methods to carry out the evaluation (Duffy and Donnell, 1999).

A detailed description of the approach followed to evaluate the method opens this chapter in Section 5.1. Following sections discuss individually each of the research sub-phases contributing to the method evaluation. Section 5.2 details the conceptual model qualification, Section 5.3 focuses on the mathematical model verification, while Section 5.4 elaborates on the validation stage, which involved both the conceptual and the mathematical model. A summary of the method evaluation concludes this chapter (Section 5.5).

5.1 Method evaluation approach

Three-steps were determined to evaluate the method. They were performed in cascade, following the dotted line represented in Figure 5.1.

1. Model qualification: building on a work from the Society for Computer Simulation, Oberkampf and Roy (2010) define model qualification as the "determination of adequacy of the conceptual model to provide an acceptable level of agreement for the domain of intended application". A conceptual model "specifies (a) the physical system, the system surroundings, and the phenomena of interest, (b) the operating environment of the system and its domain of intended use, (c) the physical assumptions that simplify the system and the phenomena of interest, (d) the system response quantities of interest, and (e) the accuracy requirements for the system response quantities of interest" (Oberkampf and Roy, 2010c). The goal of this step is to determine the utility of the model, which is the usefulness of the model and its fitness for the purpose (Hay, 2015). Semi-structured interviews are the research method adopted to perform model qualification.
2. Model verification: the mathematical issue of linking the conceptual model to the mathematical model is obtained through model verification (Oberkampf and Roy, 2010c), which is "the process of determining that a model implementation accurately represents the developer's conceptual description of the model" (USDoD, 1994). The mathematical model is developed starting from the conceptual model and includes mathematical and logical relations representing the underlying physical system through equations or other mathematical formulations (Oberkampf and Roy, 2010c). The focus of model verification is on accuracy, which could be determined through simplified model problems (Oberkampf and Roy, 2010c). A numerical example using secondary data was thus used to address model verification.
3. Model validation: the physical issue of linking the mathematical model back to the reality is finally achieved through model validation (Oberkampf and Roy, 2010c), which is the "process of determining the degree of which a model is an accurate representation of the real world from the perspective of the intended uses of the

model”(USDoD, 1994). Validation is performed to check the accuracy of the mathematical model and to demonstrate its applicability to a real-world context (Oberkampf and Roy, 2010c), in order to assess the environmental performance of supply chains. As a result, the selected research method was multiple case studies research, whose objective is to explore and showcase the applicability of the method in a specific and real situation (Yin, 2003).

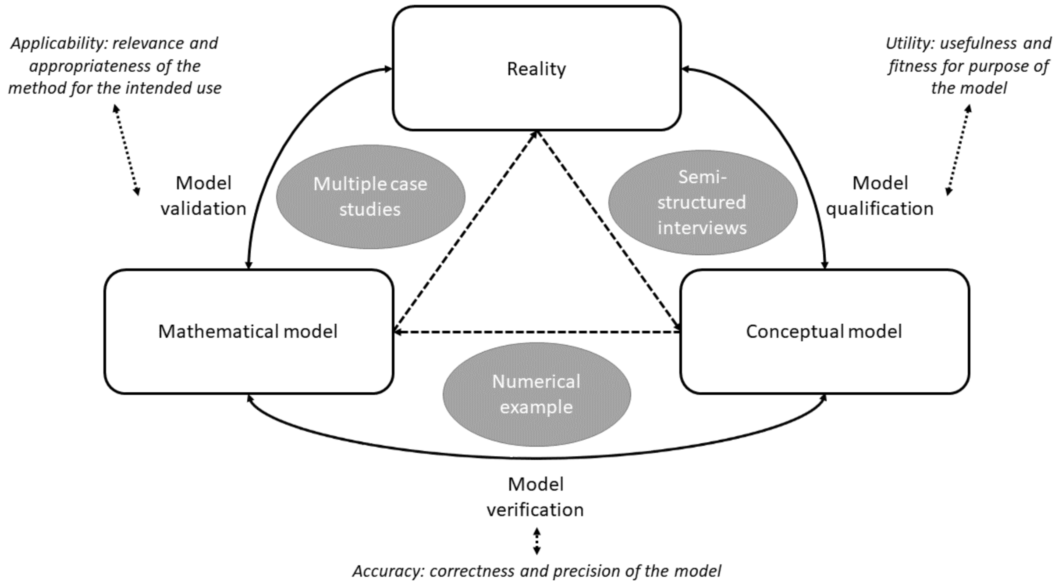

Figure 5.1: Method evaluation framework (based on Oberkampf and Roy, 2010)

5.2 Model qualification: linking reality to the conceptual model

The first stage of the method evaluation process is the model qualification, which aims to determine the usefulness of the method and its fitness for purpose for the domain of intended application. Model qualification thus bridges the gap between reality and the developed conceptual model part of the method. Semi-structured interviews were the research method adopted for this stage of evaluation, as explicated in Section 5.2.1 where the approach to model qualification is detailed, while the findings of this evaluation stage are illustrated in Section 5.2.2.

5.2.1 Model qualification approach

Since the method to assess supply chain environmental performance was based on the literature review search and thus on an academic perspective only, an industrial perspective was added in the method evaluation at the qualification sub-phase. The model qualification aimed to evaluate the utility of the model and its fitness for purpose for the domain of intended application, which is the application in commercial supply chains whose final output is a physical product.

The model underwent expert appraisal at two different stages of development through semi-structured interviews carried out with members of the Sustainability Team from Scottish Enterprise (SE), which is the main economic development agency of the Scottish Government (Scottish Enterprise, 2018). The SE Sustainability Team is a unit within the body that is dedicated to support companies improve their business practices in order to improve their environmental performance, undertaking every year over a hundred of projects and working with around two hundred Scottish companies in a variety of sectors. The individual interviewed members joined the SE Sustainability Team between 2006 and 2008, accumulating overall 39 years of experience in the organisation. Moreover, three members out of four had previous experience in the sustainability field, summing up to a total of 60 years of experience in the field within the team. Therefore, the members of the SE Sustainability Team were recognised as suitable experts to provide a basis for the evaluation of the model. The cross-industry experience of the team was considered an added benefit given the fact that the method developed in this research is meant to be applicable to multiple industries. On top of the model qualification, the interviews also aimed to explore the wider status of GSCM and SSCM from a practitioner perspective to reinforce the academic perspective obtained through the literature review search.

The first interview (I1) was held in November 2016 involving one interviewee (identified here as participant 1, P1), the team leader from the Scottish Enterprise team, whereas the second interview (I2) took place in March 2017 and involved three team members of Scottish Enterprise, identified as P2, P3, and P4, as shown in Table 5.1. Due to the different time schedule and format of the interviews, the content and the structure of the two interviews slightly differ:

- I1 aimed to investigate the perspectives of organisations on the topics of sustainability, sustainability assessment and supply chain sustainability as well as to understand the drivers pushing companies to integrate sustainability within their management. Moreover, I1 aimed to obtain an initial evaluation of the conceptual model, referring to its general pillars, methodology and utility. The first part of the interview was dedicated to the understanding the current situation in organisations to measure the internal environmental performance and the supply chain environmental performance, considering also the issue of environmental data availability and disclosure. The second part of the interview focused on the conceptual model, aiming to evaluate the indirect approach and the recursive mechanism that are a key characteristic of the method. The model outputs and the potential usefulness of outputs for companies were also briefly discussed. The duration of the interview was 45 minutes.
- I2 also touched the general issues of sustainability according to the companies' perspective, including the quantitative measurement of environmental performance both at the single company level and at the supply chain level. However, being scheduled at a more advanced stage of the research project, the focus of the interview was on the evaluation of the developed conceptual model,

covering aspects such as the utility of the model and its potential applicability in an operating supply chain. The second part of the discussion was supported by visual material provided by the researcher to the experts, who were asked to discuss between two different system boundaries, which affect the definition of the recursive mechanism equation. Experts were also asked about aspects of the conceptual model they disagreed with or felt were incomplete, requiring additional work. Visual outputs of a fictitious supply chain supported the interviewer in the explanation of the method and in directing the questioning. The interview lasted one hour and 25 minutes. The simultaneous participation of multiple experts and the discussion arising between them required to allocate more time to I2.

Table 5.1: Profile of the participants to the semi-structured interviews

Interview	**Participant**	**Position**	**Years of experience**	
			In the field	**In the organisation**
Interview 1 (I1)	Participant 1 (P1)	Team Leader	17 years	10 years
Interview 2 (I2)	Participant 2 (P2)	Team Member	10 years	10 years
Interview 2 (I2)	Participant 3 (P3)	Team Member	15 years	9 years
Interview 2 (I2)	Participant 4 (P4)	Team Member	18 years	10 years

5.2.2 Model qualification findings

The qualification of the model aimed to evaluate the utility of the conceptual model, which is determined by two elements:

- Fitness for purpose: mirroring the development of the method in its conceptual model part, experts were questioned over four key areas in order to support model qualification: eco-intensity concept, system boundaries, indirect multi-tier SCM approach (including recursive mechanism), black box approach (including input/output approach). A sub-section is dedicated to each of the areas of investigation (Sections 5.2.2.1-5.2.2.4). Moreover, other aspects that emerged during the interviews were recorded and are here reported in sub-section 5.2.2.5: these include the feedback about the general structure of the method, which led to a refinement of the method throughout subsequent versions of the conceptual and mathematical model as detailed in Chapter 4.
- Usefulness: model qualification aimed also to determine what is the value of the outputs of the method for its potential users, in order to determine the potential usefulness for industrial users to apply the method. The usefulness of the method is discussed in Section 5.2.2.6.

5.2.2.1 Eco-intensity concept

The eco-intensity concept represents the cornerstone of the environmental performance assessment, therefore experts were asked about its fitness for purpose. Experts highlighted two main aspects regarding its utility:

- *Cross-industry application*: eco-intensity can be applied consistently across different industries, which is often the case even within a single supply chain, whose member companies may not belong to the same sector. P1 pointed out that cross-industry sustainable best practices are already established as a reference point to evaluate the progress of businesses in terms of sustainability. The eco-intensity concept would add another dimension to cross-industry comparison by offering a support to quantitative performance measurement.
- *Benchmarking potential*: companies are very keen to obtain comparative evaluations of their internal performance as well as to benchmark alternative suppliers (P1). Adopting the same set of indicators, both for inputs and outputs, across different individual organisations can offer organisations information about their relative performance within the supply chain, as underlined by P3 during I2. Having a unique unit of reference was recognised as a key enabler for companies to benchmark their performance against each other and to integrate eco-intensity within their supplier evaluation systems in place:

P3: "I can see the value of the mode: to me, as the top of the supply chain, if you give me a tool or a method to measure three suppliers for their eco-intensity against each other, that is useful to me, if that is important to me"

The eco-intensity concept was not considered beneficial only to benchmark different organisations, but its value was recognised also in terms of the potential for longitudinal benchmarking, both at the single company level and at the supply chain level, as P3 pointed out. In the former case, eco-intensity indicators can be useful both for internal use to check performance improvements or to compare and evaluate suppliers. In the latter case, it can be useful to consistently measure the supply chain environmental performance and direct operational improvements efforts with informed decision-making.

P3: "It is a useful way for top of the supply chain to measure businesses and then drive the improvements across the supply chain. I can see how it is useful"

5.2.2.2 System boundaries

The issue of system boundaries was specifically targeted during I2. Visual material provided by the researcher to the experts supported this stage. Moving from the point that multi-tier supply chains need to be considered coherently with the aim of this work, experts faced two system boundaries options. The visual material consisted of a fictitious supply chain of focal firm 1 (FF1) with two potential supply chain boundaries, which are here defined as supply network system boundaries (SN), depicted in dotted line in Figure 5.2, and the extended supply chain system boundaries (SC), depicted in solid line in Figure 5.2. The former approach includes all organisation involved in all the upstream flows in the analysis, regardless of whether they are contributing directly to the final product produced by the focal company. This approach has also been described as 'ultimate supply chain' and includes flows of services and information from the ultimate supplier to the ultimate customer (Mentzer et al., 2001). The latter approach includes on top of 1st tier suppliers of the focal company only sub-suppliers that are involved in the supplies of the final product produced by the focal company (Mentzer et al., 2001), according to the transformed resources approach. These suppliers are partially or fully coloured in blue in Figure 5.2, whereas suppliers not involved with the final product of FF1 are represented in yellow. The core question was thus whether company ε had to be included within the system boundaries.

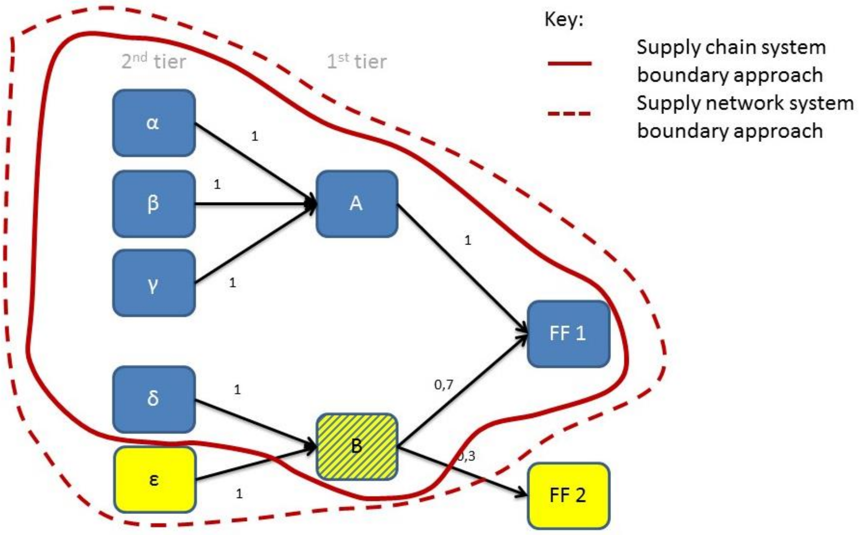

Figure 5.2: System boundaries dilemma

Experts inferred that the choice of the system boundaries has to be linked to the motivation focal companies have when undertaking the assessment of the environmental performance of the supply chain and therefore an unambiguous answer cannot be provided according to experts P2 and P4. If the main motivation is found in external reporting and green marketing, SC system boundaries are to be adopted, whereas if enlightenment or environmental risks are the main drivers, SN system boundaries were identified as the most suitable.

Advantages and disadvantages of both approaches were recognised by experts, considering several aspects (P2, P3, P4). The SN system boundaries were recognised to protect focal companies from an environmental risk and responsibility perspective, as they would minimise the risk of focal companies being associated to unsustainable behaviours (P2, P3). However, experts identified the lower number of lower tier organisations to be involved as a key reason to adopt the SC system boundaries, especially in terms of applicability of the method.

P2: *"Most would want a simple approach, so the solid line [supply chain system boundaries]"*

Moreover, P3 identified that there is no legitimacy for focal companies to influence choices of supply of their 1st tier suppliers for products that are not related to their supply chain.

P3: *"There is hard evidence of the products are coming through my supply chain"*

As a result, P3 argued that it would be impossible to apply the supply network system boundary approach unless 1st tier suppliers have a considerable disadvantage in terms of power balance against the focal company. Ultimately, experts came to an agreement to select the SC approach as the most suitable system boundary on the grounds of applicability for organisations.

5.2.2.3 Indirect multi-tier SCM approach

The indirect approach adopted in the conceptual model with no central entity taking control over the assessment was recognised as a useful approach due to the limited visibility and control of the supply chain from focal companies in operating contexts. Even companies at the forefront in terms of GSCM assess their direct suppliers but are not aware of the environmental performance of the upstream supply chain, as P2 highlighted:

P2: *"Probably, they go to their most immediate suppliers, I do not want to over generalise, but I think that in my experience they may go back one tier"*

The lack of the visibility is even more emphasised for SMEs as they generally lack the resources to track their supply chain with reliable and established methods (P2) and typically adopt informal network relationship to rule their supply network. The indirect multi-tier SCM approach can therefore reveal to focal companies precious information about the environmental performance of their multi-tier supply chain, which is not typically visible to focal companies in operating contexts. This offers organisations a quantitative understanding of the share of the impact that is imputable to the supply chain and to the focal company itself.

P1: *"For the commissioned product .. it will help them [focal companies] understand the impact of the supply chain and understand their position in the supply chain in terms of the contribution [to the environmental impact]"*

Concurrently to the indirect approach, P3 identified the ratio of turnover generated by the customer as functional not only to application of the recursive mechanism, but also as a key success factor of any supply chain project, including those related to sustainability. The share of turnover generated by each customer defines the power the customer has in the relation and influences the willingness of the supplier to endorse requirements from the customer. This value can therefore be considered as a proxy to estimate the chances of customers to successfully implement the recursive mechanism backwards in each dyadic relationship and obtain relevant data from their own suppliers.

5.2.2.4 Black box approach

Experts recognised two main useful aspects of adopting a black box approach to assess the environmental performance at each tier of the supply chain, which are the ability to capture the internal performance of each individual organisation as a whole and the applicability with currently available data.

The method offers a two-layers output: on top of the assessment of the supply chain, also the environmental performance of each single organisation is calculated. This could be useful and thus adopted from companies that are not focused on the supply chain dimension yet, but still interested to improve their internal environmental sustainability. The black box approach offers organisation a manageable way to obtain a picture of their overall internal environmental performance.

P1: *"They [companies] are quite focused on their own performance initially, that's the main focus of their attention … how they are performing overall"*

Moreover, the lack of available data was identified as an existing challenge to the implementation of any method aiming to measure environmental performance of the supply chain according to P1, since few enlightened companies are able to track accurately even their own environmental performance. This was partially contradicted by P3, who claimed that organisations are able to track their environmental inputs as these are associated to cost information. However, all participants agreed that even organisations that are actually assessing their internal performance, still lack the granularity in their assessment to allocate the different environmental impacts to their product mix due to the complexity determined by shared resources and shared production processes, as P1 highlighted.

P1: *"They may be able to tell you how much they spend on energy, but they will not know how many units they use and they will not understand where they use it"*

These challenges support the utility of a simplified assessment at the company level through a black box approach and the introduction of an allocation rule to move from the company level to the product level, identifying a simple but effective path towards applicability (P1).

P1: "The majority of the work we are going to do is going to be at the single company … the model is simple but effective"

The black box approach was thus identified suitable to the current data availability status within the majority of organisations, as key aspect to facilitate the assessment of the environmental performance.

5.2.2.5 Feedback about the method development

The semi-structured interviews were not only functional to the conceptual model qualification, but they also aimed to provide feedback about the development of the method from the experts' perspective. Experts were therefore asked with open-ended questions to identify potential areas of improvement within the conceptual model that could inform the following research phases. One key indication emerged from the interviews, which is the incorporation into the method of the environmental impact arising from transport.

During I1, P1 had already identified transport as a key area for GSCM, however during I2, P2 clearly identified the lack of an assessment of the environmental performance of transport as a potential weakness of the method, recommending its inclusion in future versions of the method.

P2: "That [transport] is an area that lots of companies might want to measure if they want to see how sustainable they are as a business, where are their inputs coming from"

P2 highlighted that in certain sectors, a significant share of the environmental impact can be imputable to the transport rather than to the supply chain tiers, thus it is critical to understand the origin of the supplies to track effectively the environmental performance. P2 further elaborated claiming environmentally sustainable behaviours of supply chain members can be undermined by a global design of the supply chain requiring long distance transport in certain industries and that such supply chains might not be as environmentally sustainable as local supply chains whose supply chain members are not individually as environmentally responsible. As a result, P2 considered important to capture the information about the environmental performance of transport to complete the method. Consequently, as an outcome of I2, transport was included into the method, leading to the fifth pillar of the conceptual model, as explicated in Chapter 4. Moreover, transport environmental impact was also later added to the mathematical model in version 3 (v3).

5.2.2.6 Usefulness of the method

On top of the evaluation of the fitness for purpose of the pillars building the conceptual model, the semi-structured interviews aimed to determine the usefulness of the general method for potential users. Overall, the experts had a positive opinion regarding the usefulness of the method, as P1 synthesised.

P1: “*The model is simple but effective* “

Further aspects regarding the usefulness of the method emerged from the interviews:

- *Set of environmental indicators*: P1 recognised the fact that environmental performance assessment is secondary to economic issues within any business and praised the simplicity of the method as an aspect to be maintained throughout its development, by keeping the number of indicators low. P2 and P3 further elaborated on this aspect, claiming that a limited set of indicators better fit the purpose of the method and is a key driver to gauge interest from companies for applicability. Moreover, P3 claimed that it is very useful for companies to have multiple environmental indicators whose values can be determined from cost factors, as this eases the data collection process. Finally, a limited set of indicators was also recognised as a key factor for effective managerial decision-making support. While having a limited set of indicators, experts agreed that the method offers an adequate coverage of the environmental aspects businesses typically want to monitor (P1, P2, P3).
- *Each company responsible for its internal assessment only*: given the limited visibility of the supply chain by organisations (P2) and the dominant focus on internal performance for environmental aspects (P1), the method fits the prevailing context of operating supply chains, without overloading focal companies with excessive data collection duties (P1). Moreover, the allocation method based on economic performance was considered favourable for SMEs as this avoids complex allocation procedures at the company level (P2).
- *Value of the outputs*: the model offers various outputs according to Figure 4.13. The matrix was presented to experts in order to evaluate the potential usefulness of the outputs based on different level of aggregation regarding the supply chain coverage and the environmental aspects coverage. Respondents did not always agree on recognising the highest usefulness to the same outputs. P1 stressed the novelty of the sustainable supply chain topic for companies and the strong focus on internal performance, acknowledging the usefulness of having an internal environmental performance assessment along with a supply chain one. At the supply chain level, P1 identified as the current most useful output the possibility to understand the aggregated impact of the supply chain members beyond the focal company on the overall product supply chain environmental performance. On the other hand, P2, P3 and P4 offered a more balanced view about outputs disaggregated at the company level and at the supply chain level, identifying the value of having a double layer of information within the same method.
- *Usefulness of the applications*: P1 foresees an interest by organisations in the benchmarking application of the method coherently with the practices of companies benchmarking economic performances against best practices or

competitors. The usefulness of eco-intensity indicators for benchmarking was stressed also by P3, who identified multiple potential uses of the method for benchmarking. First, longitudinal benchmarking can be adopted both at the single company level or at the supply chain level to check improvements over time and especially to quantitatively evaluate the outcome of operational improvements on the environmental performance. Second, benchmarking could be potentially used within the supply chain: this can be done either by comparing alternative suppliers as part of the supplier selection and evaluation process (P3) or by tracking where each company stands in the supply chain in terms of environmental performance and thus identifying the environmental hotspots (P1). Finally, the method would allow to compare also different product supply chains, having a potential for benchmarking against competitors (P2, P3). However, experts recognised that a legislative pressure would be required for this kind of application (P2, P3, P4). Experts from SE Sustainability Team thus considered the understanding of the environmental performance and its use for its various comparative applications as the most useful application offered by the method, a perspective that was pursued in the following verification stage, where multiple fictitious organisations and supply chains were evaluated against each other.

5.3 Model verification: from the conceptual model to the mathematical model

The second stage of the method evaluation is the model verification which is "the process of determining that a model implementation accurately represents the developer's conceptual description of the model" (USDoD, 1994). The verification stage aimed to check the accuracy of the method and, more specifically, that the mathematical model part of the method accurately represents its conceptual description. Therefore, model verification bridges the gap between the conceptual and the mathematical model part of the method, as shown in Figure 5.1. A worked example in the form of a numerical example is adopted as the research method for the verification stage. The model verification approach followed in the research is detailed in Section 5.3.1, while the features of the numerical example are illustrated in Section 5.3.2. Finally, the findings of the verification stage appear in Section 5.3.3.

Sections 5.3.2 and 5.3.3 are largely based on the work entitled "An innovative eco-intensity based method for assessing extended supply chain environmental sustainability" (2018), published online on the International Journal of Production Economics.

5.3.1 Model verification approach

The mathematical model is developed starting from the conceptual model and includes mathematical and logical relations representing the underlying physical system through equations or other mathematical formulations (Oberkampf and Roy, 2010c). The verification stage is an empirical process of observation in order to identify potential errors in the mathematical implementation of the conceptual model (Oberkampf and Roy, 2010c). Manual exploration of a worked example, represented in the form of a numerical example, was adopted in this work to perform the verification stage. This led to a continuous improvement of the mathematical model, which is depicted in its various developed versions, as explicated in Chapter 3. On top of the manual exploration, also the peer-review process is considered as a contributing stage to verify the accuracy of the method.

As accuracy was the focus of the verification stage, a simplified problem was considered as a referent (Oberkampf and Roy, 2010c). A numerical example using secondary data served this purpose. The numerical example was progressively built starting from an initial simple linear supply chain. Additional supply chains with a higher degree of complexity were later added to resemble operating supply chains, until the final network was completed as described in Section 5.3.2.

5.3.2 Model verification process: building the numerical example

The approach followed in Section 5.3.1 led to the development of the finalised version of the numerical example, which is illustrated throughout this section. The numerical example was developed with the aim to recreate supply chain complexity, but with the adoption of a limited set of environmental indicators, compared to the full-scale method. As the method is substantially modular in the selection of the environmental indicator set, the adoption of a limited set of indicators in the numerical example was functional to keep the range of data within a sizeable dimension to verify the accuracy of the method across the multiple refinement loops. Therefore, only two environmental indicators were adopted, covering both environmental input and environmental output categories: water consumption (m^3/year) and emissions to air (metric tonnes CO_2e/year). On the other hand, the characteristics of the supply chain have an effect on the method accuracy, therefore four different supply chains were developed in the numerical example in an attempt to recreate the complexity of operating supply chains, which are often interconnected creating a supply network. Four product supply chains originated by two focal firms and twelve other organisations create the supply network, which is depicted in Figure 5.3.

Each box in the figure represents an organisation. The colour of the box identifies which focal firm each company is serving: blue boxes belong only to supply chains of focal firm 1 (FF1), whereas yellow boxes represent companies part of the supply chains of focal firm 2 (FF2). Finally, the yellow-blue striped boxes are those companies that are part of both FF1 and FF2 supply chains. However, each focal firm produces multiple products: FF1 is producing product 1.1 and product 1.2, whereas FF2 produces product 2.1 and product 2.2. Each product supply chain is associated to a specific coloured geometrical shape in the figure. The geometrical shape next to each box helps to understand to which specific product supply chain each organisation is contributing to.

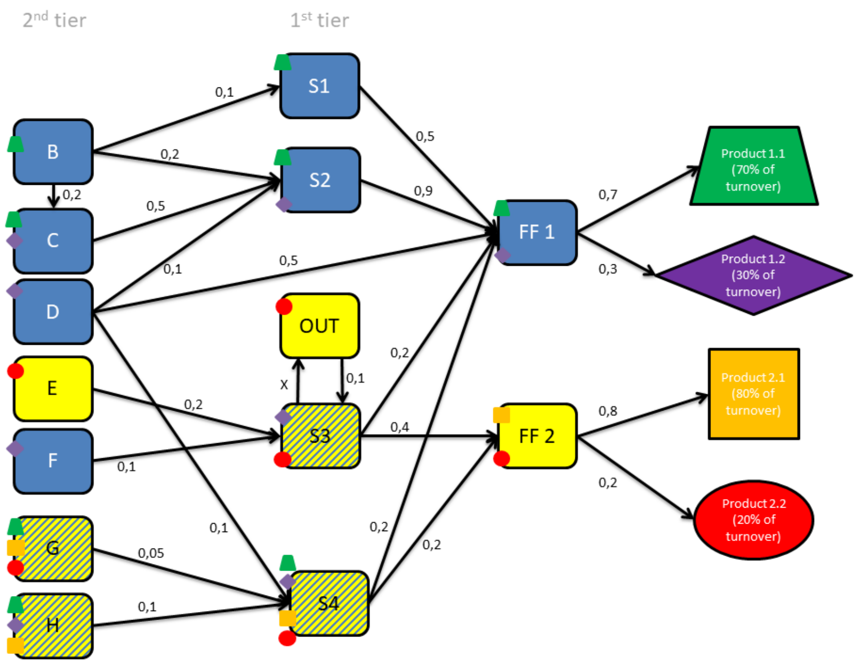

Figure 5.3: The supply network of the numerical example

As an example, B and C are both serving only focal firm 1, however B is contributing only to the supply chain of product 1.1 (green trapezoid), whereas C is supplying FF1 for both supply chain of product 1.1 (green trapezoid) and 1.2 (purple rhombus). Finally, the arrows identify the links between different organisations. The value next to each arrow is the ratio of turnover of each supplier that is generated by that specific customer, as illustrated in Section 4.2.5. As an example, 20% of the turnover of S4 is obtained thanks to deliveries to FF2: the value in Figure 5.3 is the overall turnover, which is broken down by product supply chains in Figure 5.4Figure 5.7. S4 generates 10% of its turnover through supplies to FF2 for Product 2.1 (Figure 5.6) and 10% of its turnover thanks to deliveries to FF2 for Product 2.2 (Figure 5.7) summing up to 20%.

The supply network illustrated in Figure 5.3 can be broken down in its building blocks, which are the four product supply chains, each of whom presents unique features. Supply chain of product 1.1 (Figure 5.4), is the only one including a 3rd tier supplier. Company B is acting both as a 2nd tier supplier, supplying S1 and S2, and as a 3rd tier supplier by delivering to company C, which is a 2nd tier supplier itself. The supply chain of product 1.2 (Figure 5.5), also includes a company belonging to two different tiers, as D is a direct supplier of Focal Firm 1 (FF1), thus being a 1st tier supplier, but acts also as a 2nd tier supplier. Company D serves both S2 and S4, that are themselves suppliers of FF1, thus making D a 2nd tier supplier. D shows an additional interesting feature, being at the origin of a divergent-convergent network: the material path exiting from D is divergent to S2 and S4, but later converges to FF1 again.

Supply chain of product 2.1, which is depicted in Figure 5.6 is a linear supply chain, which does not show any peculiar characteristic. Finally, supply chain of product 2.2, pictured in Figure 5.7, includes an outsourcing loop, as company S3 assigns certain production processes to organisation OUT. This specific case is solved by considering OUT as a normal supplier that is getting paid by S3 for the products delivered to the customer. Although the material path might include a physical shipping from S3 to OUT, there is no monetary flow connected to this link. The monetary flow is associated to the reverse link: S3 is the outsourcer and hires a third party (OUT) for certain services, therefore the monetary transaction flows from S3 to OUT. The lack of an economic transaction associated to the material path from S3 to OUT justifies the choice of treating OUT as a supplier. Additionally, this mechanism avoids to double count the environmental impact of company S3.

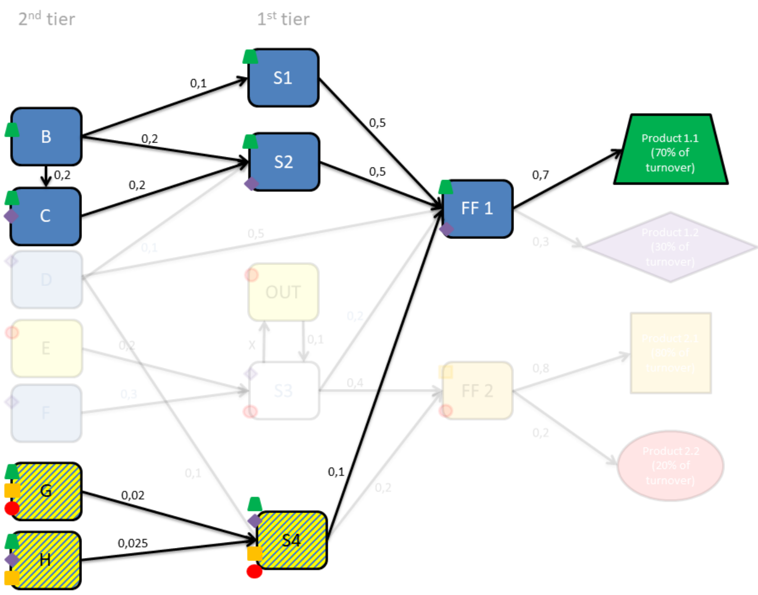

Figure 5.4: Supply Chain of Product 1.1

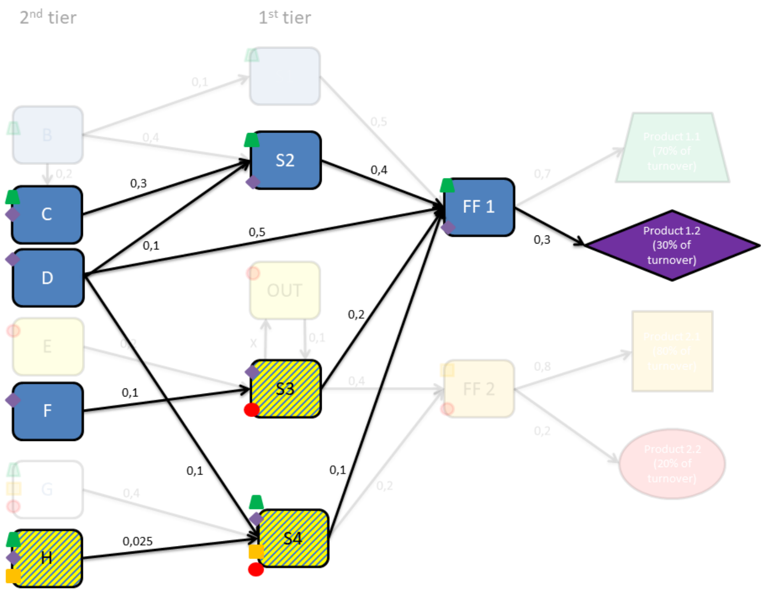

Figure 5.5: Supply Chain of Product 1.2

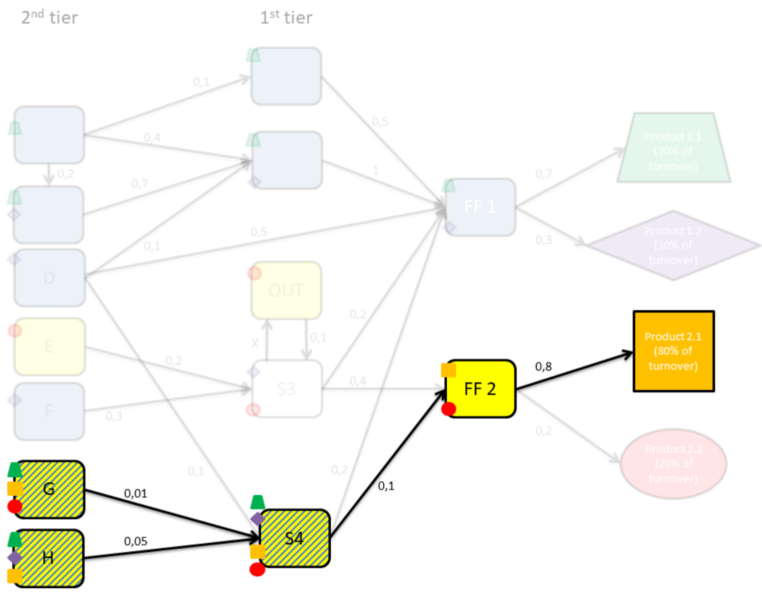

Figure 5.6: Supply Chain of Product 2.1

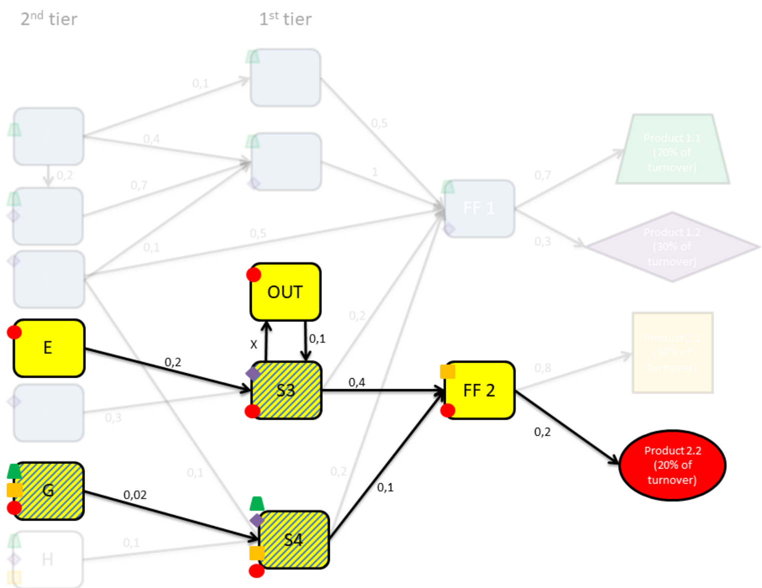

Figure 5.7: Supply Chain of Product 2.2

Moreover, the numerical example aimed to cover all possible combinations in terms of number of focal firms served and contribution to product supply chains by suppliers in order to cover all possible instances arising in real supply chains. Therefore, each 1st tier supplier was allocated a specific distribution mix, as detailed in Table 5.2.

Table 5.2: first-tier suppliers' distribution mix

1st tier supplier	Focal Firm	Product
S1	Single	Single
S2	Single	Multiple
S3	Multiple	Single (per focal firm)
S4	Multiple	Multiple

Secondary data were adopted to verify the accuracy of the mathematical model through a numerical example. Data, which are reported in Table 5.3, represent the yearly economic and environmental performance of the entire organisations. Different sources were adopted to populate information about the companies in the fictitious supply network. Turnover ($M/year) and CO_2 emissions (metric tonnes CO2e/year) values were obtained from publicly available databases of Fortune Global 500 companies: the data of the turnover and CO_2 emissions correspond to the same real organisation, despite in different calendar years (CDP, 2013; Fortune, 2016). On the other hand, water consumption data (m^3/year) were based on a dedicated work by Joa et al. (2014) and randomly allocated to the various organisations building the representative network, thus not corresponding to the same real company. Finally, all supply chain links as well as the economic values associated to them are fictitious as real organisations may belong to different industries and business relations between them may not exist. The above assumptions do not affect the purpose of verifying the mathematical model through a numerical example.

Table 5.3: key figures about the companies (model verification)

Tier	Company	Turnover [$M/year]	EP 1 – Emissions to air [metric t CO_2 e/year]	EP 2 – Water consumption [m^3/year]
2nd & 3rd tier	B*	22,126	53,587	159,000
2nd tier	C	23,208	1,263,773	365,000
	E	38,143	17,918	310,000
	F	44,294	2,551,626	1,168,000
	G	122,948	83,433	3,985
	H	20,969	213,089	1,482
	OUT	23,065	144,298	5,467
2nd & 1st tier	D*	24,861	894,206	262,800
1st tier	S1	29,636	1,075,761	74,795
	S2	23,633	4,211,808	93,045
	S3	36,604	322,000	177,250
	S4	33,196	40,996	524,000
Focal firms	FF1	482,130	851,495	578,267
	FF2	236,592	2,727,000	1,478,000

5.3.3 Model verification findings

The outputs of the numerical example are presented in this section, which is divided in three sub-sections. Each sub-section is dedicated to an output of the model. The peer-review process was considered part of the verification process of the mathematical model and is here acknowledged as an ulterior stage contributing to check the accuracy of the method.

5.3.3.1 Single company eco-intensity indicators

An eco-intensity indicator is calculated at the company level for the two environmental indicators adopted in the model verification by dividing the yearly environmental performance indicator of the organisation by its yearly turnover. These indicators do not consider any environmental impact from the supply chain. Results show a high variety in values for both eco-intensity indicators, spanning from a minimum of 0.470 tonnes CO_2e per $M for company E up to a maximum of 178.217 for S2, which is 37819% higher than the best performing organisation E. Company G is the best performing organisation in terms of water consumption eco-intensity with 0.032 m^3 per $M, whereas F is at the opposite end of the spectrum with a value of 26.369 m^3/$M.

Table 5.4: Model verification single company eco-intensities

Company	EI 1 – CO_2 emissions eco-intensity [metric t CO_2 e/$M]	EI 2 – Water consumption eco-intensity [m^3/$M]
B	2.422	7.186
C	54.454	15.727
D	35.968	10.571
E	0.470	8.127
F	57.607	26.369
G	0.679	0.032
H	10.162	0.071
OUT	6.256	0.237
S1	36.299	2.524
S2	178.217	3.937
S3	8.797	4.842
S4	1.235	15.785
FF1	1.766	1.199
FF2	11.526	6.247

The results illustrated in Table 5.4 provide a first indication on the value of eco-intensity concept, demonstrating the importance of having a monetary unit of reference to effectively compare figures of companies' environmental performances. As an example, organisations S4 and FF1 have relatively similar absolute water consumption, as FF1 uses

578,267 m^3 of water per year compared to 524,000 m^3 of water per year of S4, showing just a 10% higher water consumption volume. However, the economic output generated by FF1 is over 14 times bigger than the economic output obtained by S4. This makes the water consumption eco-intensity comparison favourable to FF1, whose EI2 equals to 1.199 m^3/\$M compared to 15.785 m^3/\$M of company S4.

5.3.3.2 Supply chain eco-intensity indicators

An eco-intensity indicator is calculated also at the supply chain level for the two environmental indicators adopted in the model verification. Table 5.5 shows the eco-intensity performance of the four product supply chains part of the numerical example and their ranking according to CO_2 emissions eco-intensity and water consumption eco-intensity.

Supply chain of product 1.1 performs best according to both eco-intensity indicators, recording 10.461 t CO_2 e/\$M and 2.056 m^3/\$M, as illustrated in Table 5.5. The results show contrasting values among the other three supply chains. Considering CO_2 emissions eco-intensity, product 2.1 ranks second with 11.609 metric t CO_2 e/\$M, followed by 14.751 metric t CO_2 e/\$M of product 2.2. Finally, product 1.2 is the most CO_2 emissions eco-intense product considering the entire supply chain, accounting for 22.637 t CO_2 e/\$M, which makes this product supply chain 116% more eco-intense than the best performing product 1.1. On the other hand, the most CO_2 emissions eco-intense product 1.2 ranks second best in terms of water consumption with a value of 4.901 m^3/\$M. Product 2.1 follows in the ranking with 6.524 m^3 of water consumed per \$M. Finally, product 2.2 is the most water-intense product supply chain requiring 395% more water per monetary unit compared to the best performing product 1.1 when the supply chain is taken into account, with an overall value of 10.176 m^3/\$M.

Table 5.5: Model verification product supply chain eco-intensities

Supply chain	EI 1 – CO_2 emissions eco-intensity [metric t CO_2 e/\$M]	Rank	EI 2 – Water consumption eco-intensity [m^3/\$M]	Rank
Product 1.1	10.461	1	2.056	1
Product 1.2	22.637	4	4.901	2
Product 2.1	11.609	2	6.524	3
Product 2.2	14.751	3	10.176	4

The results clearly show the most environmentally sustainable product being product 1.1, however do not give an overall final indication about other products due to conflicting results between the CO_2 emissions eco-intensity and the water consumption eco-intensity. An aggregation of indicators in a single eco-intensity index about performance of a product supply chain would help to come to a unique ranking of product supply chains based on their overall eco-intensity, resolving the issue of contrasting results between different indicators. However, eco-intensity indicators provide information about different environmental impacts to the decision makers, who can use it for focused interventions and operational improvement. As an example, focal firm 1, producing both products 1.1 and 1.2, can have a better understanding on which product is responsible for a high environmental impact per unit of value: they obtain clear information to tackle the supply chain members of the product 1.2 to lower the CO_2 emissions and the water consumption.

The CO_2 emissions eco-intensity scores of both products by focal firm 1 are heavily affected by the supply chain contribution due to the inclusion in the supply chain of some of the most CO_2 emissions eco-intense organisations (C, D, F and S2) that carry a much higher environmental backpack compared to the focal company. Within this scenario, product supply chain 1.2 is further penalised in its eco-intensity score by a low economic output at the supply chain level, leading to the bottom position in the ranking.

Hotspots might be located among 1st tier suppliers or further upstream. In both cases however, the focal firm will in real-life have visibility of its 1st tier suppliers only, thus not being directly aware of the poor performance of indirect suppliers. The focal firm has only the ability to engage with its direct suppliers that themselves have the visibility of the 2nd tier suppliers. In the case of product supply chain 1.1, focal firm recognizes S2 and S4 as the weak links in the chain with respect to water consumption (Figure 5.8a) and thus passes on the pressure to improve environmental operational performance to the two organisations, as showed by the blue dotted lines. The process is repeated at suppliers S2 and S4, however the outcome is different at the two suppliers. S4 water consumption eco-intensity performance is worse than the performance of its suppliers, thus improvement efforts are to be put in place within its internal boundaries and environmental pressure is not passed further upstream (Figure 5.8b). On the other hand, S2 that is the 1st tier supplier for the branch of supply chain including company C, can realise that the hotspot is located further upstream thus passing the environmental improvement effort requirements from the focal firm onto 2nd tier supplier C (Figure 5.8b). Finally, the process is repeated once again at 2nd tier supplier C (Figure 5.8.c), whose internal performance is worse than the performance of the 3rd tier supplier B. The backwards mechanism thus stops here. Therefore, it can be concluded that the combined comparison of the internal eco-intensity performance and the eco-intensity information provided by suppliers including the contribution of the supply chain allows the identification of hotspots along the supply chain. This is further explored in the case studies in Chapter 6.

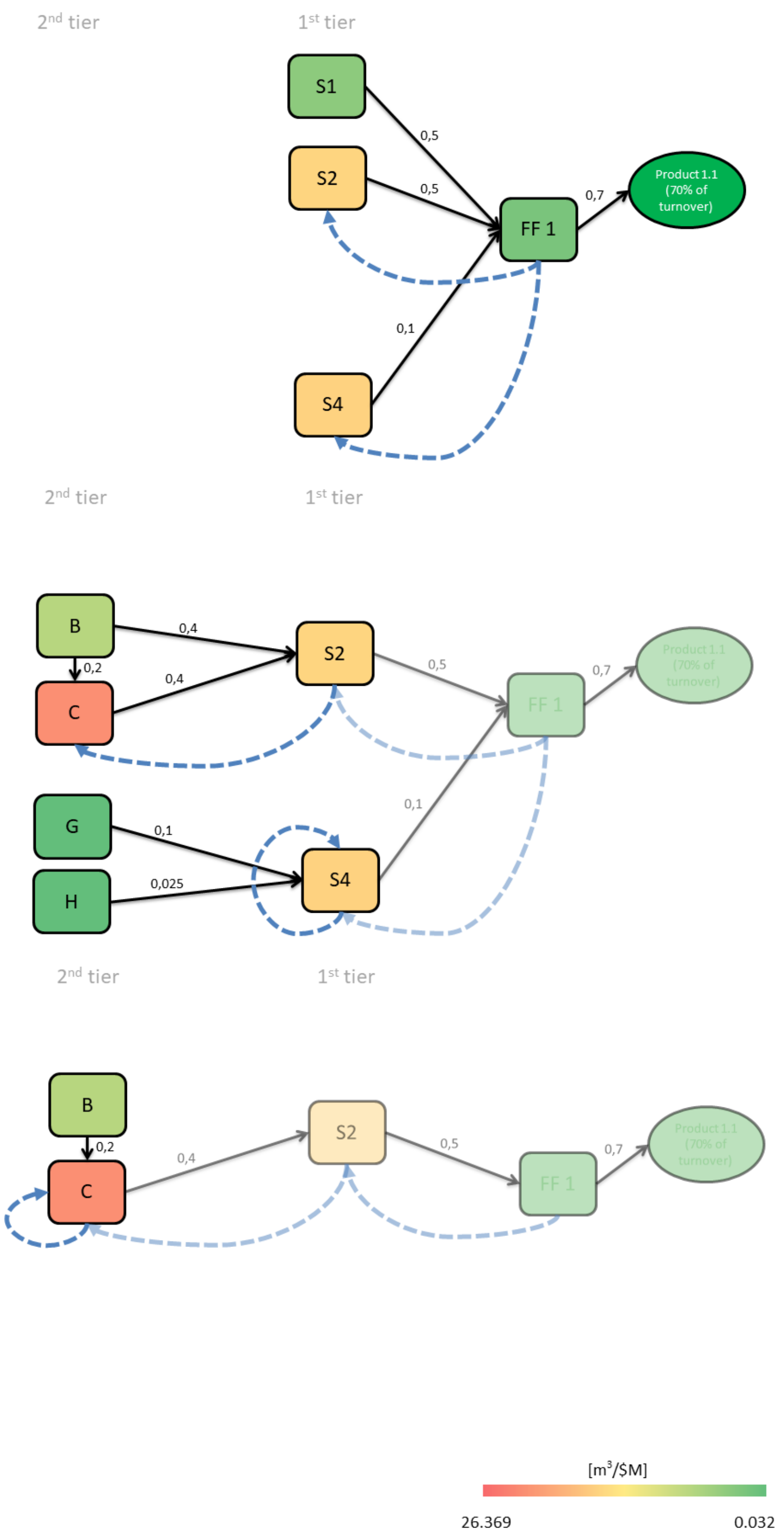

Figure 5.8: Model verification hotspot identification: (a) Explosion at the focal company; (b) Explosion at the 1st tier suppliers S2 and S4; (c) Explosion at the 2nd tier supplier C

5.3.3.3 Environmental backpack of products

The environmental backpack of products can be traced back from the eco-intensity of the supply chain, as illustrated in Chapter 4. The environmental backpacks associated to the entire yearly produced volume of each product k, both in terms of CO_2 emissions and water consumption, are shown in Table 5.6. These values represent the environmental backpack that is allocated to each product based on the economic output generated, considering the supply chain and represent the absolute values associated to each product. Product 1.1 has the overall highest CO_2 emissions, as 70% of the environmental impact of FF1 is allocated to it on top of the environmental backpack of the upstream supply chain, however it was proved in Section 5.3.3.2 that it is the best performing product in terms of CO_2 emissions eco-intensity. This finding thus reinforces the call for the use of relative indicators for comparative studies.

Table 5.6: Model verification environmental backpack of products

Product	EBP_{TOT-1} - CO_2 emissions [metric t CO_2 e/year]	EBP_{TOT-2} - Water consumption [m^3/year]
Product 1.1	3,530,475	693,724
Product 1.2	3,274,237	708,845
Product 2.1	2,197,188	1,234,914
Product 2.2	697,982	481,526

The data illustrated in Table 5.6 can be thus considered an intermediate step to provide alternative environmental reporting schemes that adopt different reference units to obtain alternative relative environmental indicators to present to relevant stakeholders. Despite the advantage of eco-intensity for benchmarking purposes, alternative indicators could be more appropriate for specific reporting or external communication. As an example, the CO_2 emissions or water consumption per unit of product can be easily obtained by dividing the figures presented in Table 5.6 by the number of units of the final product that are produced. In this case, only the final allocation of the environmental backpack to the single unit of a product needs to be 'translated' to a different relative unit, whereas upstream methodological steps would still be based on the eco-intensity principle and the recursive mechanism presented.

5.3.3.4 Accuracy of the method

The method verification aimed, through a numerical example, to determine the accuracy of the transformation of the conceptual model into an executable mathematical model, which is referred as "transformational accuracy" (Sokolowski and Banks, 2010). Moreover, the method verification also aimed to verify the solution accuracy, which is "the process of determining the correctness of the input data, the numerical accuracy of the solution obtained, and the correctness of the output data" (Oberkampf and Roy, 2010b). The verification of the two types of accuracy of the mathematical model was obtained by two verification informal methods (Sokolowski and Banks, 2010), which are the iterative manual calculation, also known as inspection, and the expert appraisal, in the form of a peer-review process. The former was finalised to verify the solution accuracy, whereas the latter verified both the transformational accuracy and the solution accuracy, as detailed in Table 5.7. The numerical example was functional in both cases to the verification of the accuracy.

Table 5.7: Types of accuracy evaluated during method verification

	Transformational accuracy	**Solution accuracy**
Iterative inspection		✓
Expert appraisal	✓	✓

The solution accuracy verification through the iterative inspection was performed first. In order to verify the solution accuracy, it was first necessary to transform the mathematical model into an executable model for use on a digital computer (Oberkampf and Roy, 2010a; Sokolowski and Banks, 2010). The executable model was developed as a spreadsheet model.

The supply chains illustrated throughout Section 5.3 were transformed into a matrix format. Rows in the matrix represent the suppliers, while columns represent the customers. The number in each cell represent the ratio T_{ijk}/T_j of the overall turnover of supplier j generated by customer i for the final product k, as illustrated in Figure 5.9 for the case of product supply chain 1.1. Moreover, the equations illustrated in Chapter 4 were adapted to be used into a spreadsheet environment.

Matrix	B	C	G	H	S1	S2	S4	FF1
B		0,2			0,1	0,2		
C						0,2		
G							0,02	
H							0,025	
S1								0,5
S2								0,5
S4								0,1
FF1								

Figure 5.9: Supply chain 1.1 represented in a matrix form

The focus of this stage was to verify the numerical accuracy of the mathematical and executable model as well as on the correctness of the outputs. This process takes a similar format to code debugging to identify mistakes in the executable form of the mathematical model and is considered an *a priori* method as it is not possible to know in advance the correct form of the executable model (Oberkampf and Roy, 2010d). The process thus aimed to determine a “reasonable confidence” in the integrity and accuracy of the reported data (Defra, 2013)

Initially, the mathematical model was verified with simple supply chain configuration (supply chain of product 2.1), in order to allow the comparison of the spreadsheet results with model outputs hand calculated and verify the accuracy of the spreadsheet results (Correll, 2014). This process was repeated in every instance a mistake in the executable model was observed or an editing of the underlying conceptual model determined a change in the formulation of any equation part of the mathematical model, such as in the case of the refinement of system boundaries in mathematical model v2. Once the comparison of spreadsheet and manually calculated results was successful for the simplest supply chain configuration, the process was repeated for the other supply chains. Given the limited set of indicators adopted in the numerical example and the reduced number of supply chain members, the inspection process was iteratively repeated at each new version of the mathematical model to verify the accuracy of the eight supply chain eco-intensity indicators represented in Table 5.5 and the eight environmental backpack results Table 5.6.

The accuracy of the mathematical model was then verified by the mean of expert appraisal through the peer-review process of the journal paper entitled “An innovative eco-intensity based method for assessing extended supply chain environmental sustainability”, published online on the International Journal of Production Economics. The paper underwent two stages of double-blind peer review process, with two reviewers independently evaluating the work. A brief outline of the conceptual model, the entire mathematical model (v2) and the numerical example, as it appears in Section 5.3.2, were all presented in the journal paper, as well as the results of the numerical example, which have been illustrated in Section 5.3.3. The mathematical model was thus evaluated through the numerical example, which served as a mean to understand the rationale of the model. Therefore, both the transformational accuracy of the conceptual model into an executable mathematical model (Sokolowski and Banks, 2010) and the accuracy of the solutions of the numerical example (Oberkampf and Roy, 2010c) were evaluated at this stage.

The transformation of the conceptual model into the mathematical model was verified as accurate by the reviewers, leading only to minor changes regarding the formulation of equations 4.6a and 4.6b, with the addition of an extra-parenthesis to separate the two summations, “since $\boldsymbol{\sum_{i=1}^{n} x_i \sum_{i=1}^{n} z_i \neq \sum_{i=1}^{n} x_i z_i}$”, as identified by reviewer 1 and illustrated in Table 5.8. This also affected all equations cascading from equations 4.6a and 4.6b throughout the mathematical model.

Table 5.8: model verification changes to fulfil transformational accuracy

Mathematical model version	Equation 4.6a	Equation 4.6b
v1 & v2	$EP_{eik} = \frac{T_{ik}}{T_i} EP_{ei} + \sum_j EI_{ejk} \sum_n Q_{ijkn}P_{ijkn}$	$EP_{ik} = \frac{T_{ik}}{T_i} EP_i + \sum_j EI_{jk} \sum_n Q_{ijkn}P_{ijkn}$
v3 & v4	$EP_{eik} = \frac{T_{ik}}{T_i} EP_{ei} + \sum_j (EI_{ejk} \sum_n Q_{ijkn}P_{ijkn})$	$EP_{ik} = \frac{T_{ik}}{T_i} EP_i + \sum_j (EI_{jk} \sum_n Q_{ijkn}P_{ijkn})$

The review process also facilitated the isolation of incorrect input data, which was identified in the spreadsheet due to the random figures adopted. In some cases, the value of the economic output generated by an organisation for a specific product was lower than the expenditures for the supplies required for that specific product. As this would be very rare in real-life supply chains, the figures were adjusted so that all organisations in the numerical example operate on a profit in every supply chain they belong to. The change in the input data determined an edit of the output data too, while the numerical accuracy was preserved.

Finally, the verification stage not only evaluated the accuracy of the method but also worked as a pilot study for the application of the method in its executable format in operative supply chains, which constitute the method validation stage, detailed in the following Section 5.4.

5.4 Method validation

The third and final stage of the method evaluation process is the method validation, which is the "process of determining the degree of which a model is an accurate representation of the real world from the perspective of the intended uses of the model" (USDoD, 1994). The validation stage aimed to evaluate the entire method in order to check its applicability in an operating context and to validate that the method can effectively assess the environmental performance of different supply chains (Oberkampf and Roy, 2010c). Multiple case studies method was adopted to validate the method.

Both models building the method are evaluated at this stage. The mathematical model is evaluated in an operating context, adopting primary data sourced from actual practice. Moreover, differently from the method verification stage, the mathematical model includes also the assessment of transport at the validation stage. The implementation of the mathematical model in an operating context involves a number of challenges in the assessment, which were not considered in the method verification, such as the decoupling of the monetary flow and material flow of the supply chain. In addition, the enablers to the applicability of the method were evaluated in the follow-up stage of the case studies.

The validation stage completes the method evaluation by closing the loop and linking back the mathematical model to the reality (Oberkampf and Roy, 2010c), as illustrated in Figure 5.1

5.4.1 Method validation approach

Multiple case studies research was the selected method to approach model validation. According to Yin (2003), an objective of case studies is to explore and showcase the applicability of models in a specific and real situation (Yin, 2003). Moreover, the choice of multiple case studies aims to generalise the findings as opposed to single case study research (Saunders et al., 2008), thanks to the adoption of multiple data sources to fulfil the purpose of validation (Creswell, 2014; Wang and Duffy, 2009).

As a result, two case studies were selected to conduct model validation. Being the method designed to be applied in any industrial sector, two supply chains from two different industrial sectors were selected to serve the purpose, in order to demonstrate the cross-industrial applicability of the method. Selected focal companies belong to the "Food Products" industry for case study 1 (CS1) and the "Machinery" industry for case study 2 (CS2) as defined according to the Global Industry Classification Standard (GICS) framework (MSCI, 2015). Moreover, the size of the focal companies differs in the two case studies. Focal company 1 (FC1) can be labelled as a micro enterprise according to the European Union classification scheme (European Union, 2003), therefore belonging to the wide spectrum of SMEs. On the other hand, FC2 can be classified as a large enterprise (European Union, 2003). The selection of focal companies with different sizes was also reinforced by opinions of experts during I2, as P2 recognised that environmental sustainability management varies based on the size of organisations. While multinational groups and large organisations typically implement a more structured approach, SMEs adopt informal approaches. The choice of focal firms positioned at the extremes of the enterprise size spectrum thus aimed to evaluate the applicability of the method in organisational contexts with different features in their environmental management. Finally, also the manufacturing production strategy was different in the two case studies, as summarised in Table 5.9, which underpin different approaches to the market as well as different organisational features.

The two case studies not only have different features in terms of the focal company, but also in terms of supply chain characteristics. Both case studies evaluated multi-tier supply chains, however a perfect overlap between the multi-tier and the extended supply chain exists in CS1 thus performing a twofold validation, whereas the raw material extraction stage could not be assessed in CS2, thus CS2 is an example of multi-tier supply chain evaluation. Moreover, the supply chain of CS1 is local and has a linear structure, while supply chain of CS2 is international and complex, thus presenting different supply chain operations as well as different challenges in terms of GSCM. The selection of multiple case studies with significant differences in their features aims to generalise the applicability of the method in different operating contexts, demonstrating the flexibility of the method in its application.

Table 5.9: Case studies details

Case study	Size of focal company	GICS Industry	Manufacturing Production Strategy	Supply chain geographical scope	Supply chain structure
CS 1	Micro	Food Products	Make-to-Stock	Local	Linear
CS 2	Large	Machinery	Make-to-Order	International	Complex

Owing to the differences in the size of organisations and to both the availability and the expertise of human resources at the two focal companies to collect the data required to validate the method, the role of researcher was also slightly different in the two case studies, as depicted in Figure 5.10:

- CS1: the researcher, while mainly having the main point of contact at the focal company, had significant interaction also with the 1st tier supplier to facilitate the application of the method within the supply chain as well as to engage with the 2nd tier supplier, that was accessed only for data collection purposes. As a result, the researcher interfaced with all organisations building up the supply chain to provide the basic support for data collection and recording, as illustrated in Figure 5.10a.
- CS2: the only interface of the researcher was with the supply chain manager of focal company 2 (FC2), who then engaged with 1st tier suppliers. The direct suppliers of FC2 then interfaced with their own suppliers (2nd tier suppliers of FC2) to obtain the relevant data. The flow of data therefore cascaded in a linear way in CS2 going from the 2nd tier supplier to the focal company in line with the indirect SCM approach and then on to the researcher, as illustrated in Figure 5.10b.

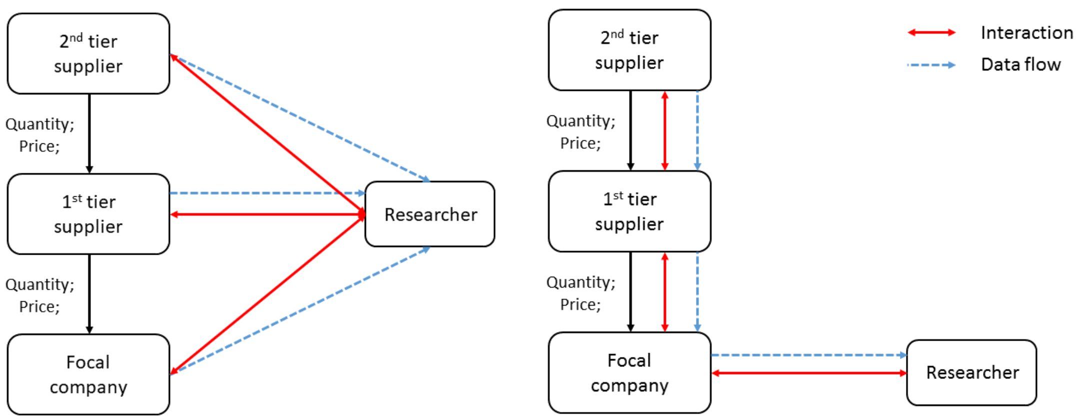

Figure 5.10: Role of researchers in CS1 (a) and in CS2 (b)

Once the data collection and analysis was completed, a detailed report was forwarded to the focal companies for both case studies. The report included information about the methodology followed, data collection, results and application of the outputs offered from the method. The reports formed the basis for the follow-up of the case studies, which was the last step of the method validation, aiming to evaluate the applicability of the method and the applicability of results and outputs arising from the method. The follow-up followed two different approaches owing once again to the different sizes of the focal company and their different organisational structure, as detailed in Table 5.10.

- CS1: the follow-up of the case study was performed by comparing the results with another case (Ashby, 2014). A previous study by Kulak et al. (2015) adopted LCA to evaluate the land occupation and emissions to air of a supply chain sharing the same features with the supply chain assessed in CS1, as Chapter 6 details. Moreover, the applicability of the method was evaluated through a semi-structured interview, adapting enablers for green multi-tier supply chain management by Dou et al. (2017) as a basis for discussion.
- CS2: the follow-up of the case study was performed by comparing the results with information on the supply chain environmental performance already available at the focal company. Two follow-up interviews were held with the supply chain manager of FC2. The first interview focused on the evaluation of the results and the outputs of the study, whereas the second interview focused specifically on the evaluation of the applicability of the method, adapting enablers for green multi-tier supply chain management by Dou et al. (2017) as a basis for discussion.

Table 5.10: Case studies follow-up applicability evaluation

Applicability aspect evaluated	CS1	CS2
Results & Outputs	Comparison with another case	Comparison with information available at the focal company
Method	Based on enablers for multi-tier GSCM through semi-structured interview	Based on enablers for multi-tier GSCM through semi-structured interview

The findings from the case studies, which constitute the results of the method validation stage, are reported in Chapter 6.

5.5 Summary

This chapter presented the work conducted to evaluate the method to assess the environmental performance of multi-tier supply chains that was illustrated in Chapter 4.

First, the method evaluation approach was introduced, providing an overview of the three research sub-phases contributing to the evaluation as well as on the aspects to be evaluated at each sub-phase along with the research methods adopted (Section 5.1). Following sections elaborated on each research sub-phase. Section 5.2 discussed the qualification stage: the conceptual model underwent experts' appraisal to evaluate its utility, which is the usefulness and fitness for purpose of the model. Four pillars of the conceptual model were evaluated through semi-structured interviews in terms of utility: eco-intensity concept, system boundaries, indirect multi-tier SCM approach and black-box approach. Moreover, the interviews were also functional to receive feedback about the method development and led to a refinement of the method by adding the environmental impact of transport as a fifth pillar to the conceptual model. Section 5.3 focused on the verification stage in order to evaluate the accuracy of the transformation of the conceptual model into a mathematical model and the accuracy of the solutions of the mathematical model. A worked example in the form of a numerical example served this purpose: four fictitious product supply chains with different characteristics were used to simulate the behaviour of real supply chains, with the accuracy verified through iterative manual calculation and expert appraisal in the form of peer-review process. Finally, Section 5.4 discussed the validation stage, which offered a combined evaluation of both the mathematical model and the underpinning conceptual model. Validation aimed to evaluate the applicability of the overall method in operating supply chains. Section 5.4 focused on the validation approach only, distinguishing the different role of the researcher in CS1 and CS2 as well as the different approach to the evaluation of the applicability of results. The findings from the method evaluation are discussed in the next chapter (Chapter 6), which illustrates the results arising from the application of the method in two case studies.

6 Case studies results and analysis

Case study method was the last method adopted in the method evaluation process. More specifically, multiple case studies technique was adopted in order to address objective 4 (O4) and objective 5 (O5). Multiple case studies were functional to complete the method evaluation by validating the method in operating contexts with primary data sourced from actual practice and evaluating the applicability of the method.

The results of the multiple case studies are presented and analysed in this chapter. Eisenhardt (1989) identifies two key activities at the stage of data analysis, which are within-case analysis and cross-case analysis. Within-case analysis is performed for each case study in sections 6.1 and 6.2. Section 6.1 introduces case study 1 (CS1) results and analysis from a food supply chain, whereas Section 6.2 outlines case study 2 (CS2) results and analysis from a machinery supply chain. Each case includes information about the organisations part of the supply chain, the environmental performance assessed and the data collected on top of the results arising from the implementation of the method. Finally, the applicability of the results is discussed within each case study as well as the implications of the results. Section 6.3 completes the data analysis by searching for cross-case comparisons (Eisenhardt, 1989), regarding the enablers for the applicability of the method. Finally, a summary of the case studies results and analysis concludes this chapter (Section 6.4).

6.1 Case study 1 (CS1)

6.1.1 Case study 1 overview

The “Patto della Farina” supply chain (SC1) is a collaborative regional supply chain adhering to “Forum beni comuni ed economia solidale del Friuli Venezia Giulia” (hereafter “forum beni comuni”), an association based in Friuli Venezia Giulia region, Italy, aiming to promote sustainable development in the region. The mission of the association is based on the triple bottom line pillars: social equity, environmental sustainability and economic support to local companies. Adopting fair trade oriented practices is at the heart of the “forum beni comuni”. The association also overviews four collaborative supply chains in Friuli Venezia Giulia region, which are aiming to expand sustainability beyond organisational boundaries of single companies.

SC1 operates in the “Food products” industry according to the GICS classification scheme (MSCI, 2015) and the final product delivered to the customer is bread. The specific bread produced through SC1 is clearly identified to the final customer by the brand “Pane del patto”, which guarantees on its origin as well as on the traceability of the wheat used to produce bread and on the product transformation practices from the raw material stage throughout the final product. SC1 features a collaborative nature: members of SC1 have a transparent price policy along the supply chain and are constantly sharing knowledge on best practices to improve the sustainability of the supply chain. Moreover, a full traceability of the raw product is mandatory in order to guarantee the origin and the quality of the final product to the consumers.

SC1 is a linear supply chain consisting of three tiers, as depicted in Figure 6.1. The transportation between the supply chain tiers is made by truck. Although supply chain members have a strong focus on sustainability, this is the only viable transportation option due to the low volumes and short distances involved, as all products are locally sourced. Figure 6.1 also includes additional information on the yearly quantities of products that are shipped between supply chain members and are sold to the final customer as well as on the price of these products.

According to the European Union enterprises classification, the focal company and the other organisations part of the supply chain could be defined as micro enterprises (European Union, 2003), as they employ fewer than 10 people and their annual turnover does not exceed EUR 2 million. Figure 6.2, Figure 6.3 and Figure 6.4 illustrate in detail the inputs and outputs of each company part of the supply chain, treated according to the black box approach. The rectangles with a red outline are those representing the supply chain under analysis according to the transformed resources principle.

- Focal company: bakery “Panificio Iordan”. The core business of the organisation is the production and distribution of bread, pastry and other bakery products. The bakery delivers to the consumers (end users) the branded “Pane del patto” bread, which is the final product under analysis.
- 1st tier supplier: mill “Molino Tuzzi”. The mill transforms wheat purchased from farmers into flour and distributes it to several customers, including bakery “Panificio Iordan”.
- 2nd tier supplier: farmer “La Fattoria”, producing wheat, which is the main raw material necessary to produce bread and is delivered to the mill “Molino Tuzzi”.

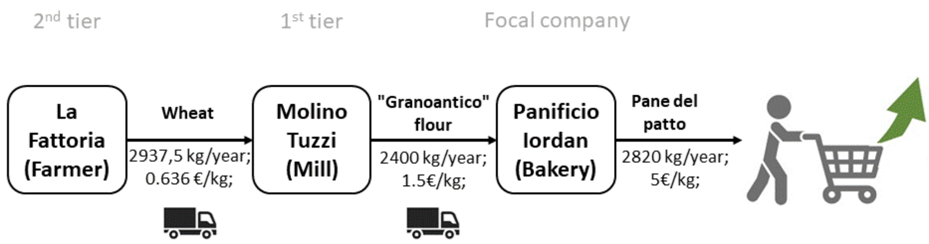

Figure 6.1: "Patto della Farina" supply chain

Following the black box approach identified in the conceptual model, a description of the inputs and outputs of each company part of the supply chain follows in the next section.

6.1.2 Profile of the organisations

6.1.2.1 Second tier supplier: farmer "La Fattoria" (LF)

"La Fattoria" is an agricultural enterprise operating in the "Food products" industry and cultivating soya, several cereals, such as wheat and barley as well as other agricultural products. The company is run according to conservative agriculture principles with "the objective of assuring a sustainable and stable productivity and, at the same time, preserving and strengthening agricultural resources and the environment" (Life HelpSoil Project, 2014). Conservative agriculture is based on three principles, which are: minimum soil disturbance by the processes, permanent covering of the soil surface and crop diversification (Life HelpSoil Project, 2014). "La Fattoria" is one of the twenty farms part of the Life Help Soil project, co-financed by the EU, aiming to demonstrate the feasibility and economic sustainability of conservative agriculture in Northern Italy.

The adoption of conservative agriculture has a number of implications on the environmental performance of the organisation. The minimum soil disturbance involving only minimum tillage has a direct impact on the use of machineries and as a consequence on energy consumption and direct emissions, with an estimated decrease of fuel consumption around 60-70% (Life HelpSoil Project, 2014). Moreover, the irrigation is also decreased and adopted only for selected crops. Finally, also the soil erosion is reduced due to reduced soil movements and constant soil cover (Life HelpSoil Project, 2014), although this environmental aspect is not covered in this work.

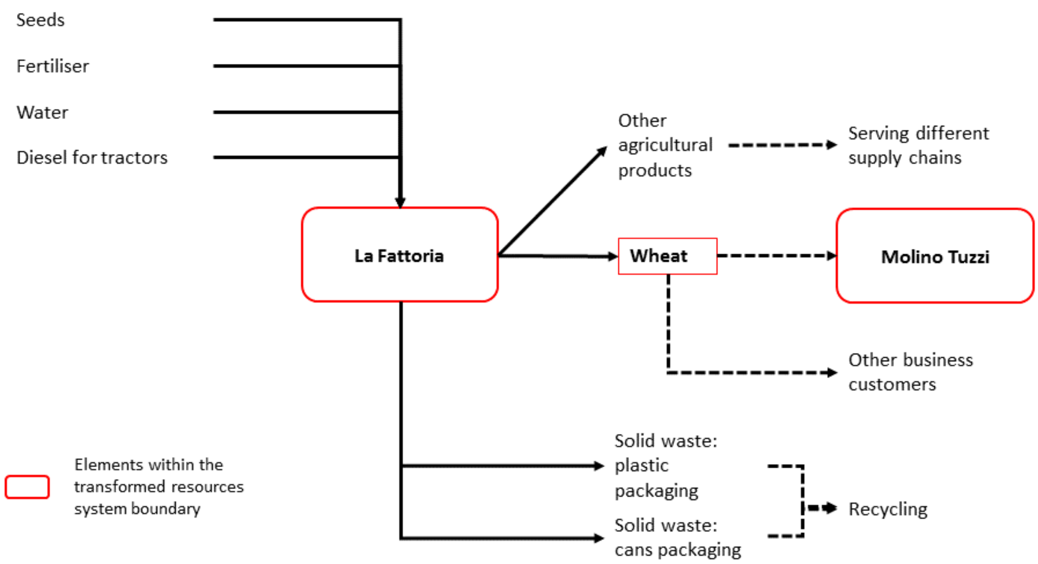

Figure 6.2: "La Fattoria" black box

A synthesised description of inputs and outputs of "La Fattoria" is presented in Figure 6.2. Major physical inputs to the company are seeds of crops and fertilisers which are both resources that reached their usage stage and whose supply chain is thus outside of the scope of analysis of this case study. Other inputs are the machineries required to work the soil and the consumables for the machinery, such as fuel, which are transforming resources for the company. Finally, water for irrigation is also an input of “La Fattoria” despite its usage is limited by the conservative agriculture principles. Physical outputs are the agricultural products and solid waste generated. Solid waste is made by plastic packaging of seeds and cans packaging of fertilisers: both types of waste are sent to recycling. Agricultural products are sold to different business customers and thus serve multiple supply chains, including SC1. Wheat is the only product sold from “La Fattoria” which is part of SC1.

6.1.2.2 First tier supplier: mill “Molino Tuzzi” (MT)

“Molino Tuzzi” is a company operating in the “Food products” industry, whose core business is the transformation of wheat into flour as well as the commercialisation and distribution of flour. On top of the transformation activities, “Molino Tuzzi” purchases flour from different producers to blend it with the internally produced flour and obtain different types of flour to offer to the market. The company operates both in a B2B and B2C contexts, selling its products to a variety of businesses including restaurants, retail shops and bakeries, as well as selling them to final consumers. The “Granoantico” flour which is the variety of flour under analysis in this case study is no exception to the general distribution strategy of the company, as it is sold both to consumers and to businesses. A detailed representation of the inputs and outputs of “Molino Tuzzi” is portrayed in Figure 6.3. By-products are generated from the production activities; however, they are successfully sold on secondary markets. The only waste resulting from the operations of the mill are the paper bags of the incoming flour from different producers, which is sent to recycling.

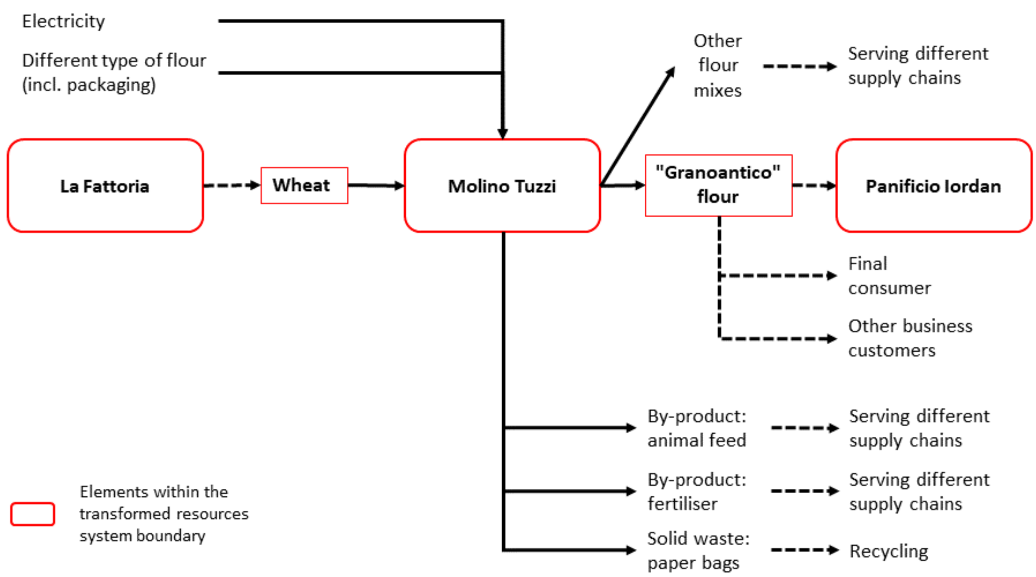

Figure 6.3: “Molino Tuzzi” black box

6.1.2.3 Focal company: bakery "Panificio Iordan" (PI)

"Panificio Iordan" is a company operating in the "Food products" industry, whose core business is the production and distribution of bread, pastry products and other baked products. The bakery provides the conduit to the customer in SC1 as it is selling the product to the final consumer.

The description of inputs and outputs of "Panificio Iordan" is depicted in Figure 6.4. The transformed resources for the product under analysis are wheat, water, sourdough and salt. Wheat and salt are purchased through the upstream supply chain, however a cut-off criterion has been introduced for salt, which is not included in the analysis as it accounts for less than 1% of the weight of the final product. Water is acquired through the public water supply, whereas sourdough is a living organism, which regenerates itself. Other inputs of the company include electricity for the machineries, wood to bake bread in the oven and other food raw products, which are used in the production of various bakery products. The wood-fired oven is not only functional to the activities of the bakery, but, thanks to an innovative system, it also satisfies the entire thermal demand of the organisation.

The physical outputs include several products, including the "Pane del patto" bread, which is the product under analysis, and multiple waste streams. The majority of waste is made by different types of packaging of the raw food products that are purchased by the bakery. Most of them are recycled, however a minority of them is sent to landfill. The only waste that is directed connected to SC1 is the paper packaging of "Granoantico" flour, whereas the remaining wastes are not directly linked to the final product under analysis.

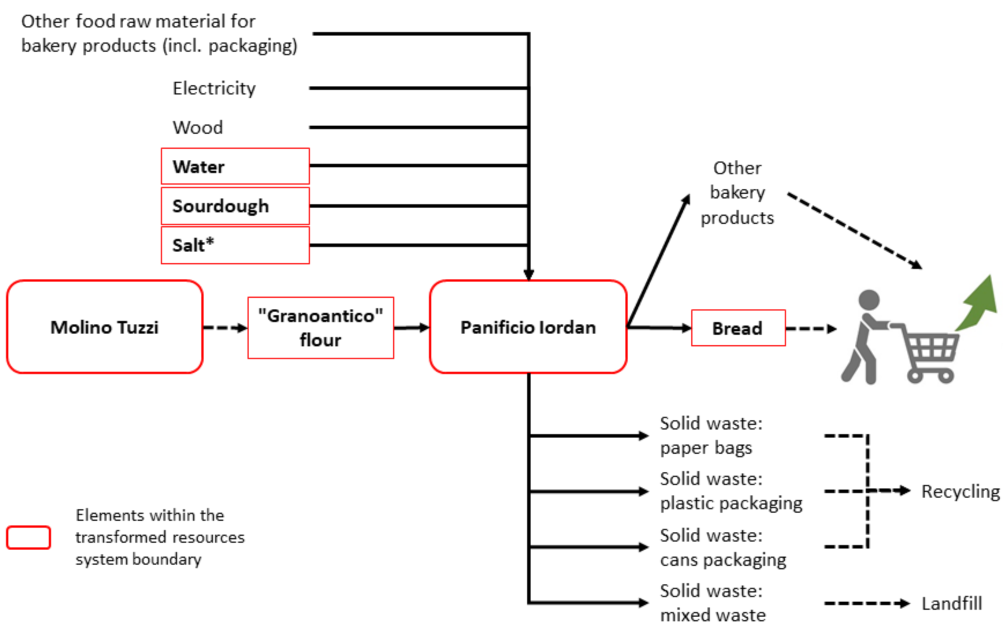

Figure 6.4: "Panificio Iordan" black box

6.1.3 Environmental performance of the supply chain

Five environmental impact areas were selected for CS1, which tackle the most critical areas in terms of environmental impacts according to the managers of the supply chain. The consultation with the managers was also functional to verify requirements of data availability, data accuracy and completeness in the application of the method. The selected impact areas are:

- Land occupation [m^2]: this indicator addresses the surface covered by the premises of the companies part of the supply chain. Land occupied can be dedicated to any use.
- Water consumption [m^3]: this indicator addresses the overall water consumption by the companies part of the supply chain.
- Energy consumption [kWh]: this indicator addresses the overall energy consumption by companies part of the supply chain, including electrical energy, thermal energy and chemical energy (e.g. fuel for machineries).
- GHG emissions [kg CO_2 e]: Scope 1 (direct emissions) and Scope 2 (indirect emissions due to electricity consumption) emissions are included in the analysis. Scope 3 emissions are omitted from the analysis, as the supply chain dimension is addressed by the method developed in this research. CO_2 directly captured by each supply chain member due to their activity (e.g. emissions captured by plants) is not accounted in the analysis. Wood, which is burned at the site of Panificio Iordan to bake bread, is considered a carbon neutral material towards emissions in this work due to the carbon sequestered by wood thanks to its biological regrowth (Sedjo and Tian, 2012).
- Solid waste: this indicator addresses the overall solid waste produced. It appears in two formulations throughout CS1, which are *unweighted* and *weighted*. In the former formulation, it assigns equal weighting to any type of solid waste regardless of its nature and destination, whereas in the latter, it assigns different weighting values to different types of solid waste based on their relative impact on the environment, as detailed in Chapter4. The indicator can be broken down into two mutually exclusive sub-indicators, which provide additional information on the type of waste:
    - Solid waste (recycled) [kg]: this sub-indicator evaluates the overall solid waste produced, which is sent to recycling.
    - Solid waste (non-recycled) [kg]: this sub-indicator evaluates the overall solid waste produced, which is disposed in landfill.

6.1.4 Data collection

Data was collected between September 2017 and December 2017, through dedicated spreadsheets that were handed out to the owners of the organisations during site visits by the researcher. Each member of the supply chain was visited a second time on site to collect the spreadsheet and to double check that data was collected according to the requirements of the study. A number of data required conversion factors either to represent them into the appropriate unit of measurement of the environmental indicators or to align them to the same unit of measurement, as they were reported adopting different units of measurement by different organisations. The CS1 conversion factors are available in Appendix A.5, while the conversion methodological process followed to obtain environmental indicators is available in Appendix A.3. The aggregation of environmental sub-indicators into indicators is available in Appendix A.6. The key information on the organisations part of the supply chain are presented in Table 6.1. These include the environmental profile of the organisations, their key economic indicators and the person contacted to obtain additional information on the supply chain operations. All figures are on a yearly basis and refer to year 2016.

Table 6.1: Profile of the organisations part of CS1 supply chain

Indicator		**LF - 2nd tier supplier**	**MT - 1st tier supplier**	**PI - Focal company**
Land occupation	[m^2]	805,000	368	204
Water consumption	[m^3/year]	4,200	0	366
Energy consumption	[kWh/year]	79,687	3,200	21,887
GHG emissions	[kg CO_2 e/year]	21,317	3,418	23,375
Solid waste	[kg/year]	300	1,950	3,465
Recycled solid waste	*[kg/year]*	*300*	*1,950*	*2,970*
Non-recycled solid waste	*[kg/year]*	*0*	*0*	*495*
Turnover	[€/year]	98,000	123,000	234,894
Supply chain share of turnover	[%]	1.9	2.9	6.0
Contacted person		Owner	Owner	Owner

6.1.5 Results

The three main outputs obtained in CS1 are presented in this section: the eco-intensity indicators at the company level (Table 6.2), the eco-intensity indicators at the supply chain level (Table 6.3) and the environmental impact allocated to final product (Table 6.4), which is calculated starting from the eco-intensity indicators at the supply chain level.

Although companies' core businesses differ, an initial analysis of the values presented in Table 6.2 demonstrates that the 2nd tier supplier "La Fattoria" shows the worst eco-intensity indicator in four out of six environmental impact areas, whereas the 1st tier supplier "Molino Tuzzi" and the focal firm "Panificio Iordan" perform worst in the two indicators tackling solid waste generated. This finding demonstrates the need to adopt a multi-tier approach to assess the environmental performance of the supply chain, as a significant portion of the environmental impact would have been neglected if considering 1st tier supplier only, thus potentially underestimating the supply chain environmental impact. Some companies interestingly score zero impact in certain indicators, such as "Molino Tuzzi" in water consumption and both "La Fattoria" and "Molino Tuzzi" in non-recycled solid waste.

Table 6.2: Single company eco-intensity indicators (CS1)

Eco-intensity indicators		**Eco-intensity performance**		
		2nd tier supplier LF	1st tier supplier MT	Focal company PI
Land occupation	[m^2/€]	8.214	0.003	0.001
Water consumption	[m^3/€]	0.043	0.000	0.002
Energy consumption	[kWh/€]	0.813	0.026	0.093
GHG emissions	[kg CO_2 e/€]	0.218	0.028	0.100
Solid waste – unweighted	[kg/€]	0.003	0.016	0.015
Solid waste – weighted	[kg/€]	0.003	0.016	0.017
Recycled solid waste	*[kg/€]*	*0.003*	*0.016*	*0.013*
Non-recycled solid waste	*[kg/€]*	*0.000*	*0.000*	*0.002*

The supply chain results are listed in Table 6.3. These values represent the eco-intensity of the multi-tier supply chain with respect to each environmental impact and are the main output of the assessment of the supply chain environmental performance. A comparison between the values of different eco-intensity indicators is not meaningful as different units of measurement are used to calculate the environmental numerator of the indicator.

Table 6.3: Supply chain eco-intensity indicators (CS1)

Product: "Pane del Patto" bread	**Supply chain eco-intensity**		**Difference compared to the focal company eco-intensity without environmental backpack**
Land occupation	[m^2/€]	1.086	124,990 %
Water consumption	[m^3/€]	0.007	363 %
Energy consumption	[kWh/€]	0.207	124 %
GHG emissions	[kg CO_2 e/€]	0.136	36 %
Solid waste – unweighted	[kg/€]	0.019	30 %
Solid waste – weighted	[kg/€]	0.021	26 %
Recycled solid waste	*[kg/€]*	*0.017*	*35 %*
Non-recycled solid waste	*[kg/€]*	*0.002*	*0 %*

However, the last column of the table points out the difference between the eco-intensity values at the supply chain level compared to the focal company eco-intensity values omitting the environmental impact from the supply chain, i.e. the environmental backpack. The values demonstrate that the eco-intensity would be significantly underestimated had the supply chain not been considered, potentially misleading managers on the environmental impact areas to tackle. The difference between the values appears particularly relevant in CS1 due to the highest environmental impact being located at the 2nd tier supplier for four environmental categories. The most significant variation is observed for the land occupation eco-intensity indicator due to the impact of the agricultural activities of 2nd tier supplier "La Fattoria". The only indicator that is not affected by adopting a supply chain perspective is the non-recycled solid waste eco-intensity, as only the focal company is responsible for this environmental impact.

Finally, the environmental backpack associated to the product was calculated (Table 6.4). The environmental backpack was calculated both for the entire yearly production of the final product and for one kilogram of "Pane del patto" bread, which is the typical unit the bread is priced at, thus introducing an alternative reference unit for the environmental impact.

Table 6.4: Environmental backpack associated to "pane del patto" (CS1)

Product: Pane del Patto	**Overall environmental backpack per year**		**Environmental backpack per kg of bread**	
Land occupation	[m^2]	15,318	[m^2/kg_{bread}]	5.432
Water consumption	[m^3]	102	[m^3/kg_{bread}]	0.036
Energy consumption	[kWh]	2,941	[kWh/kg_{bread}]	1.043
GHG emissions	[kg CO_2 e]	1,912	[kg CO_2 e/kg_{bread}]	0.678
Solid waste – unweighted	[kg]	270	[kg/kg_{bread}]	0.096
Solid waste - weighted	[kg]	300	[kg/kg_{bread}]	0.106
Recycled solid waste	*[kg]*	*240*	*[kg/kg_{bread}]*	*0.085*
Non-recycled solid waste	*[kg]*	*30*	*[kg/kg_{bread}]*	*0.011*

A quota of the overall energy consumption and GHG emissions is due to the impact of transport (Appendix A.8). However, the contribution of transport towards the overall environmental backpack in CS1 is very limited due to the local sourcing policy of the supply chain, being accountable for only 17 kWh and 4 kg CO_2 e, which represent less than 1% of the overall environmental impact imputable to the supply chain.

Finally, Figure 6.5 details the environmental backpack by identifying the relative contribution of each supply chain member towards the supply chain total. Given the minimal contribution of transportation towards the overall supply chain environmental impact, impacts arising from each transportation link were merged with the impacts of the upstream tier involved in each transportation link in Figure 6.5. It is worth noticing that the relative impact of the further upstream member of the supply chain is mostly due to environmental inputs, whereas environmental outputs dominate the impacts of the focal firm.

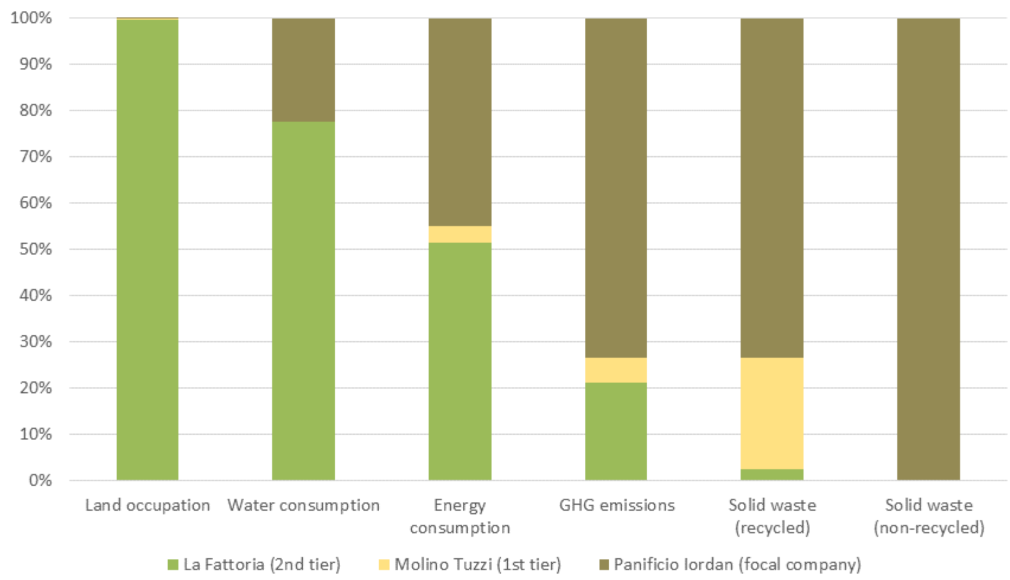

Figure 6.5: CS1 environmental backpack breakdown by supply chain member

6.1.6 Applications for practitioners

The results from CS1 illustrated in Section 6.1.5 offer several applications beneficial to various stakeholders, both external and internal to the supply chain. Based on the matrix of outputs depicted in Chapter 4 and re-called in Figure 6.6, these are presented throughout the following sections.

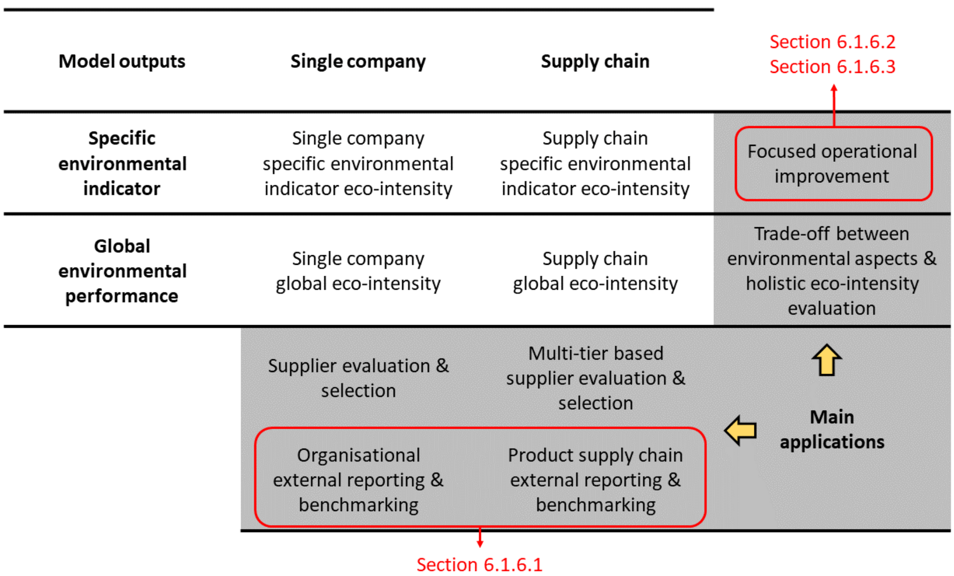

Figure 6.6: CS1 applications of the outputs of the method

The external reporting application is illustrated in Section 6.1.6.1, while the applications internal to the supply chains are outlined in Sections 6.1.6.2 and 6.1.6.3. Section 6.1.6.2 discusses the identification of hotspots to guide focused operational improvement whereas Section 6.1.6.3 discusses the environmental impact of a future planned operational improvement scenario both at the single company level at the 1st tier supplier and at the supply chain level.

6.1.6.1 External reporting

The eco-intensity indicators and environmental backpack per kilogram of bread can be both adopted to better support the marketing strategy of the supply chain, which already has a strong focus on sustainability. Customers are currently paying a premium price to the focal firm to buy “Pane del patto” bread and can be therefore considered green consumers (Borin et al., 2013), as they prefer the product over alternatives from competitors due to the traceability of the raw products and locally sourced ingredients.

The support from quantitative indicators could support the marketing strategy by providing easy-to-understand indicators to the customers that demonstrate the effort of the focal company to measure its environmental impact throughout the supply chain and also create awareness in the customers of the resources consumed and environmental impacts caused by production. A labelling scheme integrating the eco-intensity indicators and the environmental backpack indicators is under development.

Moreover, the benefits of locally sourcing could be stressed in the communication to the customers by highlighting the minimal share of energy consumptions and GHG emissions caused by transport, compared to other bread supply chains.

Finally, the eco-intensity values at the company level could be also adopted by each single organisation part of the supply chain to communicate to relevant stakeholders, including customers of other products, the environmental performance of the organisation.

6.1.6.2 Hotspot identification

The analysis of the values of eco-intensity allows identifying the hotspots along the supply chain. The focal company can compare its internal organisational eco-intensity with the eco-intensity value (including the environmental backpack) that is cascaded by the 1st tier supplier downstream: if the internal figure is greater than the value passed by the supplier, the hotspot is located at the focal company. On the other hand, if the value passed by the supplier is greater than the focal company one, the hotspot is located upstream along the supply chain. The backward mechanism can be iterated moving upstream along the supply chain by the 1st tier supplier until the hotspot is finally identified.

CS1 provides three different examples of positioning of the hotspots, with a different number of iteration stages. Energy consumption eco-intensity hotspot is located at the 2nd tier supplier "La Fattoria" (Figure 6.7), recycled solid waste eco-intensity hotspot at the 1st tier supplier "Molino Tuzzi" (Figure 6.8), whereas non-recycled solid waste eco-intensity hotspot is located at the focal company "Panificio Iordan" (Figure 6.9). The graphical visualisation of the eco-intensity values offers an alternative representation of the eco-intensity performance, which is more user-friendly and can be adopted by the users of the methods alternatively to the numerical outputs. In each figure, companies are represented in a relative colour scale based on their eco-intensity performance. At each iteration, the organisation involved in the process is represented according to its internal eco-intensity without environmental backpack, whereas its suppliers are represented according to their eco-intensity including the environmental backpack associated to their upstream supply chain, which is the actual value that is passed by each supply chain member to the next one. The eco-intensity is recalculated in a similar manner for each subsequent iteration at lower tier levels.

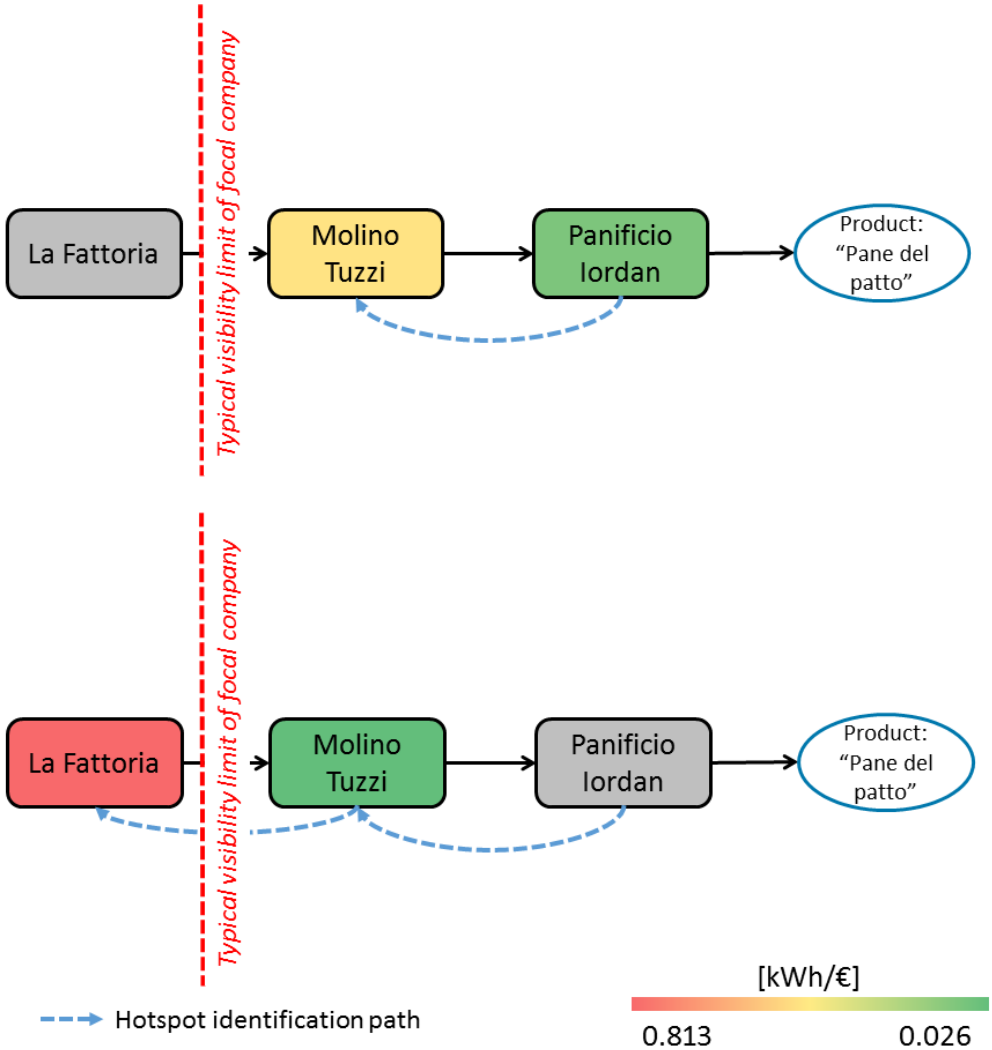

Figure 6.7: CS1 hotspot identification iterations for energy consumption eco-intensity: iteration at the focal company "Panificio Iordan" (a) and iteration at 1st tier supplier "Molino Tuzzi" (b)

Two iterations of the backward mechanism are required to identify the energy consumption eco-intensity hotspot. First, focal company recognises that the eco-intensity indicator passed on by the 1st tier supplier including backpack is greater than the one internally recorded (excluding backpack), meaning that hotspot is found in the supply chain (Figure 6.7a). However, a similar pattern reappears when the 1st tier supplier analyses the value, demonstrating that the hotspot is found at the 2nd tier supplier (Figure 6.7b).

On the other hand, Figure 6.8 illustrates that the backward mechanism stops after one iteration at Molino Tuzzi in the case of recycled solid waste indicator. Panificio Iordan identifies the hotspot is located in the supply chain in the first iteration as in the previous case (Figure 6.8a), however the second iteration at Molino Tuzzi does not proceed the recursive mechanism further upstream as the 1st tier supplier identifies itself as the hotspot for recycled solid waste (Figure 6.8b).

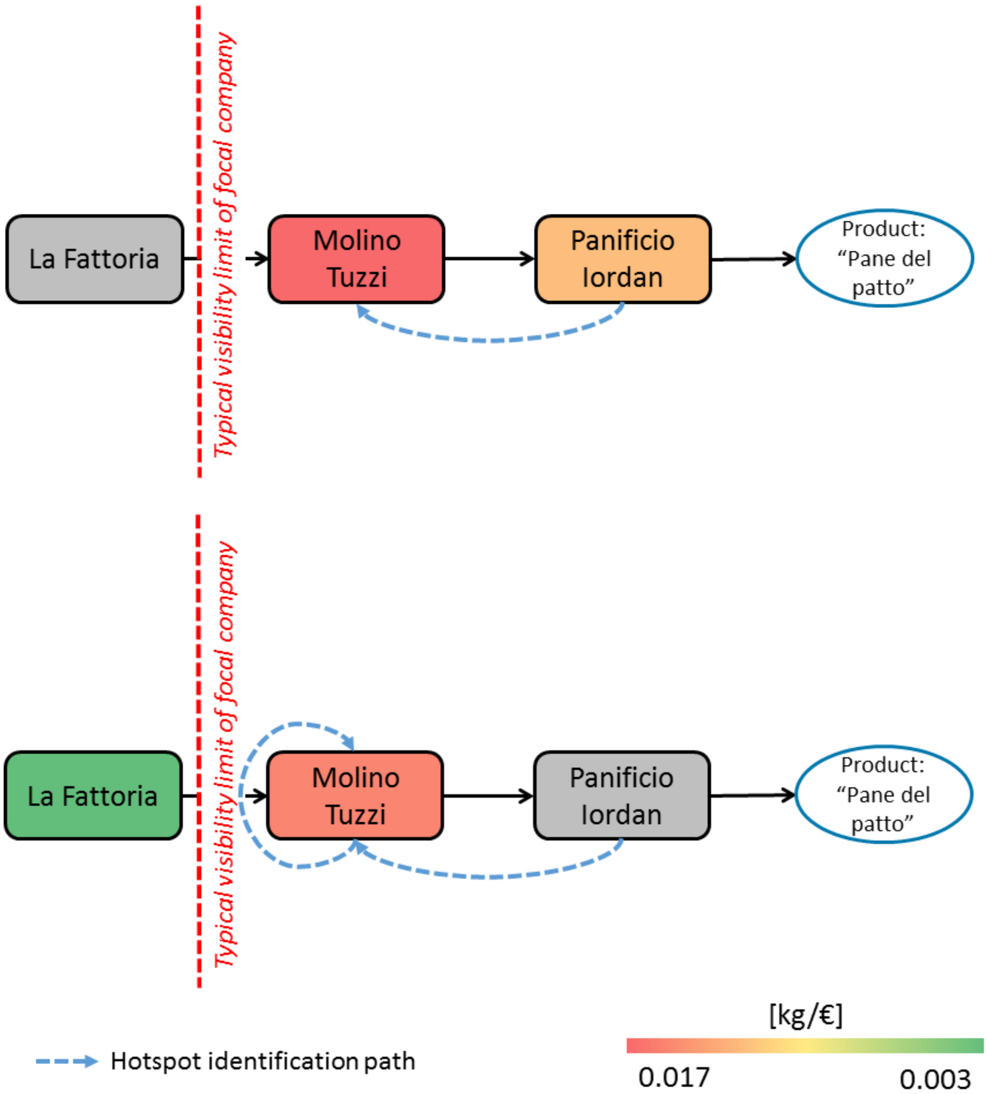

Figure 6.8: CS1 hotspot identification iterations for recycled solid waste eco-intensity: iteration at the focal company "Panificio Iordan" (a) and iteration at 1st tier supplier "Molino Tuzzi" (b)

Finally, the non-recycled solid waste indicator shows that the main hotspot is located downstream in the supply chain and no iteration of the mechanism is required, suggesting that the focal company should act first itself to improve the non-recycled solid waste eco-intensity of the supply chain, as Figure 6.9 shows.

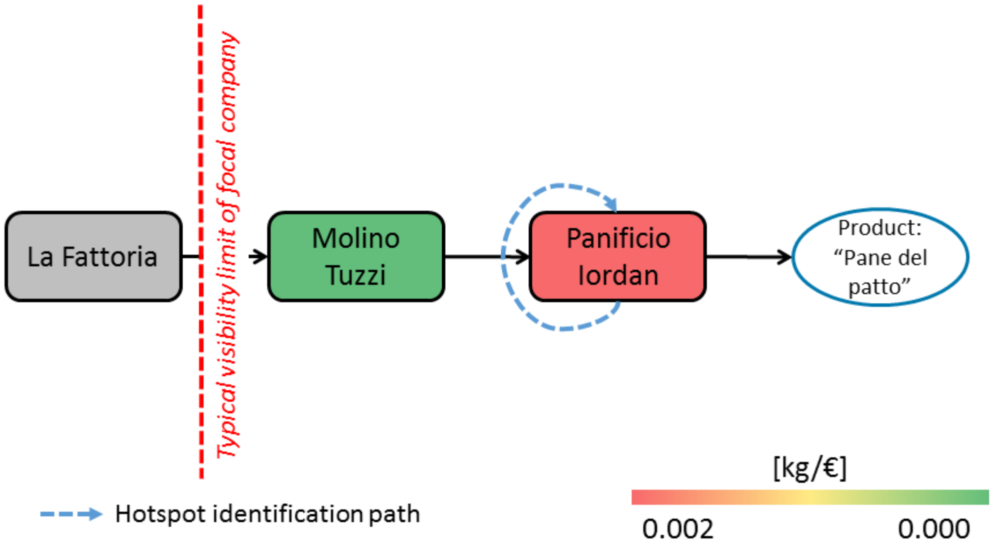

Figure 6.9: CS1 hotspot identification iteration for non-recycled solid waste eco-intensity

The identification of hotspots can be primarily adopted to drive operational improvement, recognising which members of the supply chain show promising room for improvement regarding each environmental indicator and therefore can be tackled with operational improvement plans, which would be beneficial to the entire supply chain.

While Figure 6.7, Figure 6.8 and Figure 6.9 provide explanatory examples of the potential location of hotspots along the supply chain at different tiers, the hotspots were also calculated for the other environmental indicators included in CS1. These are displayed in Figure 6.10, Figure 6.11, Figure 6.12, Figure 6.13 and Figure 6.14. To avoid replicating multiple images to show hotspot identification iterations, information is condensed in such figures. The top line shows the eco-intensity of the organisations as single entities without any contribution of the supply chain, whereas the bottom line shows the eco-intensity of each organisation including the environmental backpack associated to their upstream supply chain, which is the actual value that is passed by each supply chain member to the next one.

Figure 6.11 drew attention to some methodological pitfalls of the method, which is prone to potential underestimation or overestimation of certain environmental impacts due to the specific methodology adopted. Since the assessment of the environmental impacts is performed at the company level and then allocated to products on the basis of their economic value, certain products might carry an environmental quota they are not responsible for.

As an example, this appeared in CS1 in the case of water consumption. The hotspot for water consumption in CS1 is located at the 2nd tier supplier “La Fattoria” that is the most eco-intense organisation for this environmental aspect, as Figure 6.11 highlights. However, the owner of “La Fattoria” revealed during the follow-up site visit that, according to the conservative agriculture techniques, no water is used for the wheat crop, which is the raw material adopted in SC1. The water is used instead for different crops, which are not linked to SC1. Nevertheless, the final water consumption eco-intensity of “La Fattoria” in SC1 is affected from the use of water in crops unrelated to the specific supply chain under analysis, leading to an overestimation of the water consumption eco-intensity associated to the wheat production as well as to the final product as the indicator is cascaded downstream along the supply chain.

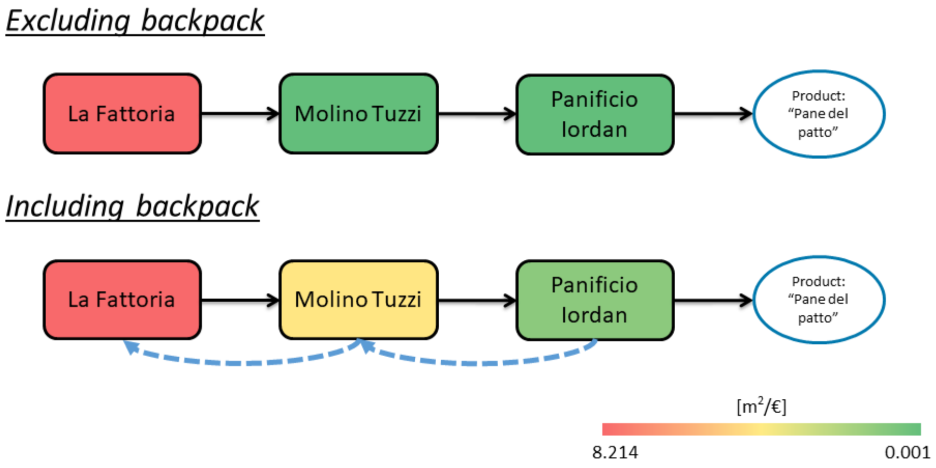

Figure 6.10: CS1 Land occupation hotspot identification

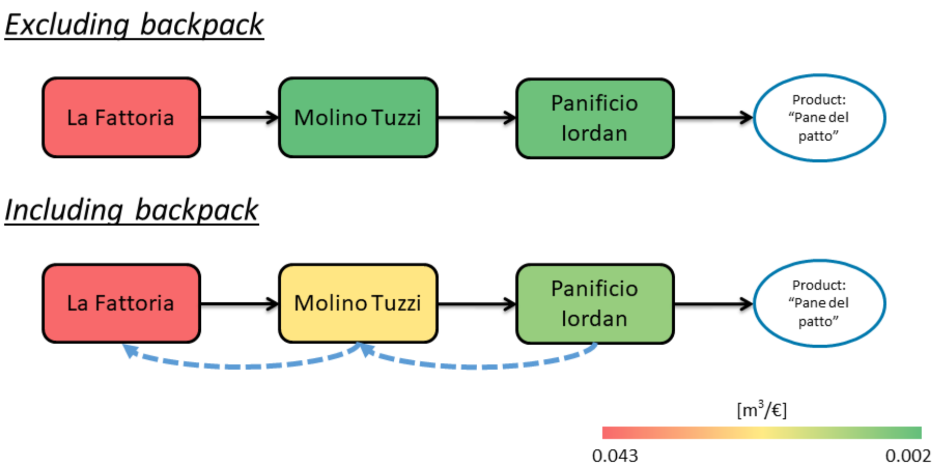

Figure 6.11: CS1 Water consumption hotspot identification

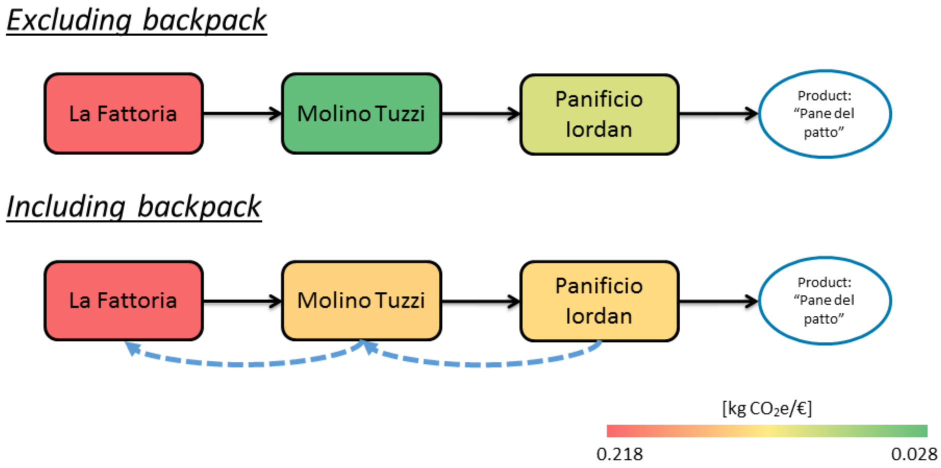

Figure 6.12: CS1 GHG emissions hotspot identification

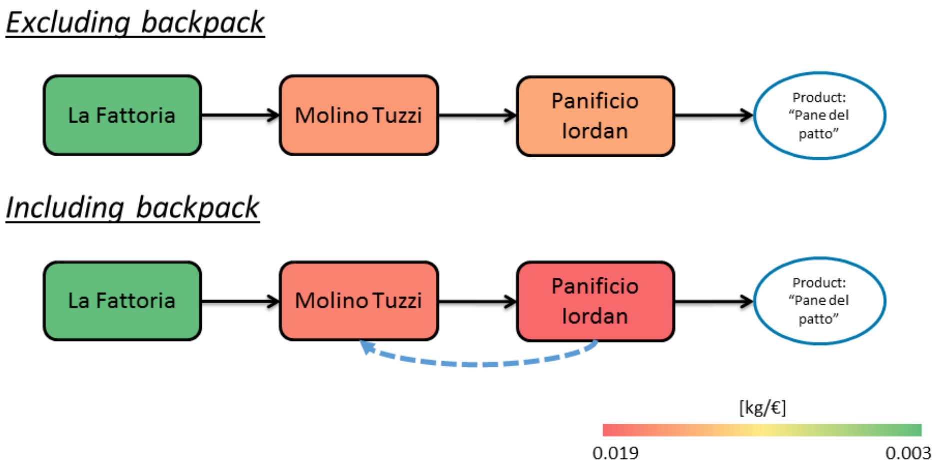

Figure 6.13: CS1 Solid waste (unweighted) hotspot identification

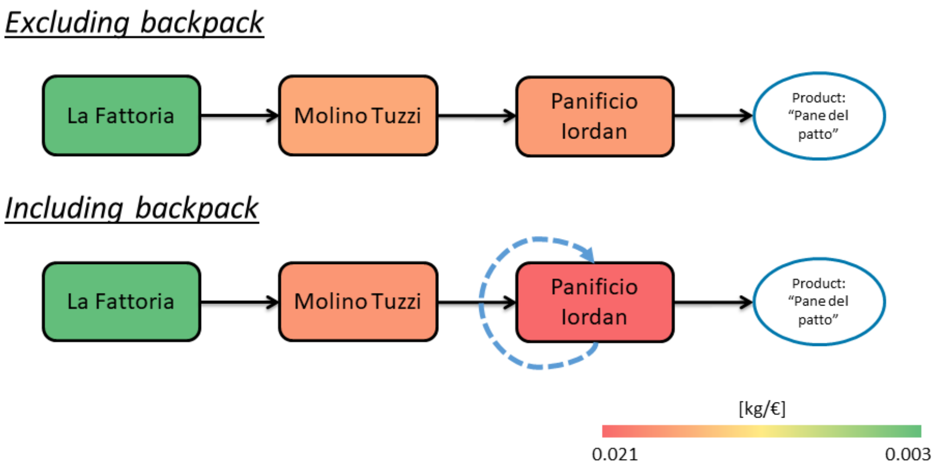

Figure 6.14: CS1 Solid waste (weighted) hotspot identification

6.1.6.3 Organisational improvement and evaluation of future scenarios

Informed by the identification of the hotspots, the method offers guidance in terms of operational improvement. As Figure 6.8 highlighted, the hotspot in terms of recycled solid-waste is located at the 1st tier supplier in CS1, suggesting to take actions to improve the environmental performance at Molino Tuzzi. The method can therefore be adopted to estimate the impact on the environmental performance of operational improvement decisions taken by organisations. Molino Tuzzi identified a potential to reduce its recycled waste eco-intensity by expanding the current flour bin facilities to store incoming flour. According to the complementary information provided by the owner, the operational improvement would allow receiving the flour entirely in batches rather than in paper packaging, transforming the organisation in a zero waste company.

In the current scenario, wheat is shipped to Molino Tuzzi in bulks, whereas the flour received from different producers to offer blended mixes of flour to the customers is currently received in 25kg packages. The paper packaging of the incoming flour causes the full amount of waste generated at the facility of the 1st tier supplier. In the future scenario, also flour would be shipped in bulks to Molino Tuzzi, similarly to wheat, thanks to the additional storage facilities. The effect on the recycled waste eco-intensity at the company level and the supply chain level were studied.

The following assumptions were made to evaluate the future scenario:

- The scenario does not take into account the investment cost to acquire the flour bins, but focuses only on the changes in the eco-intensity changes of the operations of both the organisation and the supply chain.
- Flour purchased by Molino Tuzzi is entirely shipped in bulks by its suppliers and stocked at the site in flour bins;
- Paper packaging is still adopted for flour sold, thus solid waste still exists downstream in the supply chain;
- No changes in any other relevant environmental and economic indicators;

Table 6.5: Flour bin containers operational improvement scenario

Recycled solid waste eco-intensity [kg/€]	Baseline scenario	Future scenario	Δ
Single company (1st tier supplier/Molino Tuzzi)	0.016	0.000	-100.00%
Supply chain	0.017	0.013	-23.53%

As Table 6.5 shows, the recycled solid waste eco-intensity would be null at the 1st tier supplier, Molino Tuzzi. Furthermore, the recycled solid waste eco-intensity indicator would also drop by -23.53% at the supply chain level, demonstrating a significant improvement towards the environmental performance of the supply chain. The significant contribution of

Molino Tuzzi towards the overall supply chain recycled solid waste eco-intensity and environmental backpack, as shown in Figure 6.8 determines this significant reduction at the supply chain level. Table 6.5 also highlights once more the cascade effect that the environmental performance of each tier has on the performance of the entire supply chain.

6.1.7 CS1 applicability evaluation follow-up

CS1 offered some case-specific insights about the applicability of the method in an operating context. CS1 demonstrated the applicability of the method with SMEs, which are typically lagging behind on the path towards sustainability due to limited resources to dedicate to the topic (Yusuf et al., 2013). The organisations part of SC1 are micro enterprises, therefore CS1 demonstrated that the method is applicable to organisations of any size. Moreover, it demonstrated the applicability of the method in a process industry, as in the case of flour production at “Molino Tuzzi”, and with a make-to-stock manufacturing strategy.

6.1.7.1 Validity of the results

Despite the strong focus on environmental sustainability of SC1, every activity regarding sustainability is managed informally within SC1. As a result, no internal evaluation about the validity of the results was applicable to CS1. An alternative to validate the results is the comparison of the results with another case (Ashby, 2014), which was performed in the follow-up of CS1.

A previous study by Kulak et al. (2015) adopting LCA as methodology served the purpose as the reference case. This study was selected due to the almost perfect overlapping in terms of supply chain characteristics, as highlighted in Table 6.6. Both CS1 bread supply chain and the bread supply chain in Kulak et al. (2015) adopt ancient varieties of wheat grains as the main raw material for the supply chain. Moreover, the similarities in the agricultural stage also encapsulate the Mediterranean climate and the rainfall pattern at the farming locations, which are in both cases located in Italy. Milling and baking activities are also identical in CS1 and in Kulak et al. (2015). These activities are performed in the surroundings of the premises of the farm in the reference case, whereas they are carried out in different locations in CS1, although the overall distance travelled by intermediate products is limited to 33 km, as displayed in Appendix A.8. The only significant difference between CS1 and the reference case lies in the different definition of the supply chain system boundaries, as the reference case adopts a cradle-to-consumer system boundary, thus including in the analysis an additional transport link from the downstream tier of the supply chain up to the final consumer.

Table 6.6: Key features of bread supply chains (CS1 and reference case)

	CS1	(Kulak et al., 2015)
System boundaries	Cradle-to-gate	Cradle-to-consumer
Raw material	Ancient variety wheat grains	Ancient variety wheat grains
Milling	Electric mill	Electric stone mill
Baking	Wood-fired oven	Wood-fired oven
Distribution	Bakery	Farm shop

Although the methodology adopted differs significantly, LCA is an established method to assess the environmental impact of products (Beske-Janssen et al., 2015; Finkbeiner, 2016; Low et al., 2015) and thus was considered suitable to evaluate the applicability of the results of CS1. The study by Kulak et al. (2015) adopts midpoint indicators to evaluate the environmental impact of the supply chain, therefore only a subset of the results of CS1 was fit for comparison, as the reference case aggregates certain environmental inputs and outputs in the midpoint indicators according to the LCA methodology. Land occupation and GHG emissions were the only two environmental indicators that appeared both in CS1 and in the reference case, adopting the same unit of measurement. As such, they were adopted to evaluate the applicability of CS1 results. Nevertheless, difference assumptions guided the calculation of GHG emissions, as emissions from wood baking are not considered in CS1 on the grounds of carbon neutrality of wood (Carrano et al., 2015; Sedjo and Tian, 2012; Yue et al., 2014), whereas they are taken into account in Kulak et al. (2015). Since the study by Kulak et al. (2015) uses 1kg of bread as functional unit, the environmental backpack per kg of bread was used for the evaluation of the results.

The comparison of results, as displayed in Table 6.7, demonstrates that land occupation per kg of bread and GHG emissions per kg of bread in CS1 and in the study by Kulak et al.(2015) are within a comparable range, with a difference of 19.66% and 165.48% respectively between CS1 and the reference case. While the land occupation values are directly comparable in the two instances, the difference in the GHG emission values is more pronounced due to the different definition of system boundaries and different assumptions for the calculation of emissions due to wood baking. Aligning the study by Kulak et al. (2015) to CS1 with respect to these aspects, the emissions per kg of bread in Kulak et al., (2015) drop to a calculated value of 0.9, with a difference of 32.74% to CS1, as highlighted by the values in bracket in Table 6.7. Therefore, they belong to the same order of magnitude of CS1, as in the case of land occupation.

The variations in the results between the two studies could be justified by different practices in place at the two supply chains under analysis affecting their environmental profile as well as by the differences in the two methodologies adopted to assess the environmental performance. This finding thus reinforces the validity and applicability of the results as well as the accuracy of the method outputs.

Table 6.7: Comparison of results of CS1 and reference case

Environmental backpack	CS1	(Kulak et al., 2015)	Δ
Land occupation [m^2/kg_{bread}]	5.432	6.5	19.66%
GHG emissions [kg CO_2 e/kg_{bread}]	0.678	1.8 (0.9)	165.48% (32.74%)

6.1.7.2 Applicability of the method

The evaluation of the method aimed to evaluate not only the applicability of the results obtained but also the applicability of the method in order to identify the key enablers for a successful implementation of the method in an operating supply chain without the support of the researcher. A list of enablers (E), based on the work of Dou et al. (2017), was presented to the owner of FC1 to direct the discussion through a semi-structured interview. The influence of enablers on the applicability of the method in an operating context was evaluated adopting a linguistic scale to assess each enabler (Dou et al., 2017), as summarised in Table 6.8.

Table 6.8: Influence of enablers on the applicability of the method in an operating supply chain (FC1 owner)

	Enabler (E)	No influence	Very low influence	Low influence	High influence	Very high influence
E1	Trust between a focal company and the first-tier suppliers					✓
E2	Trust between the first-tier supplier and the second-tier supplier					✓
E3	A focal company has buyer power over the first-tier suppliers		✓			
E4	The first-tier supplier have buyer power over the second-tier suppliers		✓			
E5	The first-tier and second-tier suppliers are long-time committed partners				✓	

	Enabler (E)	No influence	Very low influence	Low influence	High influence	Very high influence
E6	A focal company deeply understands its supply chain			✓		
E7	First-tier suppliers are willing to share second-tier suppliers' information with the focal company				✓	
E8	A focal company is willing to provide necessary human resource support			✓		
E9	Risk of supplier-by-passing	✓				
E10	Lower-tier suppliers have capabilities of meeting a focal company's requirements				✓	
E11	Supply chain members are geographically close to each other					✓
E12	Top managers' committed support from a focal company				✓	

The owner from FC1 identified E1 "Trust between a focal company and the first-tier suppliers" and E2 "Trust between the first-tier supplier and the second-tier supplier" as the most important ones along with E11 "Supply chain members are geographically close to each other". All these enablers were awarded a "very high influence". Both E1 and E2 enablers are relationship-centred and are considered extremely important towards the implementation of the method as sensitive data is passed along the supply chain tiers and trust between contiguous members of the supply chain is considered essential to be guaranteed about an appropriate use of the data. This was highlighted as being highly critical in the specific context of Italian food sector, where final consumers highly value the origin of the purchased food. Moreover, owner of FC1 stressed that sustainability is a collective effort, which requires the collaboration of various actors in the supply chain, including final consumers, and trust is thus a necessary element to achieve successful results in the collaborative effort to achieve sustainability. Finally, the geographical location (E11) was also considered of high importance to the wider sustainability-context as it allows maintaining a higher visibility of the supply chain, which is considered a key aspect to trace the origin of raw products in a food supply chain. The close location is considered also to be functional to sustain informal business relations between small enterprises and to facilitate the exchange of relevant environmental information between organisations. This ultimately contributes to the application of the method, as there is no legal obligation for organisations to collect and share along the supply chain such environmental information at the current stage.

A number of enablers were identified as having a high influence towards the applicability of the method in an operating supply chain. These include E5, E7, E10, and E12. Owner of FC1 considered E5 and E7 directly linked to the trust element, being a subset of the main trust enabler. A long-lasting business relationship was considered beneficial to build the necessary trust to engage in a method to assess the environmental sustainability of the entire supply chain and to successfully implement the recursive mechanism along the supply chain. Long-lasting and trustful relationships across each dyad in the supply chain were thus considered functional to share data of lower tiers downstream along the supply chain. This is also valid for the specific case of first-tier suppliers, therefore also E7 was given a “high influence” to apply successfully the method, as the recursive mechanism would be otherwise affected and method would not be to capture the environmental performance of lower tiers. Consequently, E10 was also considered having a “high influence” towards the applicability of the method while being evaluated potentially a critical one at the same time. Availability of data in lower tiers, i.e. agricultural enterprises in food supply chains, was considered potentially challenging in certain contexts where organisations are still managed informally without management systems or data tracking into place. Finally, owner of FC1 awarded “high influence” to E12 as well. The owner stated that environmental sustainability is secondary to economic sustainability in the current competitive scenario, therefore choosing to invest time and resources on the environmental dimension is only successful when companies keep the environment at the heart of their vision. In the view of the owner of FC1, the application of the method can stem only from such a vision and top management support is a necessary element to move from theory to practice. Moreover, the owner also added that this enabler is highly influential in SMEs where all key decisions are usually taken by the owner of the organisation or by a limited set of managers. As a result, securing the support from the head of the organisation is critical to apply the method.

Owner of FC1 evaluated E6 and E8 as having “low influence” towards the applicability of the method. A deep understanding of the supply chain by the focal company was not considered critical given the indirect approach offered by the method, which allows maintaining business relations only with first tier suppliers. The human resource support by focal company was also not considered being necessary towards the applicability of the method, given the accessible format of data collection, enabling also SMEs to apply the method without any external support.

Two enablers, E3 and E4, were both awarded a “Very low influence” according to the owner of FC1. It was emphasized that the trust-centric relationship approach in the supply chain is of greater importance compared to the relative power aspects. The owner of FC1 further elaborated that power-aspects might enter the picture when there is a considerable size difference between organisations, e.g. large multinational groups are part of the supply chain, but they are secondary to trust when companies of comparable size are part of the supply chain.

Finally, E9 “Risk of supplier-by-passing” was the single enabler awarded “no influence” according to the owner of FC1 as the method adopts a recursive mechanism and thus does not put focal companies directly in contact with lower tier suppliers. Moreover, the growing specialisation of companies on determined activities protects from this risk regardless the method is applied or not.

The evaluation of the applicability of the method completed CS1. The evaluation was particularly relevant to investigate the applicability of the method in the specific context of a supply chain entirely built by micro enterprises and to obtain insights on the applicability of the method in SMEs. With this respect, the evaluation highlighted certain enablers, such as E11 “Supply chain members are geographically close to each other”, E10 “Lower-tier suppliers have capabilities of meeting a focal company's requirements” and E12 “Top managers’ committed support from a focal company”, which appeared to be particularly critical towards a successful implementation of the method specifically in a SMEs context, as clearly identified by the owner of FC1.

6.2 Case study 2 (CS2)

6.2.1 Case study 2 overview

Supply chain 2 (SC2) is a non-collaborative international supply chain operating in the “Machinery” industry, according to the GICS classification (MSCI, 2015), and an engine is the final product delivered to the customer. SC2 operates in a B2B environment, delivering the product to several customers worldwide.

The three-tier supply chain is depicted in Figure 6.16 and in Figure 6.17. The figures provide different types of information: Figure 6.16 illustrates the supply chain links based on monetary flow and indicates the yearly quantities produced and the unitary prices of the intermediate products and the final product. On the other hand, Figure 6.17 captures the material flow along the supply chain, providing information about the intermediate products moved between the supply chain members as well as on the selected means of transport, which is truck for every supply chain link. Finally, the boxes representing the organisations in both figures detail which is the core activity of each organisation within the supply chain. Due to the request of the focal company (FC2) for the supply chain members to remain anonymous for commercial confidentiality purposes, the real name of the organisations will be omitted and anonymised through a coding system.

Each organisation was assigned a multi-level unique code based on a hierarchical tree designed according to the material flow supply chain, as illustrated in Figure 6.15. The focal company, which is labelled as company FC2 (or simply 2), is the root of the tree, while suppliers and sub-suppliers represent the children of the tree. The number of subsequent levels in the code represent the tier each organisation belongs to according to the material flow. As an example, 2.3 is a 1st tier supplier as only one level follows the code identifying the focal company, while 2.3.1 is a 2nd tier supplier as two levels follow the identifier of FC2. The coding system also provides information about the material path, as the code of 2nd tier supplier is obtained by adding a level to the code of its direct customer, which is the 1st tier supplier of the focal company. Therefore, the customer of each supplier in the tree can be recognised by removing the last level from the code; as an example, 2.3 can be immediately be recognised as the customer of supplier 2.3.1, while FC2 is the customer of supplier 2.3. Finally, the last digit of each code distinguishes organisations contributing to the same material path creating a unique code per each organisation, as in the case of parallel suppliers 2.2.1 and 2.2.2.

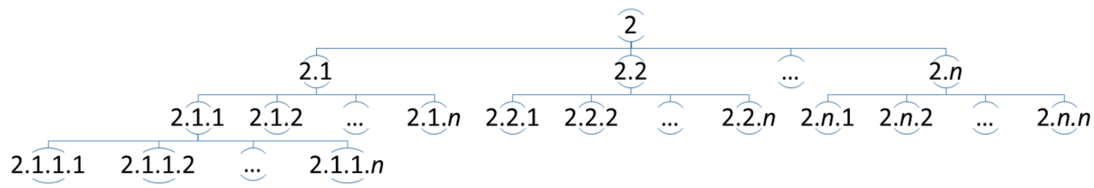

Figure 6.15: Coding system hierarchical tree

The visual comparison of the Figure 6.16 and Figure 6.17 highlights a different positioning specifically in the case of companies 2.2.1 and 2.2.2. While from the monetary flow point of view they account as 1st tier suppliers, they are considered 2nd tier suppliers from a material flow point of view. The reason for this misalignment lies in the fact that company 2.2 is actually an outsourcer for FC2. Therefore, FC2 has direct business relations with 2.2, 2.2.1 and 2.2.2 and the payments take place directly from FC2 to each of these organisations. However, the material is shipped from suppliers 2.2.1 and 2.2.2 directly to 2.2 in order to optimise the logistics and minimise the distance travelled by intermediate products. Regardless of this misalignment, the presence of supplier 2.3.1 defines the multi-tier structure of the supply chain even from the monetary flow perspective. Finally, supplier 2.3.1 along with supplier 2.3 appears twice in Figure 6.16 to stress that two intermediate products with different prices flow from 2.3.1 to 2.3 and from 2.3 to FC2.

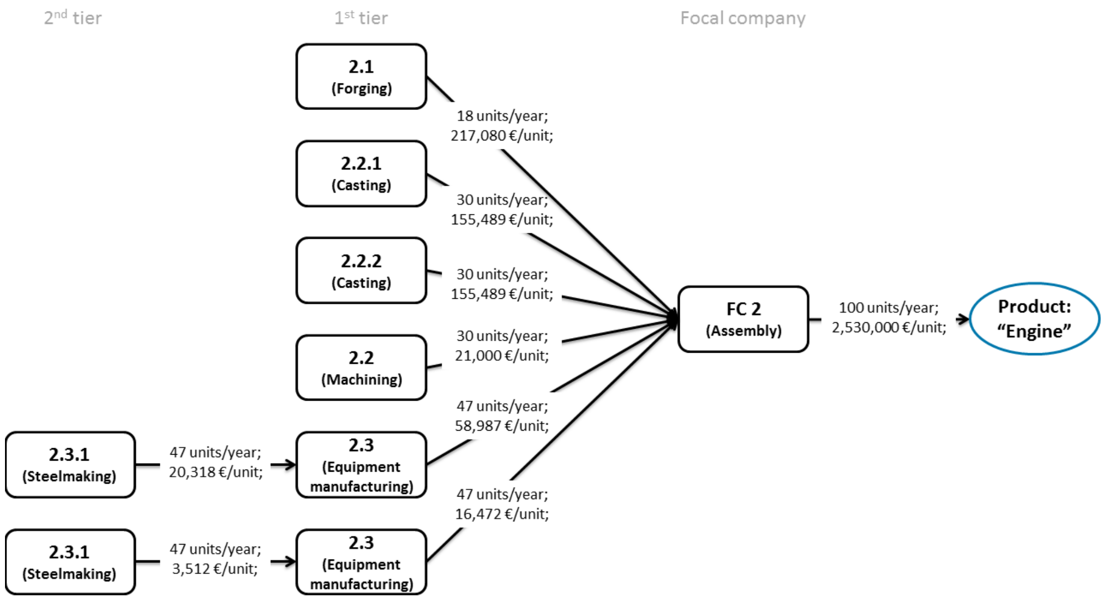

Figure 6.16: CS2 supply chain – monetary flow

Overall, seven organisations across three tiers built up the supply chain. Initially, an eighth company was involved in CS2 but later dropped out of the study due to the unwillingness to share environmental data with the 1st tier supplier and the focal company.

- Focal company: FC2. The core business of the organisation is the production of engines and post-sale servicing of engines, which are used both for fixed and mobile applications. The company assembles the components obtained from its suppliers and produces the final product, which is the engine.
- 1st tier suppliers:
  - 2.1: the core business of the organisation is the manufacturing of forged steel products. The company produces the crank shaft for the engine.
  - 2.2: the organisation is specialised in subcontracting machining services, with a special focus on heavy-duty precision machining; the company acts as an outsourcer in the supply chain, receiving the engine block from suppliers 2.2.1 and 2.2.2 and machining the engine block. The machined engine block is then transported to FC2.
  - 2.3: the company is specialised in heavy equipment and steel fabrications; it contributes to SC2 by producing the engine frame and the wet sump for the engine that are then shipped to FC2.
  - 2.2.1: the core business of the organisation is casting; it produces the engine block for the final product. The engine block does not reach directly FC2 but is moved first to 2.2 for machining.
  - 2.2.2: the core business of the organisation is casting; it produces the engine block for the final product. The engine block does not reach directly FC2 but is moved first to 2.2 for the machining.

- 2nd tier supplier: 2.3.1 is a steel company that is specialised in processing raw materials to steel. The steel plate engine frame and the steel plate oil sump are produced by 2.3.1 and then sold to organisation 2.3.

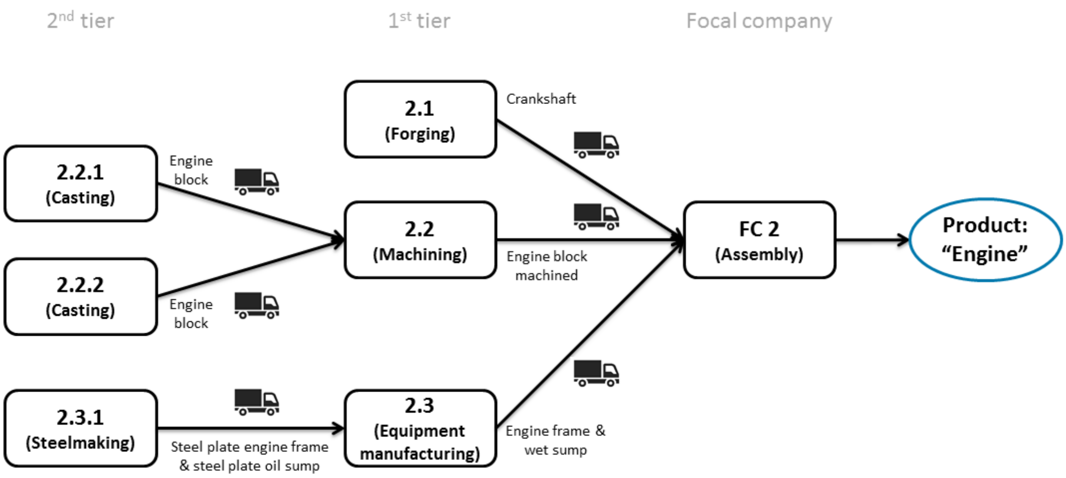

Figure 6.17: CS2 supply chain - material flow

According to the European Union enterprises classification, the focal company could be defined as a large enterprise (European Union, 2003), as it employs more than 250 people and its annual turnover exceeds EUR 50 million. The majority of the organisations part of the supply chain (2.1, 2.2.1, 2.2.2, 2.3.1) can be clustered as large organisations too, based on the EU classification, while organisation 2.3 can be defined as a medium enterprise, since its turnover ranges between EUR 10 and 50 million. Finally, company 2.2 is a small enterprise, having a turnover lower than EUR 10 million.

Given the complexity of the final product, which includes around 1,000 components sourced from 350 core 1st tier suppliers, this research, in accordance with the supply chain manager of FC2, decided to focus on a critical sub-system of the engine, which accounts for one third of its overall final value. While this does not allow generalisation about the overall supply chain environmental performance of the full product, it guarantees an adequate coverage of a significant share of the final product and some of its most critical component supply chain, including some critical manufacturing processes from an environmental perspective as identified by the supply chain manager of FC2. Moreover, the considered sub-system accounts also for one third of the final product weight, which gives some significant information in terms of the environmental impact of transport, which is assumed in this research to be linear with the weight and the distance travelled (Marcus Brandenburg, 2015). The decision to focus on a specific sub-system of the final product combined with a partial accessibility to the upstream supply chain for the selected sub-system required some adjustment of raw data obtained from companies in order to achieve a meaningful implementation of the method, as detailed in Section 6.2.2.

6.2.2 Assumptions and data processing for CS2

CS2 required some case-specific data processing to implement the environmental performance assessment method correctly. These adjustments were required for two reasons:

- The supply chain of a sub-system of the final product is assessed: the economic data of the focal company need to be processed to take this into account in order to avoid an over-allocation of the focal company's environmental impact to the product supply chain under analysis in CS2;
- Incomplete upstream supply chain availability for the sub-system: FC2 adopts a parallel-suppliers or multiple-suppliers' procurement strategy, therefore alternative suppliers are adopted for the same intermediate products. Only for the engine block intermediate product it was possible to access data of two alternative suppliers, whereas for all other intermediate products a single supplier was selected for the study. Since all intermediate products in the part of SC2 under analysis are supplied to the focal firm in a 1:1 ratio to the final product according to the bill of materials, adopting raw data without any further adjustment would have led to a misalignment between different supply chain members due to different quantities of intermediate products produced.

The following paragraphs elaborate the process followed to adjust raw data received from FC2 about organisations part of SC2 in order to remove any bias arising from different absolute values in units produced at different organisations and therefore enhance the robustness of CS2 results.

Sub-system of the final product

Since CS2 focused only on the supply chain of a sub-system of the final product, which accounts for one third of its value and of its weight, it was necessary to divide the monetary values provided by the focal company by a factor of 3, according to equation 6.1.

$$T_{FC2-\text{"}Engine\text{"}}\,(CS2) = \frac{T_{FC2-\text{"}Engine\text{"}}}{3} \tag{6.1}$$

100-units reference base

Figure 6.16 detailed the yearly quantities and the unitary prices of the intermediate products and the final product of SC2. Although all intermediate products throughout the supply chain are supplied in a 1:1 ratio to the final product, it is evident from the figure that the yearly quantities differ among the different supply chain links. FC2 produced yearly 100 units of the "Engine", while its 1st tier suppliers shipped to FC2 during the same time period intermediate products in the range of 18 (2.1 to FC2) to 47 units (2.3 to FC2). This means that the suppliers analysed in CS2 do not cover the yearly demand of intermediate products by the focal company. As FC2 adopts a parallel-suppliers or multiple-suppliers strategy, this work did not capture information about all alternative suppliers, focusing on a subset of them. This, combined with the different values of units shipped from 1st tier suppliers to FC2, urged the development of a fictitious supply chain along the real supply chain depicted in Figure 6.16 and Figure 6.17 in order to work on a common 100-units reference base across the entire supply chain. The development of a supply chain with a common reference base enables to obtain results that are not affected by the yearly quantities produced and facilitates comparisons across different supply chain members.

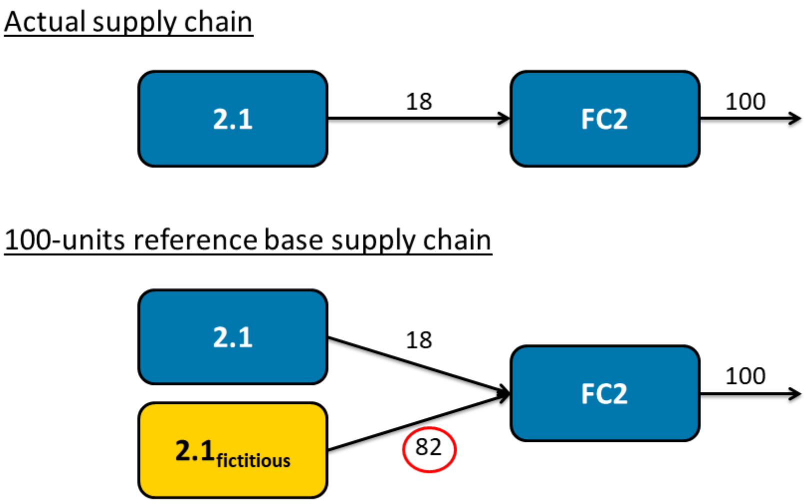

Figure 6.18: Building the 100-units reference base supply chain

The 100-units reference base was selected, as this is the yearly production of the final product by FC2. The 100-units reference base supply chain was built through system expansion (Bloemhof and Walther, 2016), which allows maintaining the relative performance of each supply chain member unchanged and does not affect the recursive mechanism logic whenever the quantities produced at different supply chain tiers are different.

System expansion is realised by adding a fictitious supply chain member to cover the remaining amount of supply of the intermediate products. As an example, supplier 2.1 ships 18 crankshaft units to FC2, therefore supplier $2.1_{fictitious}$ is introduced to cover the remaining 82 crankshaft units necessary to produce 100 units of the final product, as showed in Figure 6.18. The features of supplier $2.1_{fictitious}$ are proportionally linear to those of supplier 2.1, both in terms of environmental performance and economic performance, as shown in Equations 6.2 and 6.3, where u is the number of yearly units produced by the actual supply chain member i. Same applies to transport (Equation 6.4), as the weight is assumed linearly proportional with the units and the distance is assumed to be the same in the actual and in the fictitious supply chain, both in the case that supplier and customer of each dyad are fictitious and in the case where only one of the two organisations is fictitious whereas the other is an actual one.

$$EP_{ei-fictitious}\,(CS2) = \frac{EP_{ei}}{u}\,(100 - u) \tag{6.2}$$

$$T_{i-fictitious}\ (CS2) = \frac{T_i}{u}\ (100 - u) \tag{6.3}$$

$$EP^{tr}_{e\ j-fictitious\ i-fictitious} = \frac{EP^{tr}_{eji}}{u}\ (100 - u) \tag{6.4}$$

Once the process was concluded, the 100-units reference base supply chain was complete, (Figure 6.19). Rectangles in blue colour represent the actual supply chain members, whereas the yellow rectangles represent the fictitious supply chain members. The numbers next to each arrow represent the units of intermediate products moved within each dyad in the developed supply chain.

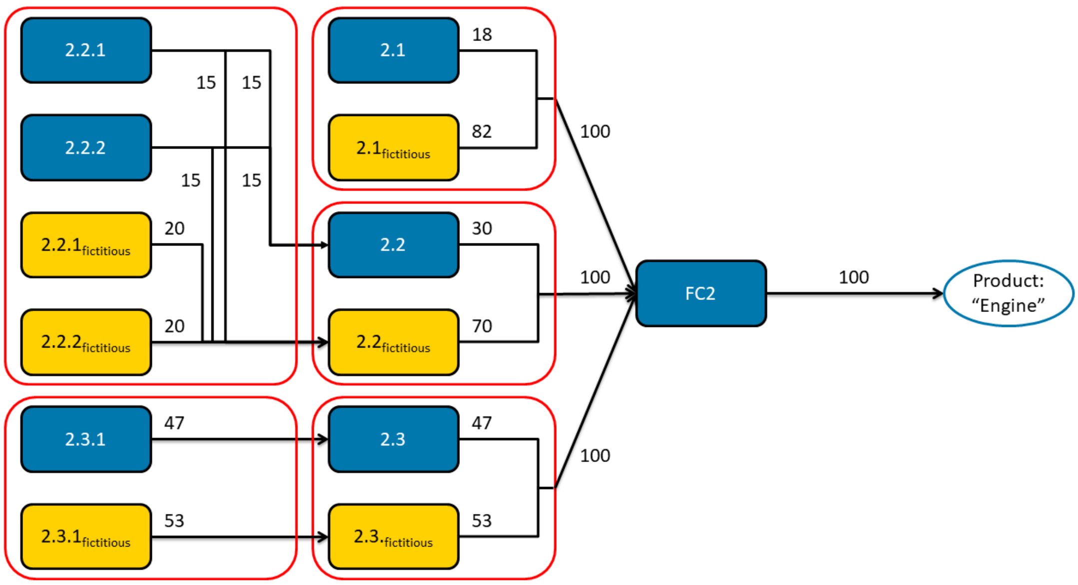

Figure 6.19: CS2 adjusted supply chain including fictitious organisations

6.2.3 Environmental performance of the supply chain

Six environmental impact areas were selected for CS2, which tackle the most critical areas in terms of environmental impacts according to the manager of FC2. The consultation with the managers was also functional to verify requirements of data availability, data accuracy and completeness in the application of the model. The selected impact areas are:

- Material consumption [kg]: this indicator addresses the overall consumption of materials. It appears in two formulations thorughout CS2, which are *unweighted* and *weighted*. In the former formulation, it assigns equal weighting to any type of material consumption whereas in the latter, it assigns different weighting values to different types of material consumption based on their relative impact on the environment, as detailed in Chapter 4. This indicator can be broken down into three mutually exclusive sub-indicators, which provide additional information on the type of material consumption:

- Material consumption (recycled) [kg]: this sub-indicator addresses the overall consumption of materials, which are the outcome of recycling activities and, while originating from a reverse supply chain, are inserted again into a forward supply chain. These resources, either biotic or abiotic, are not directly withdrawn from the natural environment and thus do not contribute to the overall depletion of the natural capital.
    - Material consumption (renewable) [kg]: this sub-indicator addresses the overall consumption of materials that are regenerated by themselves. This sub-indicator includes consumption of raw materials only and does not include components or semi-assembled products.
    - Material consumption (non-renewable) [kg]: this sub-indicator addresses the overall consumption of materials that are not regenerated by themselves. This sub-indicator includes consumption of raw materials only and does not include components or semi-assembled products.
- Land occupation [m^2]: this indicator addresses the surface covered by the premises of the companies part of the supply chain. Land occupied can be dedicated to any use.
- Water consumption [m^3]: this indicator addresses the overall water consumption by the companies part of the supply chain.
- Energy consumption [kWh]: this indicator addresses the overall energy consumption by companies part of the supply chain, including electrical energy, thermal energy and chemical energy (e.g. fuel for machineries).
- GHG emissions [kg CO_2 e]: Scope 1 (direct emissions) and Scope 2 (indirect emissions due to electricity consumption) emissions are included in the analysis. Scope 3 emissions are omitted from the analysis, as the supply chain dimension is addressed by the method developed in this research. CO_2 captured by each supply chain member due to their activity (e.g. emissions captured by plants) is not accounted in the analysis.
- Solid waste [kg]: this indicator addresses the overall solid waste produced. It appears in two formulations throughout CS2, which are *unweighted* and *weighted*. In the former formulation, it assigns equal weighting to any type of solid waste regardless of its nature and destination, whereas in the latter, it assigns different weighting values to different types of solid waste based on their relative impact on the environment, as detailed in Chapter 4. The indicator can be broken down into three mutually exclusive sub-indicators, which provide additional information on the type of waste:
    - Solid waste (recycled) [kg]: this sub-indicator evaluates the overall solid waste produced, which is sent to recycling.
    - Solid waste (non-recycled) [kg]: this sub-indicator evaluates the overall solid waste produced, which is disposed in landfill.
    - Solid waste (hazardous) [kg]: this sub-indicator evaluates the overall solid waste produced, which is labelled as hazardous according to the existing legislation.

6.2.4 Data collection

Data was collected between April 2018 and September 2018. As detailed in Chapter 5, FC2 was the only point of contact for the researcher in CS2. A standardised spreadsheet for data collection was sent to FC2. The focal company then forwarded the spreadsheet to 1st tier suppliers that subsequently reached out the 2nd tier suppliers, passing the environmental pressure information upstream along the chain. Since the majority of the organisations part of the supply chain have a developed organisational structure, it was environmental managers of the companies that mostly filled in the spreadsheets.

Although a standardised spreadsheet was provided to organisations of SC2, companies were given the option to edit the unit of measurement of the environmental indicators to facilitate the data collection process based on the data availability at each organisation. Therefore, a number of data still required conversion factors either to represent them into the appropriate unit of measurement of the environmental indicators or to align them to the same unit of measurement, as they were reported adopting different units of measurement by different organisations. The conversion factors are available in Appendix A.5, while the CS2-specific conversion methodological process followed to obtain environmental indicators is available in Appendix A.4. The aggregation of environmental sub-indicators into indicators is available in Appendix A.7. The key environmental information on the organisations part of the supply chain are presented in Table 6.9, while the key economic indicators are presented in Table 6.10. All figures are on a yearly basis and refer to year 2017.

It is worth noticing that the share of turnover generated by SC2 for FC2 refers to the entire product “Engine”, while only a sub-system of the product is analysed in CS2. This value thus required further adjustment to take this aspect into consideration, as detailed in Section 6.2.2. Other values in the same row do not require any further adjustment as the turnover generated by intermediate products are fully allottable to the supply chain of the sub-system of the product under analysis.

Table 6.9: Environmental profile of the organisations part of CS2 supply chain

Indicator		**2.1**	**2.2.1**	**2.2.2**	**2.2**	**2.3.1**	**2.3**	**FC2**
Material consumption	[kg/year]	1,323,042,000	67,950,000	910,000	0	5,069,610,066	8,979,000	28,229,381
Recycled material consumption	*[kg/year]*	*1,323,000,000*	*40,100,000*	*0*	*0*	*83,100,000*	*8,305,575*	*0*
Renewable material consumption	*[kg/year]*	*0*	*10,050,000*	*0*	*0*	*0*	*0*	*75,513*
Non-renewable material consumption	*[kg/year]*	*42,000*	*17,800,000*	*910,000*	*0*	*4,986,510,066*	*673,425*	*28,153,868*
Land occupation	[m^2]	2,700,000	110,000	36,000	9,700	5,300,000	88,000	560,000
Water consumption	[m^3/year]	1,200,000	75,000	16,500	1,891	170,820,000	8,501	351,942
Energy consumption	[kWh/year]	1,401,012,478	67,283,347	32,422,441	1,458,499	545,172,370	11,507,136	135,600,198
GHG emissions	[kg CO_2 e/year]	1,582,215,984	67,264,431	33,405,355	1,344,618	247,984,241	6,083,986	48,957,066
Solid waste	[kg/year]	195,000,000	28,572	1,860,000	540,976	108,728,000	2,645,284	993,283,222
Recycled solid waste	*[kg/year]*	*175,000,000*	*20,962*	*60,000*	*539,000*	*2,115,000*	*2,543,506*	*5,675,781*
Non-recycled solid waste	*[kg/year]*	*0*	*3,520*	*0*	*1,526*	*105,143,000*	*44,620*	*985,382,023*
Hazardous solid waste	*[kg/year]*	*20,000,000*	*4,090*	*1,800,000*	*450*	*1,470,000*	*57,158*	*2,225,418*

Table 6.10: Economic profile of the organisations part of CS2 supply chain

Indicator	2.1	2.2.1	2.2.2	2.2	2.3.1	2.3	FC2
Turnover [€/year]	509,834,500	75,000,000	30,000,000	8,325,000	348,400,000	17,670,000	346,575,342
Share of turnover generated by SC2 [%]	0.8 %	6.2 %	15.5 %	7.6 %	0.3 %	20.0 %	73.0 %*

** Value refers to the share of turnover generated by the entire product and not only by the sub-system of the product under analysis in CS2; Equation 6.1 allows calculating the value of the turnover generated by the sub-system under analysis;*

6.2.5 Results

The three main outputs obtained in CS2 are presented in this section: the eco-intensity indicators at the company level (Table 6.11), the eco-intensity indicators at the supply chain level (Table 6.12) and the environmental impact allocated to final product (Table 6.13), which is calculated starting from the eco-intensity indicators at the supply chain level.

Table 6.11 introduces the eco-intensity indicators at the company level. Since the fictitious supply chain members' environmental and economic performances are linear proportional to those of the equivalent actual supply chain members, the relative indicators, such as eco-intensity indicators, are the same for both the fictitious and the actual organisations. Therefore, only the eco-intensity indicators of the actual companies are presented.

Although companies' core businesses differ, an initial analysis of the values presented in Table 6.11 demonstrates that the 2nd tier supplier 2.3.1 shows the worst eco-intensity in three out of six environmental impact areas (material consumption, land occupation and water consumption). Particularly in the case of material consumption, both for the unweighted and weighted indicator, the eco-intensity of supplier 2.3.1 is several orders of magnitude greater compared to that of other companies part of the supply chain. As supplier 2.3.1 converts raw material into steel, the consumption of raw materials is naturally very significant, as depicted by the findings of this research. The 1st tier supplier 2.1 performs worst in two environmental categories (energy consumption and GHG emissions), whereas FC2 is imputable for the worst performance in terms of solid waste.

Table 6.11: Single company eco-intensity indicators (CS2)

Eco-intensity indicators		**Eco-intensity performance**						
		2.1	2.2.1	2.2.2	2.2	2.3.1	2.3	FC2
Material consumption - unweighted	[kg/€]	2.595	0.906	0.030	0.000	14.551	0.508	0.081
Material consumption – weighted	[kg/€]	2.595	1.515	0.091	0.000	43.176	0.584	0.244
Material consumption (recycled)	*[kg/€]*	*2.595*	*0.535*	*0.000*	*0.000*	*0.239*	*0.470*	*0.000*
Material consumption (renewable)	*[kg/€]*	*0.000*	*0.134*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
Material consumption (non-renewable)	*[kg/€]*	*0.000*	*0.237*	*0.030*	*0.000*	*14.313*	*0.038*	*0.081*
Land occupation	[m^2/€]	0.005	0.001	0.001	0.001	0.015	0.005	0.002
Water consumption	[m^3/€]	0.002	0.001	0.001	0.000	0.490	0.000	0.001
Energy consumption	[kWh/€]	2.748	0.897	1.081	0.175	1.565	0.651	0.391
GHG emissions	[kg CO_2e/€]	3.103	0.897	1.114	0.162	0.712	0.344	0.141
Solid waste – unweighted	[kg/€]	0.382	0.000	0.062	0.065	0.312	0.150	2.866
Solid waste - weighted	[kg/€]	0.461	0.001	0.182	0.065	0.622	0.159	5.722
Recycled solid waste	*[kg/€]*	*0.343*	*0.000*	*0.002*	*0.065*	*0.006*	*0.144*	*0.016*
Non-recycled solid waste	*[kg/€]*	*0.000*	*0.000*	*0.000*	*0.000*	*0.302*	*0.003*	*2.843*
Hazardous solid waste	*[kg/€]*	*0.039*	*0.000*	*0.060*	*0.000*	*0.004*	*0.003*	*0.006*

The findings of CS2 confirm once again the need to extend the assessment of the supply chain beyond 1st tier suppliers to achieve a holistic view of the supply chain environmental performance, as the biggest environmental performance per value generated is found at the 2nd tier supplier for half of the environmental categories. Finally, it is interesting to notice that supplier 2.2 performs best in all four environmental input categories, which reflects its role as an outsourcing organisation at the edge between manufacturing and servicing, with limited inputs incoming into the company.

The supply chain results are listed in Table 6.12, which numerates the eco-intensity indicators of the 100-units reference base supply chain introduced in Section 6.2.2, including fictitious supply chain members. This specific choice avoids potential errors in the results due to different values in the number of produced units at different actual supply chain members.

Table 6.12: Supply chain eco-intensity indicators (CS2)

Product: "Engine"	**Supply chain eco-intensity**		**Difference compared to the focal company eco-intensity without environmental backpack**
Material consumption - unweighted	[kg/€]	1.292	1,487 %
Material consumption – weighted	[kg/€]	2.332	855 %
Material consumption – recycled	*[kg/€]*	*0.265*	*NA %*
Material consumption - renewable	*[kg/€]*	*0.013*	*5670 %*
Material consumption – non-renewable	*[kg/€]*	*0.514*	*532 %*
Land occupation	[m^2/€]	0.004	156 %
Water consumption	[m^3/€]	0.016	1,443 %
Energy consumption	[kWh/€]	1.449	270 %
GHG emissions	[kg CO_2 e/€]	1.196	747 %
Solid waste – unweighted	[kg/€]	2.994	4 %
Solid waste – weighted	[kg/€]	5.891	3 %
Recycled solid waste	*[kg/€]*	*0.120*	*630 %*
Non-recycled solid waste	*[kg/€]*	*2.852*	*0 %*
Hazardous solid waste	*[kg/€]*	*0.022*	*250 %*

The values in Table 6.12 represent the eco-intensity of the multi-tier supply chain with respect to each environmental impact and are the main output of the assessment of the supply chain environmental performance. A comparison between the values of different eco-intensity indicators is not meaningful as different units of measurement are used to calculate the environmental numerator of the indicator. However, the last column of the table points out the difference between the eco-intensity values at the supply chain level compared to the focal company eco-intensity values as an autonomous entity without the environmental backpack associated with the supply chain. The values demonstrate that the eco-intensity would be significantly underestimated had the supply chain not been considered, potentially misleading managers on the environmental impact areas to tackle. The values show that the supply chain eco-intensity can be over 1,000% higher than the focal company's eco-intensity in some instances, like in the case of material consumption and water consumption environmental categories. The raw material and water required to produce steel at 2nd tier supplier 2.3.1 contribute significantly to these results, which are then cascaded along the supply chain. The only indicator that is not affected by adopting a supply chain perspective is the solid waste eco-intensity, with a very limited variation between the supply chain eco-intensity and the focal company eco-intensity. As observed already in Table 6.11, FC2 was identified as the worst performing organisation in this category, anticipating the limited deviation of the supply chain score from the focal firm's one.

Finally, the environmental backpack associated to the product was calculated (Table 6.13). Once again, the values refer to the 100-units reference base supply chain. The environmental backpack was calculated both for the entire yearly production of the final product and for one unit of the engine, which is the typical unit the final product is priced at, thus introducing an alternative reference unit for the environmental impact.

A quota of the overall energy consumption and GHG emissions is due to the impact of transport. However, the contribution of transport towards the overall environmental backpack in CS2 is limited compared to the impact of supply chain members, being accountable for 5,196,429 kWh and 1,314,215 kg CO_2 e, which represent 4% and 1% of the overall environmental impact imputable to the supply chain respectively. Despite being an international supply chain with long distance transport required, SC2 includes some very energy-intensive and carbon-intensive production activities, such as forging, casting and steel production, which take on the biggest share of the environmental impact in these categories.

Finally, Figure 6.20 details the environmental backpack by identifying the relative contribution of each supply chain member towards the supply chain total. Given the minimal contribution of transportation towards the overall supply chain environmental impact, impacts arising from each transportation link were merged with the impacts of the upstream tier involved in each transportation link in the figure.

Table 6.13: Environmental backpack associated to the selected engine (CS2)

Product: "Engine"	**Overall environmental backpack per year**		**Environmental backpack per engine unit**	
Material consumption – unweighted	[kg]	108,987,007	[kg/unit]	1,089,870
Material consumption – weighted	[kg]	196,703,268	[kg/unit]	1,967,033
Material consumption – recycled	*[kg]*	*67,029,445*	*[kg/unit]*	*670,294*
Material consumption – renewable	*[kg]*	*1,060,149*	*[kg/unit]*	*10,601*
Material consumption – non-renewable	*[kg]*	*43,328,056*	*[kg/unit]*	*433,281*
Land occupation	[m^2]	348,190	[m^2/unit]	3,482
Water consumption	[m^3]	1,321,281	[m^3/unit]	13,213
Energy consumption	[kWh]	122,226,841	[kWh/unit]	1,222,268
GHG emissions	[kg CO_2 e]	100,855,185	[kg CO_2 e/unit]	1,008,552
Solid waste – unweighted	[kg]	252,495,060	[kg/unit]	2,524,951
Solid waste – weighted	[kg]	496,799,352	[kg/unit]	4,967,994
Recycled solid waste	*[kg]*	*10,085,294*	*[kg/unit]*	*100,853*
Non-recycled solid waste	*[kg]*	*240,515,242*	*[kg/unit]*	*2,405,152*
Hazardous solid waste	*[kg]*	*1,894,525*	*[kg/unit]*	*18,945*

The environmental backpack of some environmental categories is completed dominated by one company: FC2 is responsible for the over 90% of the overall waste generated throughout the product supply chain, whereas 2.3.1 determines almost the same share of water consumption. Also GHG emissions environmental backpack is largely imputable to a single organisation, with supplier 2.1 being accountable for over 60% of them. On the other hand, other environmental categories show a more distributed pattern in terms of absolute environmental impact through the supply chain members. This is the case especially for land occupation, where no single organisation contributes for more than 40% of the supply chain environmental backpack.

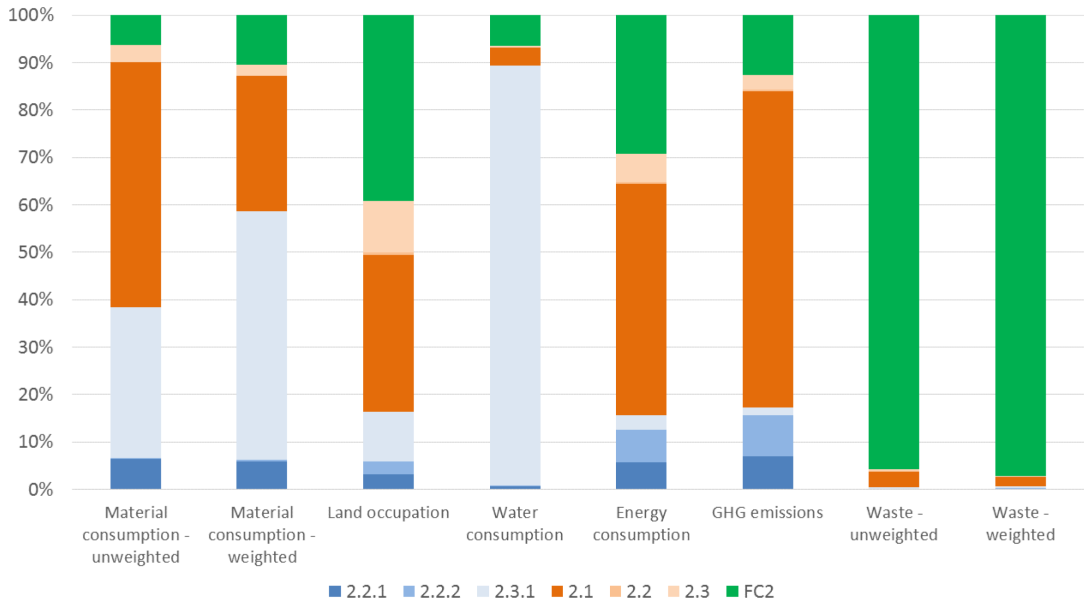

Figure 6.20: CS2 environmental backpack breakdown by supply chain member

While the eco-intensity results show the relative performance of each supply chain member, the environmental backpack breakdown (Figure 6.20) highlights the absolute environmental impact contribution allocated to each supply chain member for the product under analysis. The absolute values are affected by the annual turnover each company generates through the supply chain. This is particularly evident in the case of unweighted material consumption, where 2.1 contributes to almost 50% of the overall absolute consumption while 2.3.1 is accountable for 32% in absolute values, despite their eco-intensity indicators are respectively 2.595 kg/€ and 14.551 kg/€.

6.2.6 Applications for practitioners

The three main outputs of the method outlined in Section can be adopted to support a variety of managerial decisions, which are outlined throughout the following sections, based on the output matrix depicted in Chapter 4 and re-called in Figure 6.21. Section 6.2.6.1 illustrates the application of the eco-intensity indicators at the single company level to evaluate alternative suppliers, Section 6.2.6.2 leads to the identification of hotspots at the supply chain level in order to guide operational improvements, whereas Section 6.2.6.3 exposes the external reporting opportunities. Finally, Section 6.2.6.4 introduces an additional application of the method to analyse the environmental impact of a potential future supply chain scenario.

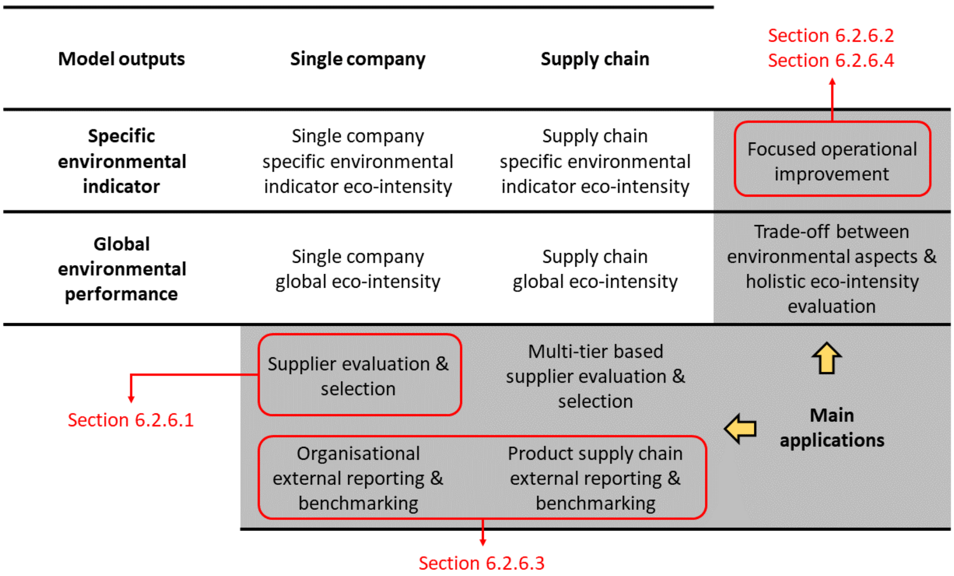

Figure 6.21: CS2 applications of the outputs of the method

6.2.6.1 Supplier evaluation

CS2 offered the possibility to evaluate the applicability of the method for supplier selection and evaluation thanks to the inclusion of two parallel suppliers, 2.2.1 and 2.2.2, in the case study. They both supply the engine block to FC2, which is machined by outsourcer 2.2 before reaching the focal company. Both companies 2.2.1 and 2.2.2 are organisations whose core business is casting, and the products offered to the market are also comparable.

Table 6.14 details the numerical results of the benchmarking between the two parallel suppliers. The scores only take into account the internal performance of the suppliers and do not consider any contribution from the supply chain, as no suppliers of 2.2.1 and 2.2.2 were involved in the case study. The two companies show comparable performance in terms of two eco-intensity indicators (land occupation and water consumption), which however take on limited importance for companies involved in casting operations. On the other hand, being an energy-intensive industry, a greater attention is paid to energy consumption eco-intensity and GHG emissions eco-intensity with the latter largely emanating from energy consumption. For both eco-intensity indicators, 2.2.1 performs better of 2.2.2, with an improved performance of 17% and 19% respectively. Supplier 2.2.1 also scores significantly better in terms of solid waste eco-intensity, as the company barely generates any waste. The situation flips over if the material consumption eco-intensity is considered: in this case, the consumption of 2.2.2 is very limited which is reflected in a lower eco-intensity score.

Table 6.14: CS2 parallel supplier benchmarking

Eco-intensity indicator (at the company level)		**2.2.1**	**2.2.2**
Material consumption – unweighted	[kg/€]	0.906	0.030
Material consumption - weighted	[kg/€]	1.515	0.091
Land occupation	[m^2/€]	0.001	0.001
Water consumption	[m^3/€]	0.001	0.001
Energy consumption	[kWh/€]	0.897	1.081
GHG emissions	[kgCO_2 e/€]	0.897	1.114
Solid waste - unweighted	[kg/€]	0.000	0.062
Solid waste - weighted	[kg/€]	0.001	0.182

The comparison of the eco-intensity indicators in Table 6.14 indicates that supplier 2.2.1 outperforms supplier 2.2.2 in terms of energy consumption, GHG emissions and solid waste, while it shows a worse performance in terms of material consumption. However, this indication does not take into consideration the gap in the performance between the suppliers. In order to effectively compare the overall performance of the two parallel suppliers, an aggregated index is required to provide comprehensive information about the behaviour of the suppliers (Zhou et al., 2012). As illustrated in Chapter 4, three steps are required to obtain an aggregated eco-intensity index, which are: normalisation, weighting and aggregation of the eco-intensity indicators (Salvado et al., 2015; Zhou et al., 2012).

These are expressed in different units of measurement, as shown in Table 6.14, therefore the first required step is the normalisation of the indicators in order to obtain adimensional values, that can be compared (Zhou et al., 2012). For the sake of the evaluation of alternative suppliers, normalisation can be performed by comparing different "alternatives with respect to specific aspects" (Tugnoli et al., 2008), as the alternatives are comparable in nature (Heijungs et al., 2007; Tugnoli et al., 2008). Parallel suppliers belong to the same industrial sector with comparable products offered to the market, meeting the requirement criterion to use internal normalisation to normalise eco-intensity indicators for this specific application.

Normalisation is achieved by dividing the eco-intensity indicator EI_{ei} of each supplier i with respect to environmental category e by the sum of the eco-intensity indicators of the z suppliers being benchmarked for each environmental indicator e (Mahdiloo et al., 2015; Tsoulfas and Pappis, 2008), thus respecting the unit-invariance of indicators. As in CS2 only two parallel suppliers are compared, the denominator of equation 6.5 is obtained simply by adding the eco-intensity indicators of supplier 2.2.1 and 2.2.2 for each environmental indicator e.

$$EI_{eiN} = \frac{EI_{ei}}{\sum_i^z EI_{ei}} \tag{6.5}$$

The normalised eco-intensity indicators of suppliers 2.2.1 and 2.2.2 are displayed in Table 6.15, highlighting in green the more environmentally sustainable supplier and in red the more eco-intense supplier for each environmental category, while Figure 6.22 illustrates the results in a graphical format through a radar graph.

The second step is weighting. Equal weighting was applied to the indicators as it generates "results nearly as good as those optimal weighting methods" (Wang et al., 2009), while requiring limited knowledge and input from decision makers. Accordingly, the unweighted score of the suppliers was compared for material consumption and solid waste environmental categories.

Table 6.15: CS2 normalised scores of parallel suppliers 2.2.1 and 2.2.2

Eco-intensity indicator (at the company level)	2.2.1	2.2.2
Material consumption – unweighted	0.968	0.032
Land occupation	0.550	0.450
Water consumption	0.645	0.355
Energy consumption	0.454	0.546
GHG emissions	0.446	0.554
Solid waste - unweighted	0.006	0.994
Total	**3.069**	**2.931**

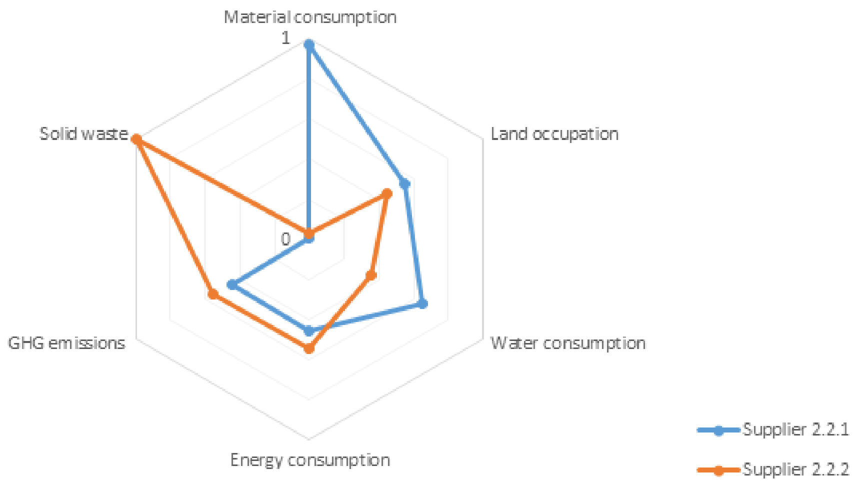

Figure 6.22: CS2 radar graph benchmarking of parallel suppliers

Finally, the normalised eco-intensity indicators are aggregated according to linear aggregation (Salvado et al., 2015). The total eco-intensity of the parallel suppliers is calculated by simply adding the normalised score in an aggregated index as it appears at the bottom line of Table 6.15. The aggregated eco-intensity scores show that the suppliers are very close in terms of overall environmental performance, however supplier 2.2.2 has a small edge, performing 5% better than supplier 2.2.1, with an overall eco-intensity score of 2.931.

6.2.6.2 Hotspots identification

The analysis of the values of eco-intensity allows identifying the hotspots along the supply chain. This is an iterative process that aims to identify the supply chain branches and supply chain organisations with the highest environmental impact in order to prioritise action and operational improvement at the companies where the environmental impact per value generated is higher.

Companies are represented in a relative colour scale based on their eco-intensity performance. The figure on the left (a) shows the eco-intensity of the organisations as single entities without any contribution of the supply chain, whereas the figure on the right (b) shows the eco-intensity of each organisation including the environmental backpack associated to their upstream supply chain, which is the actual value that is passed by each supply chain member to the next one. While the eco-intensity indicators are cascaded downstream along the supply chain, the recognition of the hotspots goes in the opposite direction, moving upstream from FC2, with different number of iterations required to reach the hotspot. This is highlighted in a blue dotted line in the following figures.

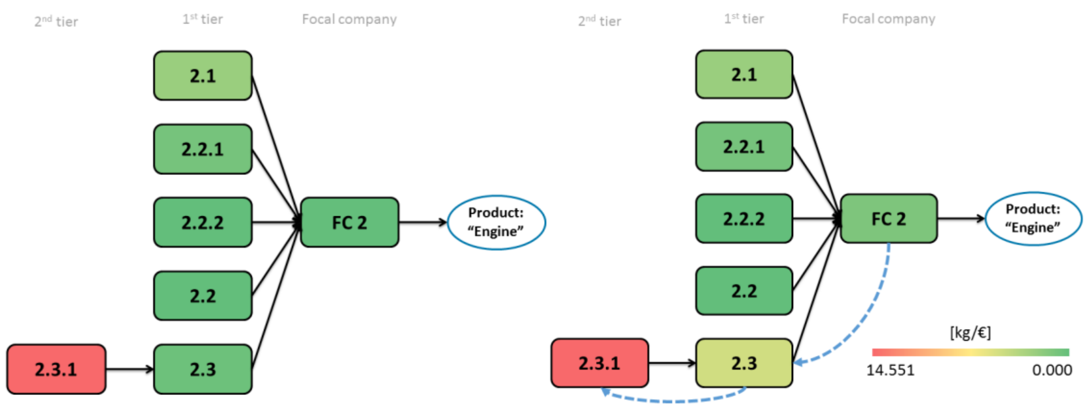

Figure 6.23: CS2 material consumption eco-intensity (unweighted) hotspot identification: excluding backpack (a) and including backpack (b)

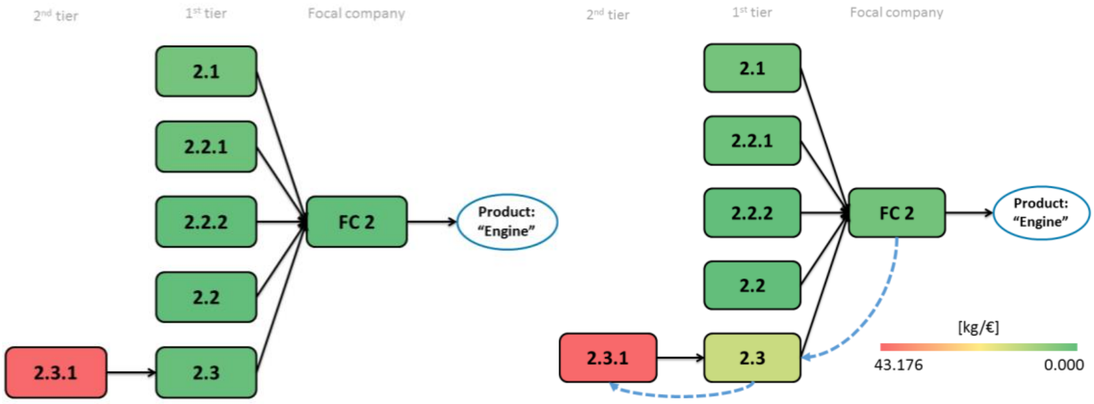

Figure 6.24: CS2 material consumption eco-intensity (weighted) hotspot identification: excluding backpack (a) and including backpack (b)

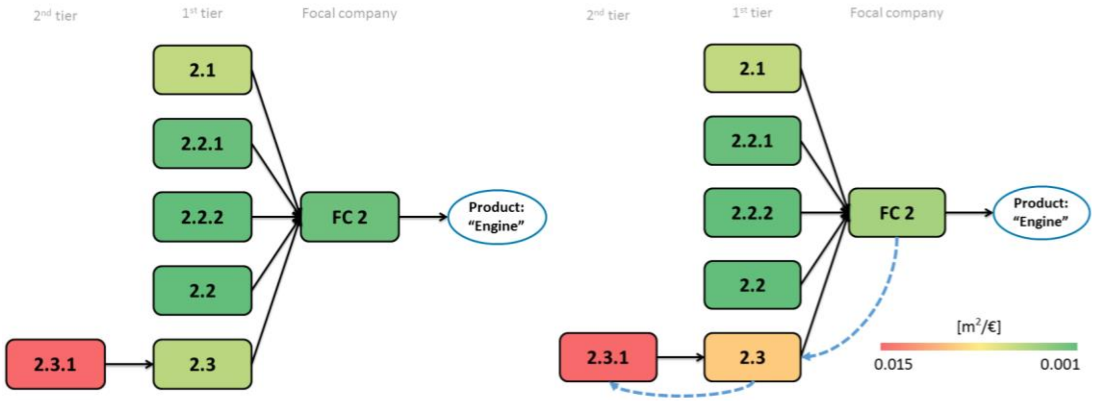

Figure 6.25: CS2 land occupation eco-intensity hotspot identification: excluding backpack (a) and including backpack (b)

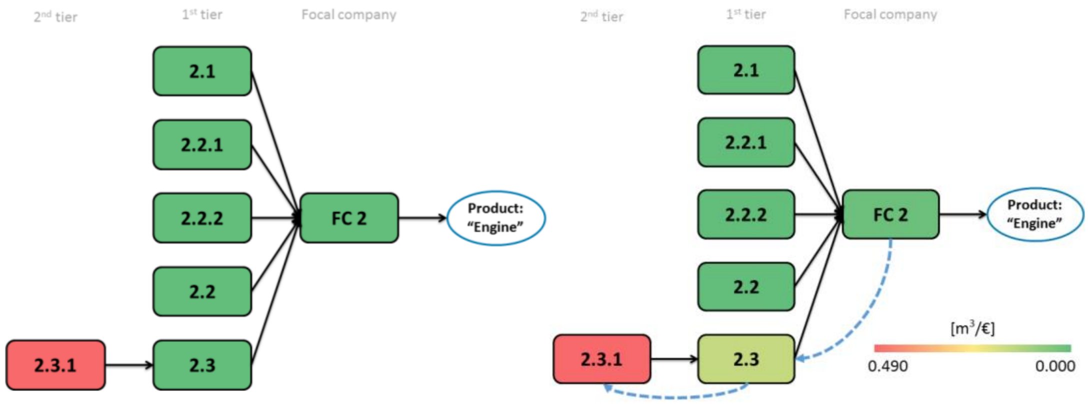

Figure 6.26: CS2 water consumption eco-intensity hotspot identification: excluding backpack (a) and including backpack (b)

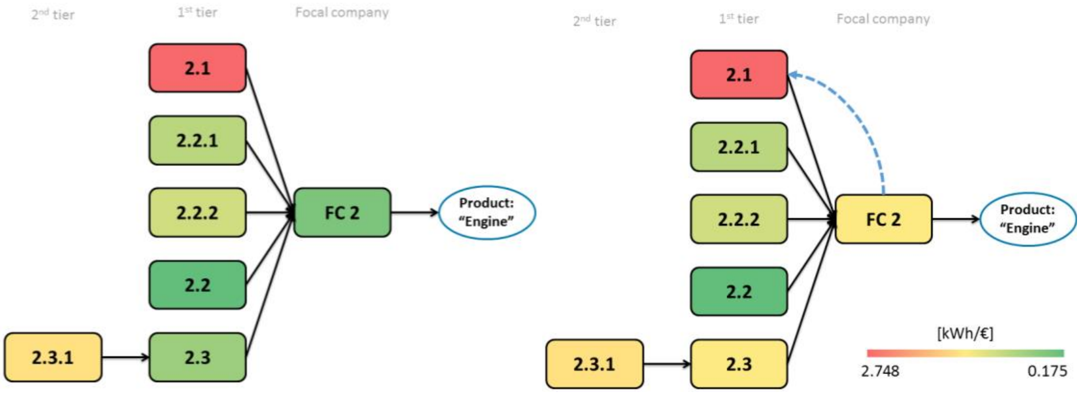

Figure 6.27: CS2 energy consumption eco-intensity hotspot identification: excluding backpack (a) and including backpack (b)

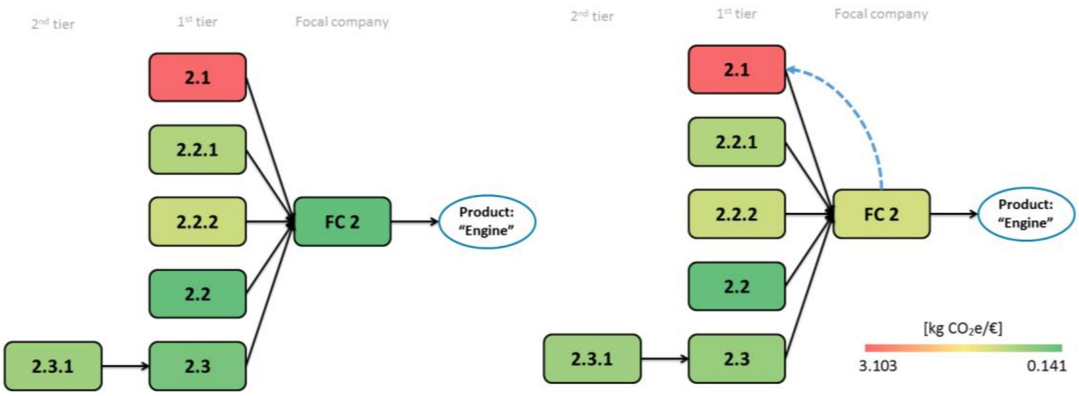

Figure 6.28: CS2 GHG emissions eco-intensity hotspot identification: excluding backpack (a) and including backpack (b)

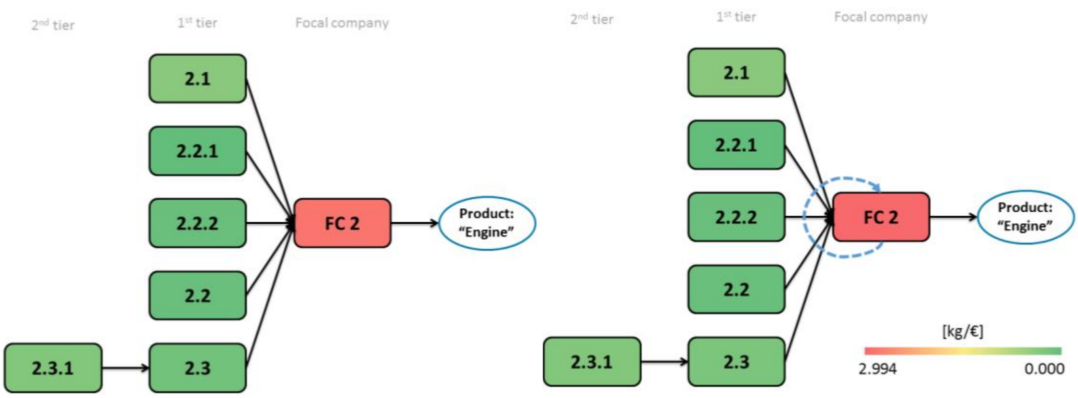

Figure 6.29: CS2 waste eco-intensity (unweighted) hotspot identification: excluding backpack (a) and including backpack (b)

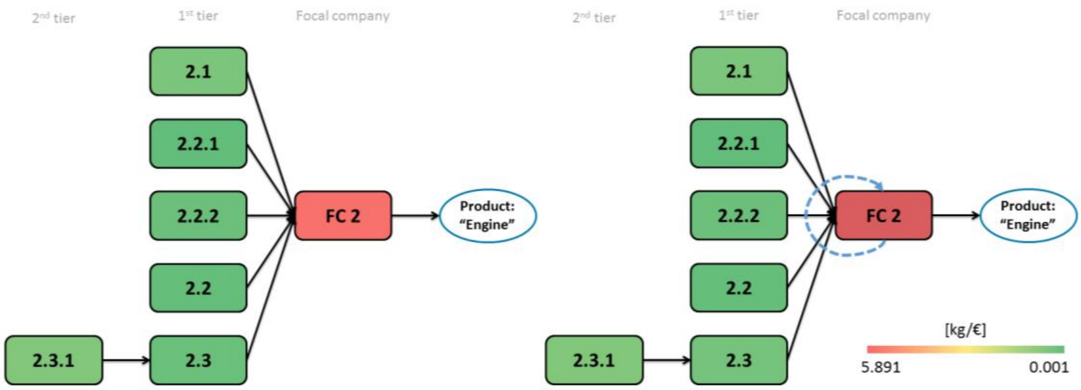

Figure 6.30: CS2 waste eco-intensity (weighted) hotspot identification: excluding backpack (a) and including backpack (b)

CS2 provides three different examples of positioning of the hotspots, similarly to CS1, with a different number of iteration stages to identify the supply chain hotspots. Two iterations are required to identify the hotspots of the material consumption eco-intensity, both weighted and unweighted, the land occupation eco-intensity and the water consumption eco-intensity. In all these cases the hotspot is located at the 2nd tier supplier 2.3.1, as depicted in Figure 6.23b, Figure 6.24b, Figure 6.25b and Figure 6.26b. In all these cases, FC2 does not have a direct visibility of the poor environmental performance of supplier 2.3.1, but recognises 2.3 as the most eco-intense organisation among its 1st tier supplier, as the example for water consumption shows in Figure 6.31a, where it is evident that FC2 is not directly aware of the performance of 2.3.1 due to the lack of visibility. FC2 identifies 2.3 as the most eco-intense organisation at the first iteration by comparing its internal eco-intensity excluding backpack with the eco-intensity values including backpack passed on by its 1st tier suppliers (Figure 6.31a). Then, it is company 2.3 that performs the second round of iteration in accordance to indirect supply chain management approach, by comparing its own internal water consumption eco-intensity excluding backpack with the eco-intensity value including backpack passed on by supplier 2.3.1. It is worth noticing that the recognition of supplier 2.3 as the most eco-intense in the first iteration is largely due to the backpack carried as the colour associated to supplier 2.3 changes significantly from Figure 6.31a to Figure 6.31b. In the former figure, the eco-intensity value includes the backpack and is light green, while in the latter, the colour associated to the supplier is only due to its internal performance and turns to dark green, thus being associated to a more environmentally sustainable behaviour. From the second iteration, it is finally recognised that the hotspot is located at the 2nd tier supplier 2.3.1 and that the operational improvement for water consumption in SC2 has thus to be prioritised at 2nd tier supplier 2.3.1.

A similar mechanism is applied for the other environmental categories where the hotspot is located at the 2nd tier supplier 2.3.1, such as material consumption and land occupation. This constitutes an example of indirect supply chain management approach, as the hotspot is identified at the 2nd tier of the supply chain without FC2 having direct visibility of its supply chain beyond its direct suppliers.

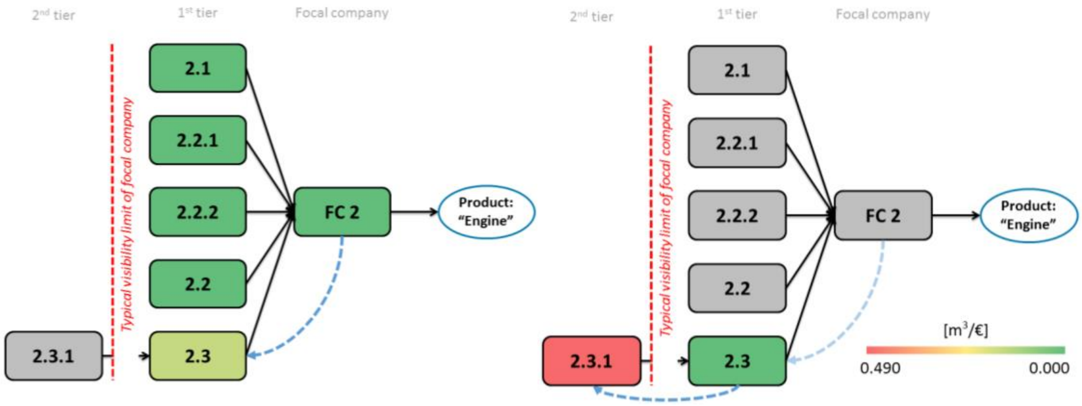

Figure 6.31: CS2 hotspot identification iterations for water consumption eco-intensity: iteration at the focal company FC2 (a) and iteration at 1st tier supplier 2.3 (b)

On the other hand, only one iteration is instead required to identify the hotspot for the energy consumption and GHG emissions eco-intensity indicators, which are both located at the 1st tier supplier 2.1, as Figure 6.27b and Figure 6.28b respectively showed. In this case, FC2 identifies supplier 2.1 as the most eco-intense by comparing its internal eco-intensity excluding backpack with the eco-intensity indicators of its 1st tier suppliers including backpack (Figure 6.32). The process is not repeated at supplier 2.1 as there are no lower tier suppliers upstream in that specific supply chain branch. Therefore, hotspot is localised at 2.1 and operational improvement for energy consumption and GHG emissions has to be prioritised at this company.

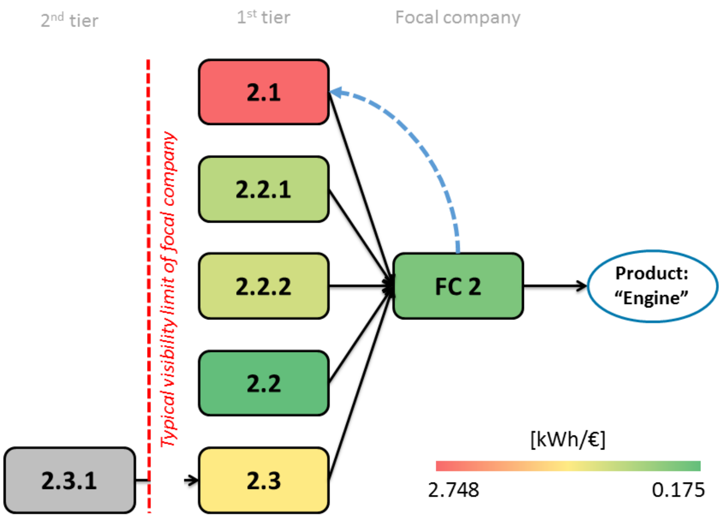

Figure 6.32: CS2 hotspot identification iteration for energy consumption eco-intensity

Finally, no iteration is required for the solid waste eco-intensity, both in the case of the unweighted and of the weighted indicator, as focal company 2 is the hotspot for these environmental impacts, as illustrated in Figure 6.29b and Figure 6.30b. The example of unweighted solid waste is depicted in detail in Figure 6.33, where FC2 recognizes itself as the hotspot by comparing its internal eco-intensity performance excluding backpack with the eco-intensity indicators including backpack that are passed on by the 1st tier suppliers. Therefore, operational improvement for solid waste has to be prioritised at the focal company in CS2.

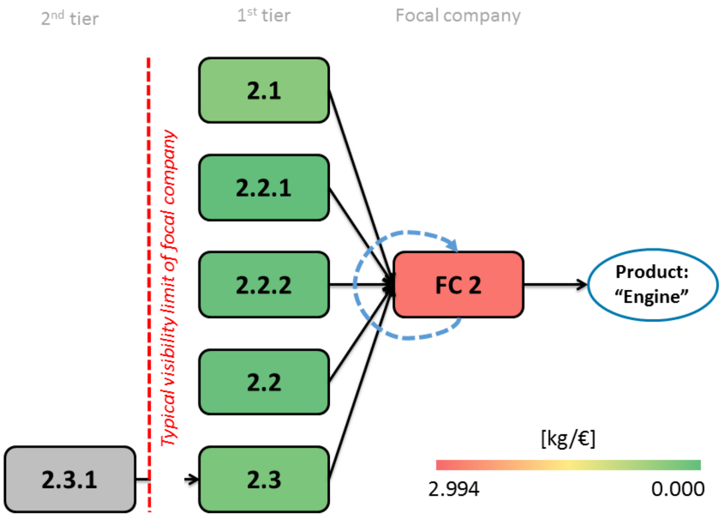

Figure 6.33: CS2 hotspot identification iteration for solid waste (unweighted) eco-intensity

6.2.6.3 External reporting

The eco-intensity indicators and environmental backpack per unit of engine produced can be both adopted to demonstrate the responsible approach of the focal company towards the environment and as an additional leverage to brand the final product in a green perspective in the B2B context, where FC2 operates. Moreover, the environmental backpack values can be integrated with the environmental performance measurements FC2 has already in place for the usage phase of the engine, thus providing an easy tool to support lifecycle environmental performance assessment.

Finally, the eco-intensity values at the company level could be also adopted by each single organisation part of the supply chain as part of their corporate sustainability reports and to communicate to relevant stakeholders, including customers of other products, the environmental performance of the organisation as a whole.

6.2.6.4 Supply chain re-design environmental impact

A future scenario analysis was performed also for CS2, assessing the potential effect on the supply chain environmental performance of a supply chain re-design, which is potentially happening in the short term according to the supply chain manager of FC2. The 1st tier supplier 2.3 is considering to move its plant from its current location in Hungary to Finland, where the 2nd tier supplier 2.3.1 is located. This decision is motivated by the fact that supplier 2.3 considers it critical to have accessibility to the steel required to manufacture its products and thus would like to achieve supplier proximity. However, this relocation decision would affect also the supply chain design and have an effect on the supply chain environmental performance. The current base case and future scenario supply chain design are pictured in Figure 6.34.

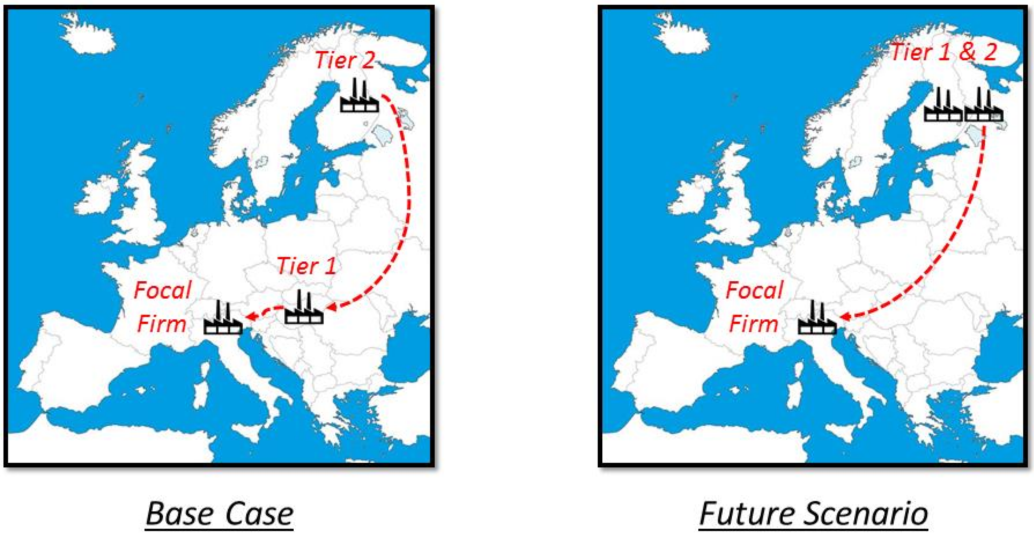

Figure 6.34: CS2 supply chain re-design base case and future scenario (Map image derived from UI Download, https://www.uidownload.com/free-vectors/map-of-europe-template-227957, accessed on 24/10/2018)

The following assumptions were made to evaluate the future scenario:

- The scenario does not take into account the investment cost to relocate the plant of supplier 2.3 from Hungary to Finland, but focuses only on the changes in the eco-intensity of the operations of both the organisations and the supply chain;
- Quantity and price of the engine frame and wet sump sourced through the supply chain branch remain unchanged;
- Since no detailed information about the environmental performance of supplier 2.3 in its future Finnish plant are available, it is assumed that similar technologies are going to be adopted and no significant changes in the internal environmental profile compared to the Hungarian plant;
- Transport between 2nd tier supplier 2.3.1 and 1st tier supplier 2.3 can be omitted in the future scenario due to the proximity of the two sites;
- No changes in any other relevant environmental and economic indicators.

Based on the above mentioned assumptions, only two eco-intensity indicators are affected in the future scenario analysis, which are energy consumption eco-intensity and GHG emissions eco-intensity due to:

- The re-design of the supply chain affects the transport environmental impact both in terms of energy consumption and GHG emissions;
- Electricity mix is country-specific; therefore, the relocation of the plant affects the Scope 2 emissions of supplier 2.3;

The results of the scenario analysis for energy consumption are summarised in Table 6.16, while those for GHG emissions are showed in Table 6.17. Part of the results are displayed in the format of the actual supply chain data, based on the real quantities produced and transported by SC2. These include the environmental performance of the supply chain branch transport and the internal performance of supplier 2.3. On the other hand, the total results, such as the environmental performance of the entire supply chain transport network and the supply chain eco-intensity performance are reported on a 100-base data to balance the results on a common basis for the entire supply chain as explicated in Section 6.2.2.

Table 6.16: CS2 energy consumption future scenario analysis

Aspect		Base Case	Future Scenario	Δ
Energy consumption of SC branch transport[1]	[kWh]	1,358,838	1,218,317	-10%
Total energy consumption of transport[2]	[kWh]	5,196,429	4,897,447	-6%
Supplier 2.3 internal energy consumption eco-intensity[1]	[kWh/€]	0.651	0.651	0%
Supply chain energy consumption eco-intensity[2]	[kWh/€]	1.449	1.446	-0.24%

[1] *Actual supply chain data*

[2] *100-base data built upon the fictitious supply chain*

Table 6.17: CS2 GHG emissions future scenario analysis

Aspect		Base Case	Future Scenario	Δ
GHG emissions of SC branch transport[1]	[kgCO2e]	342,000	303,000	-11%
Total GHG emissions of transport[2]	[kgCO2e]	1,314,215	1,231,236	-6%
Supplier 2.3 internal GHG emissions eco-intensity[1]	[kgCO2e/€]	0.344	0.210	-39%
Supply chain GHG emissions eco-intensity[2]	[kgCO2e/€]	1.196	1.183	-1.09%

[1] *Actual supply chain data*

[2] *100-base data built upon the fictitious supply chain*

The re-design of the supply chain would lead to a moderate impact on transport-specific environmental impact thanks to the merging of 2.3.1-2.3 transport link with 2.3-FC2 transport link in a unique transport link. This would result in a decrease of 10% of the energy consumption and 11% of the GHG emissions for the specific supply chain branch involving 2.3 and 2.3.1, which supplies the engine frame and the wet sump to FC2. The effect on the overall environmental impact of the transport activities would be weaker as other supply chain branches also contribute towards the total environmental impact. The decrease would still add up to 6% for both energy consumption and GHG emissions, due to the significant contribution of this supply chain branch towards the overall transport impact, being the longest distance route.

The relocation of the plant of supplier 2.3 from Hungary to Finland would have a sensible effect on the GHG emissions of the organisation: the more environmentally friendly electricity mix in Finland would lead to a decrease of 39% of the internal GHG emissions eco-intensity.

Although these improvements in the environmental performance at various stages are noticed, the overall impact on the supply chain eco-intensity indicators is very limited with a modest -0,24% energy consumption eco-intensity result and -1,09% in terms of GHG emissions eco-intensity. Two main reasons are behind this limited improvement in the environmental performance at the supply chain level:

- Transport is not a major contributor to the supply chain energy consumption and GHG emissions compared to the impact of supply chain tiers, as detailed in Section 6.2.5, therefore a small improvement of the transport environmental impact is marginal at the supply chain level;
- Supplier 2.3 is not a hotspot for any of the environmental categories affected by the reshoring decision nor a sizeable contributor in terms of environmental backpack. Therefore, despite a significant improvement in the GHG emissions eco-intensity score, the outcome at the supply chain level is once again marginal.

As a result, based on the assumptions made and the performed scenario analysis, it can be concluded that benefits in terms of environmental performance improvements at the supply chain level exist but are limited.

6.2.7 CS2 applicability evaluation follow-up

The follow-up of CS2 aimed specifically to complete the method validation stage by tackling the applicability criterion with the supply chain manager of FC2. As detailed in Chapter 5, two aspects related to applicability were evaluated at this stage:

- Applicability of the results: to identify which results and applications derived from the findings are more practical for practitioners in an operating context and thus considered favourable to be applied to support decision making;
- Applicability of the method: to determine the key enablers for a successful implementation of the method in an operating supply chain without the support of the researcher.

Each aspect was evaluated in a dedicated semi-structured interview. Each interview lasted approximately two hours. Interviews took place between August 2018 and October 2018. The following sub-sections illustrate the findings emerging from the follow-up of the case study.

6.2.7.1 Validity of the results

The supply chain report that was forwarded to FC2 summarised the main findings and applications offered by the method in CS2 and was adopted as the basis for the semi-structured interview dedicated to the evaluation of the applicability of the results.

While the supply chain manager of FC2 recognised the value of the outputs offered by the method, two applications were considered of greater interest for practical applications, which are the support for supplier selection and evaluation and the identification of hotspots. Other applications were considered challenging to be applicable: the supply chain re-design is largely driven from economic considerations and, being a strategical decision, the importance of environmental considerations is still considered marginal in the decision-making process, whereas the environmental external reporting at the product level is not as impactful in a B2B context, as much as in a B2C, according to the supply chain manager of FC2.

The supplier selection and evaluation was evaluated to be particularly beneficial at the stage of the evaluation of the suppliers, rather than at the stage of selection as environmental aspects are not considered critical at the stage of selection and other criteria of the suppliers, such as the technical and economic performance, are of greater importance. However, FC2 constantly monitors its existing suppliers and, given the growing value associated to sustainability by multiple stakeholders, it is willing to introduce an evaluation of the sustainable performance of suppliers, incorporating the environmental performance along with traditional indicators, such as cost and quality. The eco-intensity indicators offer a quantitative output that can support decision-making according to the supply manager of FC2, although a single index of the overall environmental performance would be preferable to be incorporated with other indicators evaluated by the organisation.

The follow-up interview with the supply chain manager also confirmed the validity of the comparative results of parallel suppliers 2.2.1 and 2.2.2, as the outcomes accurately represented the different production processes adopted by the organisations. Supplier 2.2.1 adopts a casting technique, which is more material-intensive than casting in place at 2.2.2 due to the different preparation of moulding boxes. In the specific case of the engine block, cylinder liners holes are created on the upper part of the engine block at 2.2.1, whereas they are created on the bottom part of the engine block at 2.2.2. Thanks to the different casting technology in use, 2.2.2 is able to internally recycle a high share of the metal sward and produces the same casts with lower material in the produced pieces, resulting in a reduced material consumption, a result that is confirmed by the findings of CS2. On the other hand, 2.2.1 outscores supplier 2.2.2 in the key environmental indicator for casting industry, which is the energy consumption. Organisation 2.2.2 adopts a more energy-intensive production process due to the casting technologies, which requires more time in the foundry for the produced casts. This also determines a higher GHG emissions eco-intensity, due to the less technologically advanced production process coupled with a lower sensibility towards sustainability from the supplier compared to supplier 2.2.1, according to the supply chain manager of FC2.

The method was also able to capture the hotspots adequately, according to the supply chain manager of FC2, who claimed that the hotspots are located coherently with expectations. Results revealed that the focal company is the hotspot for solid waste, which was largely imputable to the high amount of packaging related to semi-assembled products according to the supply chain manager, a hypothesis compatible with the role of assembler of FC2 within the supply chain. According to the manager, this requires future internal action by FC2 as well as improved collaboration with direct suppliers to reduce the amount of packaging waste generated, although part of the waste cannot be eliminated. According to the manager, other hotspots that were adequately captured from the case study are the material consumption and the water consumption, both located at 2nd tier supplier 2.3.1, which is a steel producer. Steelmaking requires high amounts of raw material, either non-renewable minerals or recycled minerals, and of water (Van Caneghem et al., 2010), with the results highlighting different orders of magnitude in the material consumption and water consumption eco-intensities of 2.3.1 compared to other organisations of the supply chain. On the other hand, the energy consumption eco-intensity and GHG emissions eco-intensity showed limited differences between supply chain member, as forging, casting and steeling are all considered energy-intensive industries (Van Caneghem et al., 2010; UK Department for Business, Energy & Industrial Strategy, 2018), an aspect that is also captured by the results, as shown in Section 6.2.5.

The practical applicability of the hotspot identification was highlighted by FC2 supply chain manager in combination with the supplier evaluation and benchmarking. The outputs of the method not only identify environmental hotspots but also best-in-class organisations that can serve as a performance target for other companies, in order to quantify the gap to be filled by organisations currently performing worse in terms of environmental impact, thus offering an additional outlook to the proposed applications.

6.2.7.2 Applicability of the method

The evaluation of the applicability of the method aimed to determine the key enablers for a successful implementation of the method in an operating supply chain without the support of the researcher. A list of enablers, based on the work of Dou et al. (2017), was presented to the supply chain manager of FC2 to direct the discussion throughout the semi-structured interview. At the end of the interview, once every enabler on the list was thoroughly addressed, the supply chain manager was asked to evaluate its influence on the applicability of the method in an operating context on a linguistic scale (Dou et al., 2017). Table 6.18 reports the findings of this evaluation.

Table 6.18: Influence of enablers on the applicability of the method in an operating supply chain (FC2 manager)

	Enabler (E)	No influence	Very low influence	Low influence	High influence	Very high influence
E1	Trust between a focal company and the first-tier suppliers				✓	
E2	Trust between the first-tier supplier and the second-tier supplier				✓	
E3	A focal company has buyer power over the first-tier suppliers				✓	
E4	The first-tier supplier have buyer power over the second-tier suppliers				✓	
E5	The first-tier and second-tier suppliers are long-time committed partners				✓	
E6	A focal company deeply understands its supply chain			✓		
E7	First-tier suppliers are willing to share second-tier suppliers' information with the focal company				✓	
E8	A focal company is willing to provide necessary human resource support				✓	
E9	Risk of supplier-by-passing		✓			
E10	Lower-tier suppliers have capabilities of meeting a focal company's requirements					✓

E11	Supply chain members are geographically close to each other		✓			
E12	Top managers' committed support from a focal company				✓	

The supply chain manager from FC2 identified E10 “Lower-tier suppliers have capabilities of meeting a focal company's requirements” as the most prominent one, the only enabler having a “very high influence”. The main concern of the manager lied in the availability of quantitative data along the supply chain to support an effective cradle-to-gate application of the method. The manager specifically stressed the issue about the existing challenges in obtaining visibility and traceability about raw materials that are acquired on the world commodity markets, claiming that this would be very difficult to achieve.

A number of enablers were identified as having a high influence towards the applicability of the method in an operating supply chain. Some of them can be clustered as supply chain relations enablers, including E1, E3 and E5. On top of that, E2 and E4 mirror E1 and E3, considering the relationship between 1st and 2nd tier suppliers instead of the relations between the focal company and the 1st tier supplier. The supply chain manager from FC2 stressed that a good relation is necessary to obtain similar information from the suppliers, as they are not currently part of any legislation or industry requirement. Unless this information is established in the procurement contracts, only a trustful relationship is able to push suppliers to voluntary collect and disclose certain environmental data with their customer. Furthermore, he highlighted that all 1st tier suppliers involved in CS2 have been working along the focal firm for at least ten years and can thus be considered long-time committed partners (E5). According to FC2 supply chain manager, trust building is a lengthy process that start with a monetary expenditure from the customer to the supplier. This determines a working collaboration between the two companies. If the supplier is satisfied with the remuneration and the customer with the quality of the work, this leads to increased volumes of work between the organisations leading to increased monetary flow. If both parties remain satisfied in the long term, this leads to a development in the supply chain relationship, which can be labelled as trust between the customer and its suppliers.

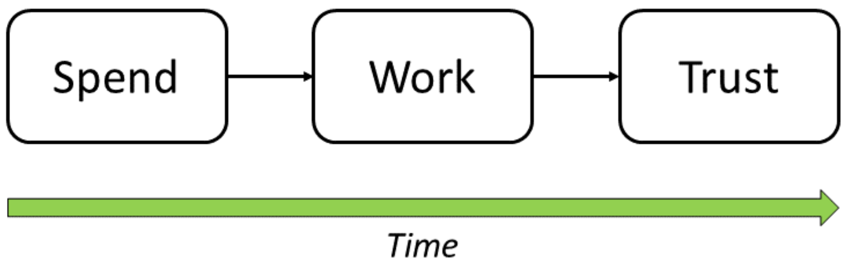

Figure 6.35: Trust building according to FC2 supply chain manager

E6, “A focal company deeply understands its supply chain” was the only enabler, which was considered of low influence towards the applicability of the method. The supply chain manager detailed that the indirect multi-tier supply chain approach adopted by the method does not require extended understanding or visibility of the supply chain for the method to function, thus determining the low influence of this enabler. Finally, “Risk of supplier by-passing” (E9) and “Supply chain members are geographically close to each other” (E11) were the only two enablers, which were given very low influence in the context of applicability of the method. E9 is not considered critical specifically in the industrial sector where FC2 operates into, as large focal companies would already be enough powerful to by-pass the 1st tier supplier if they wanted to. Finally, CS2 demonstrated that the method is applicable in an international supply chain, thus the geographical location of the supply chain members was considered of neglectable importance by the manger, who highlighted the prominent use of IT systems in modern supply chains. However, the manager recognized that this aspect might become influential if organisations located in developing countries need to be reached out through the method, owing to cultural differences and lack of organisation in some of these companies.

On top of the discussion built upon the list of enablers presented in Table 6.18, the final part of the interview was left for open discussion between the researcher and the supply chain manager of FC2 in order to identify potential additional critical aspects for the applicability of the method. The supply chain manger remarked that, in the absence of specific legislation and/or contract obligations, the application of the method would rely on the willingness of suppliers to provide the data, therefore the integration of the method within available software packages would be beneficial. This would facilitate data extraction from individual organisations without affecting existing operations at the companies and integration within existing IT packages. Furthermore, the manager suggested that risk management packages could be a potential destination for the IT integration of the method, as the supply chain environmental performance is often perceived in a risk perspective from focal companies.

6.3 Cross-case applicability evaluation

CS1 and CS2 differentiated among several features to enhance the method validation and the generalisability of the applicability of the method. Differentiating features include size of focal company, industrial sector, manufacturing production strategy, supply chain geographical scope as well as the final product offered to the market. Consequently, the results of the supply chain environmental performance assessment are not strictly comparable. On the other hand, managers of focal companies in both case studies evaluated the influence of the same enablers towards the applicability of the method in an operating context.

The cross-case comparison of the evaluation of the applicability can help to draw additional insights on the generalisability of the applicability of the method considering the significant differences between the case studies. Overall, the opinions of the owner of FC1 (in black, in Table 6.19) and the supply chain manager of FC2 (in orange, in Table 6.19) were perfectly aligned regarding the influence of four enablers (E5, E6, E7, E12). In five instances their opinions differed by a single level on the linguistic scale (E1, E2, E8, E9, E10). However, E1, E2 and E10 were all recognised having a significant influence on the applicability, but different intensity of influence were assigned to such enablers by respondents, ranking them either as 'high influence' or 'very high influence'. Similarly, E9 was evaluated as having a very limited influence with different degree of intensity at the other end of the spectrum. E8 shows a first misalignment between the opinions of the two respondents as it was recorded as having 'low influence' in CS1 and as 'high influence' in CS2. The different size of focal companies could possibly justify this misalignment, as FC1 is a micro-enterprise with no resources to actively support suppliers in line with most SMEs (Dou et al., 2017; Grimm et al., 2014), whereas FC2 is a large organisation, part of an international supply chain and providing support to suppliers is part of the organisational culture, sustainability being no exception. Finally, a disagreement was recorded regarding the remaining three enablers (E3, E4, E11), thus requiring further investigation in the future.

E3 and E4 are related to the power balance within the supply chain: buyer power was deemed having a 'high influence' in CS2, whereas a 'very low influence' in CS1. This is possibly because of the collaborative nature of SC1, as collaborative supply chains rely primarily on trust, while power asymmetries between supply chain members become less influential compared to non-collaborative supply chains (Tachizawa and Wong, 2014). Moreover, E3 and E4 may be perceived as more influential at FC2 as "larger focal firms have more power to influence supplier behavior, because they have more opportunity to allocate business to suppliers" and "asymmetric power are intrinsic to global supply network", thus determining the higher influence awarded to power in CS2 (Hartmann and Moeller, 2014; Tachizawa and Wong, 2014).

Finally, E11 was considered having a 'very high influence' in CS1, due to the local configuration of the supply chain and informal business relations among supply chain organisations, whereas it was evaluated 'very low influence' in CS2, reflecting the successful application in the international supply chain of FC2. While close proximity of supply chain members was recognised beneficial to implement multi-tier GSCM performance assessment (Dou et al., 2017; Grimm et al., 2014), this aspect can be further de-coupled into physical and institutional distance among supply chain members (Wilhelm et al., 2016b). The misalignment regarding E11 can be thus attributed to the different perception of this enabler from the respondents. Owner of FC1 reported that the local design of the supply chain as a key feature to boost collaboration and data gathering along the supply chain as well as to enable face-to-face meetings (Grimm et al., 2014), which are required to implement new practices within a supply chain made up by micro-enterprises. Viceversa, the institutional distance was the predominant perceived element in CS2. Despite the international supply chain design, the insititutional distance among organisations of CS2 is still low, as all organisations investigated in the case study are located within European Union (Wilhelm et al., 2016a, 2016b) and potentially justifying the 'very low' influence attributed to this enabler. This aspect requires further investigation in future research, given the contradictory results emerging from the case studies, and potentially distuingishing between physical and institutional distance. The application of the method in supply chains including organisations in developing countries could provide further insights with this respect.

Table 6.19: Cross-case comparison on the influence of enablers on the applicability of the method in an operating supply chain

Enabler (E)		No influence	Very low influence	Low influence	High influence	Very high influence
E1	Trust between a focal company and the first-tier suppliers				✓	✓
E2	Trust between the first-tier supplier and the second-tier supplier				✓	✓
E3	A focal company has buyer power over the first-tier suppliers		✓		✓	
E4	The first-tier supplier have buyer power over the second-tier suppliers		✓		✓	
E5	The first-tier and second-tier suppliers are long-time committed partners				✓✓	
E6	A focal company deeply understands its supply chain			✓✓		
E7	First-tier suppliers are willing to share second-tier suppliers' information with the focal company				✓✓	
E8	A focal company is willing to provide necessary human resource support			✓	✓	

E9	Risk of supplier-by-passing	✓CS2	✓CS1		
E10	Lower-tier suppliers have capabilities of meeting a focal company's requirements			✓CS1	✓CS2
E11	Supply chain members are geographically close to each other		✓CS2		✓CS1
E12	Top managers' committed support from a focal company			✓CS1 ✓CS2	
		✓CS1	✓CS2		

The combined evaluation of the influence of enablers on the applicability of the method identified three enablers having the highest influence (Table 6.19), which are E1, 'Trust between a focal company and the first-tier suppliers', E2, 'Trust between the first-tier supplier and the second-tier supplier' and E10 'Lower-tier suppliers have capabilities of meeting a focal company's requirements'.

E1 and E2 detail the importance of trust to apply the method, confirming that trust, along with power, is a significant enabler in the "supply network actors' engagement in sustainability initiatives" (Gong et al., 2018). However, findings from the cross case analysis highlight that trust is awarded a higher importance in the supply chains under analysis, despite the open structure of the supply chains under analysis would suggest the predominance of power, according to Mena et al. (2013). At the same time, the use of solely power for sustainability purposes was acknowledged as leading to "unfair perceptions and negative reciprocity", thus supporting the higher influence awarded to the E1 and E2 for the applicability of the method (Soundararajan and Brammer, 2018). Trust is required primarily due to the sharing of potentially confidential environmental data along the supply chain and a trust-based relationship has been recognised as encouraging a fruitful sustainability data exchange (Fritz et al., 2017). Moreover, trust in the focal company/first-tier supplier dyad (E1) is also required to kick-off the sustainability initiatives and to stretch such initiatives out to the upstream supply chain, given the crucial role played by first-tier suppliers in disseminating sustainability requirements upstream along the supply chain (Dou et al., 2017; Wilhelm et al., 2016a). This is particularly the case for the GSCM performance assessment method presented in this thesis, which relies on indirect multi-tier GSCM approach and a recursive mechanism logic. Higher-quality information was also identified as an outcome of increased trust among supply chain members (Dou et al., 2017), which is a particular important aspect for a performance assessment method relying on quantitative environmental data. Trust in the first-tier supplier/second-tier supplier dyad (E2) mirrors E1. Lack of such trust can indeed hamper the sustainability efforts of the focal company as not only it does not allow achieving effective multi-tier GSCM but it also lowers the engagement of first-tier suppliers indirectly (Dou et al., 2017).

Finally, E10 points toward capabilities and data availability among lower-tier suppliers. These suppliers typically do not face intense pressure from stakeholders about their environmental performance, differently from focal companies, and are typically SMEs, which are more prone to lack resources to dedicate to sustainability and adequate environmental capabilies (Tachizawa and Wong, 2014). As a result, lower-tier suppliers were recognised by managers of focal companies as the critical element within the supply chain for a correct implementation of the method.

6.4 Summary

This chapter presented the findings emerged from the application of the method in an operating context through multiple case studies technique in order to address objective 4 (O4), “Apply the method to operating supply chains”, as well as contributing towards the method evaluation process detailed in Chapter 5, thus addressing objective 5 (O5), “Evaluate the utility, accuracy and applicability of the method”.

Two case studies were presented and analysed. Section 6.1 outlined CS1, which illustrates the application of the method in a linear, local, food supply chain in the Friuli Venezia Giulia region of Italy involving micro enterprises, while Section 6.2 illustrates CS2 from a complex, international, machinery supply chain involving mostly large organisations. Each of the two sections fulfils a within-case analysis by following a similar pattern, illustrating information about the organisations part of the supply chain, the environmental performance assessed and the data collected on top of the results arising from the implementation of the method. The results can be easily adopted for external reporting both at the company level and at the product level. The multiple outputs and applications of the method are also presented, displaying how supply chain managers from focal companies can benefit from the method. The range of applications include understanding the impact of the upstream supply chain on the overall environmental impact of a product, evaluating and comparing alternative suppliers, identifying the environmental hotspots along the supply chain to guide operational improvement and evaluating potential future supply chain scenarios from an environmental perspective. Findings also include the evaluation of results, which was achieved with a comparison of results with another case in CS1 and with a comparison with information available at the focal company in CS2 through a semi-structured interview with the supply chain manager of FC2. Being part of the method evaluation process, the case studies were followed-up by interviews with supply chain managers to investigate the applicability of the method adopted. Three enablers were identified as having the highest influence on the applicability of the method by the evidence emerging from the cross-case analysis presented in Section 6.3: ‘Trust between a focal company and the first-tier suppliers', 'Trust between the first-tier supplier and the second-tier supplier' and 'Lower-tier suppliers have capabilities of meeting a focal company's requirements'.

In the next chapter, the results of the case studies, along with the findings from the other evaluation stages and the underpinning conceptual and mathematical models are discussed against the literature.

7 Discussion

The aim of the research reported in this thesis is to *facilitate quantitative assessment of the environmental sustainability performance of multi-tier supply chains*, while respecting the multi-organisation nature and non-collaborative characteristics of the majority of supply chain. Informed from the gaps identified through the systematic literature review, an eco-intensity based method to assess the environmental performance of multi-tier supply chain was developed, which relates the environmental performance of the supply chain to its economic output and adopts an indirect multi-tier supply chain approach (Chapter 4). The method was then evaluated through different methods as illustrated in Chapter 5 and 6.

This chapter presents reflections on the research, touching upon all its previous phases in three different ways. First, the research findings are discussed, with a specific focus on the developed multi-tier GSCM performance assessment method (Section 7.1). Second, the research methods adopted are individually discussed in Section 7.2 and, third, Section 7.3 reflects upon their combination into the overall research approach. Finally, a summary of the chapter is provided in Section 7.4.

7.1 Research findings

The main contribution of this research is the developed method to assess the environmental performance of multi-tier supply chains. Its advantages and limitations, including the assumptions guiding the methodological choices are discussed in Section 7.1.1, whereas the outputs generated through the method and the main applications are discussed in Section 7.1.2. Finally, Section 7.1.3 reflects on the lessons learned from the evaluation of the method, with a particular focus on the case study applications of the method and the identified challenges to the applicability of the method.

7.1.1 Reflections on the multi-tier GSCM performance assessment method

The method presented in this research offers some advantageous features as well as having some limitations. These are discussed in more detail by breaking down the discussion to the five pillars shaping the conceptual model part of the method throughout Sections 7.1.1.1 to 7.1.1.5. Finally, a global discussion about the pillars and their contribution to fulfil the requirements for the sustainability assessment of multi-tier supply chains is presented in Section 7.1.1.6.

7.1.1.1 Eco-intensity

Eco-intensity was used to conceptualise the environmental impact within the multi-tier GSCM performance assessment method. Eco-intensity relates the environmental impact of a system to its economic outputs and, as such, shares advantages and limitations of any relative indicator. The main point in favour of the adoption of relative indicators is that they are not prone to fluctuations as result of changes in the produced outputs, which have the potential to hide real changes in the environmental performance (Michelsen et al., 2006). Size of company and product output can vary across time and such factors are not taken into account by absolute indicators. On the contrary, relative indicators are able to capture whether changes in the environmental performance are the result of changes in such factors or are the outcome of environmental management efforts (Schaltegger et al., 2008). As a result, they are preferred to be included in performance measurement systems and to support decision making (Shokravi and Kurnia, 2014). On the other hand, the main shortcoming of relative indicators lies in the lack of a direct indication regarding the overall absolute environmental impact associated to the system under analysis, which is the supply chain in this case. This may be critical whenever there are stringent legal limits imposed on the absolute environmental impact allowed which are irrespective of the relative values (Schaltegger et al., 2008). However, this drawback was mitigated in this research by calculating the environmental backpack associated to products and thus providing an indication about the absolute environmental impact of the supply chain.

Monetary unit is one of the multiple options available as reference factors for environmental impacts. Alternative options have been adopted in the literature, like weight (Chaabane et al., 2011; Tan et al., 2014), volume (Tokos et al., 2012), unit of product (Abdallah et al., 2012; Du et al., 2015; Lenny S.C. Koh et al., 2012; Lee, 2012), functional unit (Mellor et al., 2002). The selection of the monetary unit as the reference factor is justified by its applicability to any commercial supply chain, irrespective of the physical characteristics of the final product and intermediary products within the supply chain. The eco-intensity can tackle with the same logic both products that are sold in units, like engine components and sub-systems in CS2, and those that are typically sold in bulk, by weight or volume, as it was the case of wheat and flour in CS1. Moreover, the selection of monetary unit as reference factor has also some implications on the benchmarking potential of the method. These are discussed thoroughly in Section 7.1.2.4. The section discusses first the environmental numerator and economic denominator independently and then addresses eco-intensity indicators as a whole.

Numerator: environmental impact

The selected environmental indicators were based on the outcomes of the systematic literature review (Section 2.5.3), aiming to extend the coverage of environmental aspects compared to existing method and to capture relevant environmental inputs and outputs of organisations while using primary data sourced from actual practice. The literature review provided directions on the environmental impact areas to address, however did not clearly identify the specific indicators to be adopted in the method given the low standardisation of metrics identified in the literature review. Since the aim of this research was to develop a method to assess the environmental performance of multi-tier supply chain, the focus was on the construction of the method for a supply chain context rather than on the development of environmental indicators, as multiple indicators are already available in the literature.

As a result, environmental indicators were adapted from the pool of environmental indicators available in the literature, generating a single indicator for each of the most addressed clusters within each environmental category, as the set of indicators needs to be manageable in size for practical applications, but at the same time broad in scope. SI units of measurement were adopted wherever the systematic literature did not offer a clear direction on the units of measurement to be adopted. Alternative units may have been adopted in certain instances. As an example, solid waste was reported in kilograms, whereas a volume-based metric could have been alternatively adopted.

The environmental indicators are on purpose generic rather than being industry-specific to facilitate a cross-industrial applicability, as confirmed by the case studies. This may be seen as a limitation in industries characterised by specific environmental impacts, as these may not be captured by the suggested set of indicators. However, this shortcoming can be easily addressed thanks to the modular structure of the method: additional environmental indicators can be included in eco-intensity ratios to represent industry-specific environmental impacts or particular priorities of the supply chains. At the same time environmental indicators not relevant for a specific industry can be also removed.

Finally, the environmental indicators do not take into consideration location-specific factors regarding the environmental impacts generated. Some environmental impacts have consequences locally or at a regional level, whereas other environmental impacts have a global impact on the environment. For example, water consumption is considered critical as it can generate water scarcity at a regional level due to the impossibility of transporting water over long distances efficiently (Schornagel et al., 2012). On the other hand, GHG emissions are tackled due to their contribution to global warming, which is a phenomenon with consequences worldwide (Vasan et al., 2014; Zamboni et al., 2011). However, there is not a general consensus on the geographical scale of other environmental categories, such as material consumption, as this depends on the underlying assumptions and definitions of the concept of environmental sustainability. For this reason, no distinction about local, regional and global impacts was evidenced in the proposed environmental indicators. However, future research may introduce location-specific factors, such as water stress index (Pfister et al., 2009), to weight certain environmental impacts based on the locations of the site. This research direction appears particularly interesting to study international and global supply chains to investigate the impact of supply chain design decisions and reshoring decisions.

Denominator: economic output

The economic output, expressed in monetary units, is adopted as the reference factor for the environmental impact, being the denominator of the eco-intensity indicators. More specifically, this is expressed within this research as the turnover of each organisation i (T_i)

for the eco-intensity at the company level or the amount of turnover generated by a product k sold by organisation i (T_{ik}) at the product supply chain level. This choice was guided by the nature of the supply chain context, where independent organisations coexist: both values can be shared with other supply chain members without undermining the competitive advantage of organisations. The organisation-wide turnover is a value that is typically publicly available, whereas the turnover generated by a product is the multiplication of quantities times their unitary price, thus being already known to both organisations in each dyad along the supply chain as part of their business transactions. This is a key advantage of the selected economic indicators adopted, in contrast to other economic indicators widely used in the literature such as cost or net present value. Finally, the application range of the selected denominator is particularly extensive, being applicable to virtually any physical product.

Moreover, the selected denominator adequately captures variations of the economic outputs in most instances. T_{ik} is defined in this research as the product of quantities and prices and is therefore a function of these two variables. The variation of T_{ik} is determined by a change of the quantities Q_{ik} or the price P_{ik} or both. An increase of Q_{ik} represents a positive variation in the annual volume produced, which is generally associated to an improved economic performance. Alternatively, an increase of price P_{ik} may be the effect of focal companies selling deliberately its products at higher prices seeking for additional profits or the influence of a broader volatility of prices within an economic system (Bernardi et al., 2012).

In the first case, the increase of the price P_{ik} is the result of an arbitrary increase of the price by the focal company only, seeking for additional profits. Under the formulation of the method, this could also reflect an attempt to greenwash the organisational and supply chain environmental performance. However, an arbitrary increase of P_{ik} is extremely difficult to be achieved in a competitive market without affecting the quantities Q_{ik} unless the demand is fully inelastic. While considerations on the price elasticity of demand and its effects on the product supply chain eco-intensity are outside the scope of this research, an overall increase in the turnover generated by an increase of P_{ik} with a stable or less than proportional decrease of Q_{ik} is here considered as a proxy of an improved economic performance.

Vice versa, the increase of the economic output, and therefore an improvement in the eco-intensity indicators, determined by market prices instead of operational improvements, is considered a disadvantage of the selected denominator. Price volatility may be determined by a variation in the market demand, by a variation of prices along the supply chain with a “domino effect” along the chain (e.g. resulting from a variation in the price of raw materials) or may be the result of a general increase of the level of prices within the economy (e.g. due to inflation, discussed in detail in Section 7.1.2.4). Both these instances do not represent a real improvement of the economic output but they are a consequence of market forces, which have an influence on the eco-intensity indicators.

Full ratio: eco-intensity

Building on the paragraphs dedicated to the environmental numerator and economic denominator, a comprehensive discussion of the full eco-intensity ratio is provided here. The values of the eco-intensity indicators can be lowered and therefore improved through five different paths, as illustrated in Figure 7.1:

(A) Improvement of the absolute environmental performance, which means maintaining a stable economic performance while lowering the environmental impact for one or more environmental indicators; this improvement path moves along the environmental performance axis at the intersection between the 'win-win' and the 'trade-off with environmental preference' quadrants;

(B) Improvement of the absolute economic performance, which means maintaining a stable environmental performance while increasing the generated turnover; this improvement path moves along the economic performance axis at the intersection between the 'win-win' and the 'trade-off with economic preference' quadrants;

(C) Simultaneous improvement of the absolute environmental and economic performance: a combination of the two previous strategies, which implies an improvement path anywhere in the 'win-win' quadrant;

(D) Improvement of the absolute economic performance proportionally greater than the worsening of the absolute environmental performance; this improvement path lies anywhere in the orange area within the 'trade-off with economic preference' quadrant;

(E) Improvement of the absolute environmental performance proportionally greater than the worsening of the absolute economic performance; this improvement path lies anywhere in the orange area within the 'trade-off with environmental preference' quadrant;

While all paths determine an improvement in terms of eco-intensity, they denote different features in terms of absolute environmental performance. Three paths (A, C, E) show an improvement of the absolute environmental performance, path B implies a stable absolute environmental performance, while path D even endorses a worsening of the absolute environmental performance if this is balanced by disproportionally higher improvement in the economic performance. In the instances of improvement B and D, the improvements in the economic output need to be properly assessed to determine whether they are the effect of an actual better economic performance or the effect of market forces, as illustrated in the previous paragraphs on the economic denominator. While improvement paths B and D are both legitimate according to the weak sustainability perspective, a better economic performance due to solely market forces could potentially determine a greenwashing of the eco-intensity indicators of the supply chain, without any actual operational improvement of the supply chain.

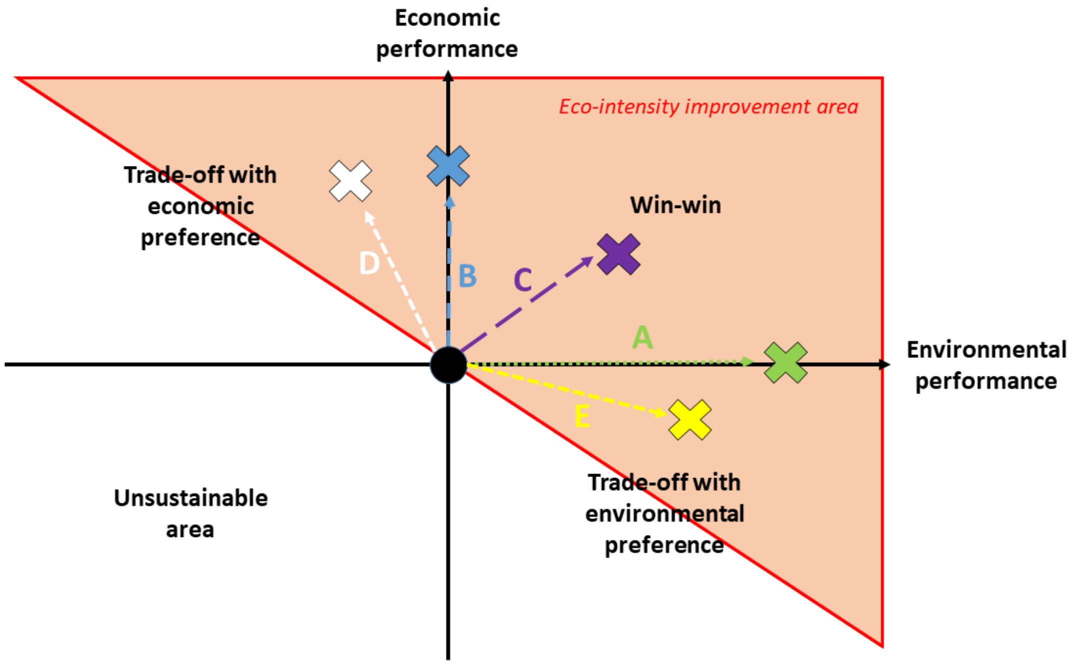

Figure 7.1: Eco-intensity improvement paths

Ultimately, Paths B and D highlight one feature embodied in the concept of eco-intensity, which is realising improvement in the eco-intensity performance without any actual improvement in the absolute environmental performance. This is however legitimate under the weak sustainability perspective embraced in this research, which adopts a techno-centric stance and implies a perfect substitutability between the sustainability dimensions. While criticism towards weak sustainability have been raised on the account of making 'bad' systems 'less bad' and due to the lack of consideration for the irreversibility of the natural capital (Hay, 2015), weak sustainability is the perspective adopted by organisations as their existence depends on economic outputs (Fritz et al., 2017). This is aligned with the current economic paradigms of development, which are still primarily based on economic growth (Braungart and McDonough, 2008). As organisation are required to operate in such context, eco-intensity is tailored for business as it complements environmental improvement and economic prosperity (WBCSD, 2000). Consequently, eco-intensity ultimately expresses how efficient an economic activity is towards nature and drives organisations to create more value with less impact, in line with efficiency-oriented philosophies (Huppes and Ishikawa, 2005).

7.1.1.2 System boundaries

The system boundaries are defined according to the cradle-to-gate approach and the transformed resources concept, as detailed in Section 4.1.2, and are applied to forward supply chains, as per the scope of this work. This choice implied that other entities outside these boundaries were not included in the assessment. The choice of excluding the usage phase and EOL of the product is the most notable exclusion, as the selected system boundaries may determine an underestimation of the environmental impact of products in a lifecycle perspective, whenever the direct or indirect environmental impacts of the usage and EOL are the most significant (Chatzinikolaou and Ventikos, 2015; Cichorowski et al., 2015; Veleva et al., 2003).

However, the inclusion of usage and EOL stages is incompatible with the black box approach, which prescribes data being collected at the company level and allocated to the products based on the economic output they generate. Black box approach cannot be extended to the usage phase for two reasons. First, if the focal company operates in a B2C context, customers are individual consumers rather than businesses, making the allocation logic from the company level to the product level inapplicable. Second, even if the customer is a business (B2B), a company using a product, i.e. a machinery for the production process, does not generate a direct economic output out of the product by re-selling it, as the product does not necessarily carry a monetary market value at the end of its useful life.

Moreover, additional factors limit the extension of system boundaries downstream. The method focuses on the part of the lifecycle of products that focal companies have power to influence. Vice versa, they have limited control over usage and EOL lifecycle stages. Furthermore, the extension of system boundaries downstream is hampered by the challenges and uncertainties associated to the collection of primary environmental data for these stages as well as the potential different EOL options faced by products in different geographical markets (Michelsen et al., 2006). The combination of such factors strengthens the decision to exclude these lifecycle stages as their inclusion within the method would have affected its usefulness for organisational decision making.

The cradle-to-gate system boundaries determines that reverse supply chain and closed-loop supply chains are excluded from the domain of use of the method at the current stage. Closed-loop supply chain cannot be assessed due to the specific design choices inherent in the method, which naturally exclude the usage phase from the environmental performance assessment. On the other hand, reverse supply chains could be addressed in future work as all entities part of the supply chain are typically organisations and the black box approach could be systematically adopted, should all organisations part of the supply chain be profit-oriented. However, a re-shaping of the cradle-to-gate system boundary would be required regarding the definition of the concept of 'cradle'.

7.1.1.3 Black-box approach

The method presented in this thesis blends collection of environmental data at the company level with an assessment of the supply chain at the product level. The adoption of black-box approach is functional to this, along with the allocation method of the environmental impacts within each organisation based on the economic output generated by each product.

The black box approach facilitates the data collection process, as each organisation is required to collect the data for each environmental indicator only once, even in the presence of a wide product mix. Data collection at the company level significantly lowers the effort required by companies compared to data collection at the product or process level and is suitable for SMEs as well, which are typically lagging behind in the path towards sustainability (Yusuf et al., 2013).

The combination of data collection at the company level with the allocation mechanism ensures that all environmental impacts of an organisation are taken into account and transparently assigned to the product mix, assigning mutually exclusive portions of environmental impacts to each product (Wiedmann et al., 2009). This allocation method aims also to avoid greenwashing practices, which may occur when only a specific product or a set of products are analysed with respect to the environmental performance. The production processes in use for those specific products along the supply chain may be environmentally friendly, but may take place in organisations that are not environmentally sustainable as a whole. This would ultimately expose to reputational risk the focal companies against their stakeholders, as the organisations are held responsible for their selection of the upstream suppliers as a whole rather than at a product level (Gimenez and Tachizawa, 2012).

On the other hand, the allocation of environmental impacts based on the economic output risks to overestimate or underestimate the actual environmental impact associated with each product supply chain internally to each organisation, as in the case of water consumption in CS1. Although a clear liability for the environmental impact is assigned to each organisation part of the supply chain (Defra, 2006; Ding et al., 2014) and the overall evaluation of its product mix is fair, products contributing to a higher share of the turnover are allocated a higher environmental backpack despite not necessarily carrying a proportional polluting contribution in terms of production processes. This is a challenge faced commonly by allocation rules for products made sharing the same processes or facilities. Finally, products with a long lead time may also face issues of overestimation or underestimation across consecutive years if the demand is irregular.

7.1.1.4 Indirect-multi-tier supply chain management approach

The indirect multi-tier supply chain management approach was used in the method to reach lower-tier suppliers based on the evidence that focal companies do not have visibility beyond 1st tier suppliers (Egilmez et al., 2014; O'Rourke, 2014).

The indirect multi-tier supply chain management approach entails that the eco-intensity assessment of multi-tier supply chains is realised through a decentralised approach thanks to a recursive mechanism to pass the eco-intensity values from one tier of the supply chain to the next. In their systematic review of multi-tier sustainable supply chains, Tachizawa and Wong (2014) asserted that "it is difficult for a single company to manage compliance within the entire supply chain, thus cross-tier collaboration is essential", owing to the limited visibility of the supply chain by focal companies (Acquaye et al., 2014; Egilmez et al., 2014; Michelsen and Fet, 2010). The multi-tier GSCM performance assessment method introduced in this research thus advocates for a cross-tier ripple effect along the supply chain within the area of GSCM performance assessment (Koh et al., 2012), recognising that it is crucial to share responsibilities between supply chain tiers in order to advance the transformation of supply chains towards sustainability (Jabbour et al., 2018).

The adoption of indirect multi-tier SCM approach in the method has the advantage of respecting the multiple-organisation nature of supply chains considering organisations as independent entities with potential conflict of interest arising between them. The decentralised approach differentiates from approaches developed in the literature so far, which either neglect the multi-tiered structure of supply chains assuming the existence of a centralised superior coordination of the supply chain or assume a collaborative relationship between different tiers of the supply chain. The indirect approach not only facilitates application in non-collaborative contexts thanks to a limited exchange of information required between different tiers of the supply chain, but it also facilitates the evaluation of the supply chain in contexts where organisations have a limited visibility and traceability of their supply chain.

The limited information focal companies have about their own supply chain has implications also on the level of control and influence these organisations are able to achieve throughout their supply chain. It is difficult for a company to manage directly the multi-tier supply chain, therefore suppliers play a pivotal role to reach further upstream supply chain tiers (Wilhelm et al., 2016a). Sustainability issues are no exception to this. In this work, the capability of the supplier to involve the sub-supplier in the calculation of the supply chain environmental impact is a key aspect for a successful application of the method. The ability of a company to "measure and manage sustainability performance of a supply chain depends largely on the level of influence it has on the other partners in the chain" (Beske-Janssen et al., 2015). A developed relationship, such as a partnership, between a supplier and a customer might facilitate the participation of the supplier to the assessment and the inclusion of its upstream suppliers. On the other hand, if the relationship between the supplier and the customer is transactional, the success of pressure from each supply chain tier to its upstream supplier will depend on the relative supplier and buyer power as defined by Porter (1979). Companies are able to significantly influence their direct suppliers when they have a high relative power balance to their suppliers due to relative utility, the share of the suppliers' turnover they generate, the relative scarcity of resources that are exchanged between the two parties and the easiness of substitutability of the suppliers (Cox et al., 2007; Michelsen and Fet, 2010; Scott and Westbrook, 1991). This importance of relative power for the implementation of sustainability initiatives was also confirmed by experts during I2 and by the supply chain manager of FC2 during the follow-up interview. The applicability of the method is therefore influenced by power asymmetry in the multiple supplier-customer dyads along the chain, alike most environmental sustainability supply chain initiatives. This may determine an increased easiness in the applicability of the method for focal companies having positional power in the supply chain, i.e. providing the conduit to the market (Mena et al., 2013). This may be the case of many large organisations which are then more likely to involve dependant suppliers within the assessment process and are potentially able to generate a multiplier effect along the chain (Grimm et al., 2018, 2014; Lee et al., 2014).

7.1.1.5 Transport

Transport was the last pillar introduced within the conceptual model, based on the model qualification findings. Based on the insights of I2, transport was added both to the conceptual and the mathematical model allowing to calculate 'Energy consumption' and 'GHG emissions' of transport activities linking supply chain member.

Transport is largely outsourced to third party logistics providers in contemporary supply chain (Christopher, 2011; Santibanez-Gonzalez and Diabat, 2013) and, acknowledging this feature, the developed method is able to capture the key variable that supply chain members are able to influence, which is the mode of transport adopted. Moreover, this variable is also critical to the overall environmental performance (Bouchery et al., 2012; Kannegiesser and Günther, 2013), along with distance travelled and quantities transported. With this respect, the method captures the decision-making process of organisations while achieving a complete evaluation of the environmental performance.

On the other hand, formulation of transport assumes a mono-directional transport within each dyadic supply chain link, a condition that may not always be satisfied in the case of outsourcing companies, with a potential underestimation of the environmental impact of transport activities. Moreover, since products do not undergo any physical transformation during transport apart from spatial transformation, transport is considered as a service and, as such, it is treated outside the black box approach. As a result, a potential shortcoming of this choice is the fact that, differently from organisations part of the supply chain, selected third party logistics providers are not evaluated as an organisation overall, but limited to the service offered within the supply chain. As a result, they may be an unsustainable organisation, even if they provide environmentally sustainable transport for the specific supply chain. This is due to the adopted conceptualisation for supply chains, which relies on physical transformation to associate an organisation to a tier of the supply chain.

This limitation can be extended to any other service supplier within the supply chain. Due to the assumptions and definitions adopted to model the supply chain, the environmental impact of service activities is not considered within the current method. The manufacturing activities are extensively reported as those having the greatest environmental impact (Ramani et al., 2010; UNEP, 2010), however the extension of the method to include service activities is an interesting future research direction, which would require a re-definition of several conceptualisations adopted in this research, such as the system boundaries and the identification of tiers.

7.1.1.6 Summary of the conceptual pillars

Each of the pillars of the conceptual model discussed throughout Section 7.1.1.1 to 7.1.1.5 contributed to develop a method suitable for supply chain-wide sustainability assessment. Schöggl et al. (2016) identified seven key requirements for sustainability assessment in multi-tier supply chains. Table 7.1 summarises the main issues associated to each requirement and the actions undertaken in this research to address each of them, while mentioning the conceptual pillar mostly contributing to the fulfilment of the requirement. Currently, the method fulfils six out of seven criteria, lacking only in the adaptability to regional and cultural characteristics, an aspect that is to be further developed in future research. Moreover, Table 7.2, adopting the same set of criteria, compares the GSCM performance assessment method developed in this research with other methods available in the literature.

Table 7.1: Summary of key requirements of multi-tier supply chain sustainability assessment

Requirement	Main issues	Pillars	Action
Accessibility for companies inexperienced in sustainability assessment	Limited resources in SMEs and developing countries to conduct sustainability assessment; Low level of detail of information available; Amount of workload to dedicate to sustainability assessment;	Black-box approach	Simplified data collection at the company level; Multiple sources usable to feed environmental data into the method;
Applicability with respect to different types of sustainability data	Meaningful aggregation of data along the supply chain;	Eco-intensity; Transport;	Eco-intensity concept to standardise data among different organisations, independently from industrial sector or product; Standardised collection of environmental impact from transport through EcoTransIT;
Applicability in supply chain-wide assessment	Dyadic approach dominating supply chain sustainability assessment; Supply chain wide assessment of non-mandatory issues non-existent;	Indirect SCM approach	Dominating dyadic relationships along the chain are replicated in the method; Decentralised approach to extend progressively the assessment towards upstream supply chain;
Adaptability to supply chain dynamics	Dynamic nature of supply chain requiring metrics to evolve over time	Eco-intensity	Modular method with additional environmental numerators potentially integrated in the method within eco-intensity indicators
Adaptability to regional and cultural characteristics	Importance of sustainability issues varying across different areas	Not available	Future research to tackle geographical differences in environmental indicators

Requirement	Main issues	Pillars	Action
Comparability of results	Cross-company and cross-supply chain benchmarking difficult because of different guidelines	Eco-intensity; System boundaries;	Economic output as unique reference value for environmental impacts, allowing extensive benchmarking; Unique definition of system boundaries to enhance comparability of results;
Robustness in the face of insufficient information	Issues of confidentiality in the multi-tier supply chain; Data exchange to be limited to dyads; Incomplete information;	Indirect SCM approach;	Data exchanged only with direct suppliers and customers with no risk of leakage of data; Fictitious supply-chain mechanism developed to work with incomplete information (supply chain breadth);

Table 7.2: Comparison of the developed GSCM performance assessment method with other existing methods

Requirement	Process LCA	Input-output LCA	Green SCOR	*This work*
Accessibility for companies inexperienced in sustainability assessment	- Experience in sustainability assessment required to frame the study; - Not suitable for SMEs due to the lengthy data collection process and amount of dedicated workload required; - High level of detail of information required;	- Experience in sustainability assessment required to frame the study; - Access to relevant input-output tables and relevant database required; - Challenging application for SMEs; - Limited data available for developing countries;	+ Multiple secondary sources usable for the assessment - Experience in the overall SCOR framework beneficial; - Significant workload for each organisation due to the allocation of environmental impacts to various processes; - Limited data available for developing countries;	*+ Simplified data collection at the company level, making it suitable for SMEs and resulting in low workload for organisations;* *+ Multiple sources usable to feed environmental data into the method;*
Applicability with respect to different types of sustainability data	+ Meaninfgul aggregation of supply chain data achieved typically through midpoint indicators; + Aggreagation of different environmental indicators possible;	+ Meaninfgul aggregation of supply chain data achieved typically through midpoint indicators; + Aggreagation of different environmental indicators possible;	+ Standardised data collection across different organisations thanks to the SCOR framework logic; - No aggregation of different environmental indicators;	*+ Eco-intensity concept to standardise data among different organisations, independently from industrial sector or product;* *- No aggregation of different environmental indicators;*

Applicability in supply chain-wide assessment	- Applicable only for simple products due to the high detail of data required; - No consideration of supply chain dynamics arising between different organisations, limiting applicability in non-collaborative contexts;	+ Assessment carried out at focal company, with indirect impacts arising in the supply chain accounted through database values; - No consideration of supply chain dynamics arising between different organisations;	- No information available on the inclusion of organisations different from the focal company in the assessment; - No consideration of supply chain dynamics arising between different organisations;	*+ Dominating dyadic relationships along the chain are replicated in the method;* *+ Decentralised approach to extend progressively the assessment towards upstream supply chain;* *- Application with complex products challenging*
Adaptability to supply chain dynamics	+ Modular method with indicators selected based on the initial stage of goal and scope of the study; - No explicit consideration of supply chain dynamics;	+ Modular method with indicators selected based on the initial stage of goal and scope of the study; - No explicit consideration of supply chain dynamics;	+ Fixed set of indicators, revised constantly by the Supply Chain Council; - Additional indicators not supported due to closed design of the method;	*+ Modular method with additional environmental numerators potentially integrated in the method within eco-intensity indicators*
Adaptability to regional and cultural characteristics	- No consideration of regional characteristics	+ Multi-regional input-output LCA capturing some geographical differences	- No consideration of regional characteristics	*- No consideration of regional characteristics*
Comparability of results	+ Longitudinal benchmarking - Limited cross-case benchamrking, due to high influence of assumptions introduced in the definition of the goal and scope of the study, including the definition of the system boundaries	+ Longitudinal benchmarking - Limited cross-case benchamrking, due to high influence of assumptions introduced in the definition of the goal and scope of the study, including the definition of the system boundaries	+ Fixed set of indicators facilitating comparability of results over time; - No clear definition of system boundaries limiting cross-case benchmarking;	*+ Economic output as unique reference value for environmental impacts, allowing extensive benchmarking;* *+ Unique definition of system boundaries to enhance comparability of results;*

Robustness in the face of insufficient information	- Low robustness due to the extensive data collection required, with risks of incomplete information, often calling for a cut-off criterion along the supply chain; - Risks for data confidentiality due to the sharing of environmental data across all organisations part of the supply chain;	+ High robustness due to the extensive use of database values; + Low risks for data confidentiality due to the use of secondary data; - Multi-regional tables constantly being developed, thus different data available for different geographical regions;	+ High robustness due to the extensive use of database values; + Low risks for data confidentiality due to the use of secondary data;	*+ Data exchanged only with direct suppliers and customers with no risk of leakage of data;* *+ Fictitious supply chain mechanism developed to cope with incomplete information (supply chain breadth);* *- Potentially incomplete information in the lower-tier suppliers (supply chain depth);*

7.1.2 Reflections on the outputs and applications of the method

Three direct outputs are generated from the method, which are the single company eco-intensity, supply chain eco-intensity and the environmental backpack of products, which are all generated through the mathematical model (Figure 4.6).

The three outputs obtained through the method determined four areas of application to support practitioners, based on the different level of aggregation in terms of environmental aspects and distinguishing between the company and the supply chain level. These areas of application are discussed in the following sub-sections.

7.1.2.1 Operational improvement

The single environmental indicator supply chain eco-intensity has the identification of environmental hotspots as one of the main applications. The identification of hotspots fulfils the purpose of highlighting optimisation potential of the environmental performance (Jasch, 2000), which is to be subsequently pursued through operational improvements.

The identification of hotspots is achieved recursively moving upstream from the focal company. Indirect multi-tier SCM approach is applied consistently also for the identification of hotspots based on the fact that focal companies do not have visibility beyond 1st tier suppliers. At each iteration, the most eco-intense supply chain branch for each environmental indicator e is recognised, by identifying the organisation with the highest eco-intensity including environmental backpack. Hence, from the focal company perspective, the method identifies the 1st tier supplier with the worst performance, which represents the hotspot for that supply chain tier. This ultimately aligns the method with multi-tier supplier evaluation, as each supplier carries the environmental backpack of its own suppliers. Repeating the mechanism moving upstream, the absolute hotspot, i.e. the organisation within the entire supply chain with the highest eco-intensity, is not necessarily identified through the method, as it does not always belong to the supply chain branch of the most eco-intense 1st tier supplier. This was the case in a specific counter-example in the mathematical model verification stage (EI2, SC2).

This apparent limitation in the hotspot identification is actually mirroring the visibility and dynamics in actual supply chains, which are based on dyadic relationship, hence companies are interested in identifying hotspots among their direct suppliers through a tier-by-tier approach rather than identifying the absolute hotspot in the supply chain, as they may not have business relations nor be able to influence this organisation.

The method is effective in identifying the hotspots for each environmental indicator e, providing guidance on directions to follow towards operational improvement. The organisations identified as hotspots through the recursive iterative approach are those where action is to be prioritised to improve the eco-intensity performance. The organisations identified as hotspots face five potential paths to improve eco-intensity, which do not all necessarily imply an improvement in the absolute environmental performance, as illustrated in Section 7.1.1.1.

As eco-intensity is a relative indicator, it does not inform directly about the absolute environmental impact, an information that is instead conveyed by the environmental backpack output. This determines that undertaking operational improvements at such organisations does not necessarily provide the most impactful results at the supply chain level in terms of operational improvement. The absolute environmental backpack associated to the most eco-intense suppliers may not be significant if their contribution to the economic output of the supply chain is limited, resulting in their eco-intensity value being "diluted" by the eco-intensity indicators of sizeable suppliers. As a result, the hotspots mapping of suppliers needs to be evaluated in combination with the absolute values represented by the environmental backpack in order to identify areas for more effective results at the supply chain level.

Moreover, the identification of hotspots through the method serves only as a starting point towards operational improvement as the method does not further detail the performance within each black box, i.e. organisation, nor the actions required to improve the performance, as both aspects remain beyond the scope of this research. An interesting future research direction would be to identify how organisations deploy the insights provided by the method in actual improvement plans within their organisational boundaries and a detailed investigation of their effect at the supply chain level. Such operational improvement actions need to be evaluated through a cost benefit analysis at the hotspot company in order to identify the areas within the organisation where investments will be more effective (Tidy et al., 2016).

While directions for operational improvement are provided through the method, each organisation ultimately remains an independent entity and, as such, the decision to undertake operational improvement actions cannot be dictated by the focal company or any other member of the supply chain unless there is a legislative requirement pointing towards it. Focal companies can act only based on their relative power position and pressure their suppliers accordingly, as discussed in Section 7.1.1.4. The ultimate decision on the operational improvement actions belongs to organisational strategy and is here not discussed as outside of the scope of the research.

7.1.2.2 Trade-off between environmental aspects

The trade-off between environmental aspects is to be consolidated by the single company global eco-intensity and the supply chain global eco-intensity outputs. While the theoretical foundations for the calculation of these outputs were laid in this work, the lack of a suitable normalisation technique prevented its full realisation.

Global eco-intensity is an aggregated index. Three steps are required to obtain aggregated indexes: normalisation, weighting and aggregation (Salvado et al., 2015; Zhou et al., 2012), as outlined in Chapter 4. Equal weighting and linear aggregation were identified in Chapter 4 as techniques to address two steps. Both were selected because of their objectivity, without requiring the inputs of decision makers (Wang et al., 2009). On the contrary, no normalisation technique available in the literature was deemed appropriate to be included in the method at the current stage. An external normalisation technique (Tugnoli et al., 2008) is required to allow external comparability of results and avoid a narrow self-referential approach within the supply chain, which would be achieved with internal normalisation. However, most normalisation technique, which do not rely on opinions of experts, adopt internal normalisation, as detailed in Section 4.2.2. The rationale behind this decision is that, adopting internal normalisation a relative comparison between supply chain members would be applied. Internal normalisation is not deemed suitable as a normalisation technique to be adopted within the developed method, as an organisation with an environmentally sustainable profile within a supply chain could prove to be unsustainable in comparison to its competitors belonging to different supply chains. Therefore, the method would not meet one of the requirement guiding the development of environmental performance measurement system, which is the cross-case comparability (Jasch, 2000).

Potential external normalisation factors were explored but later deemed not appropriate or applicable to the method for different reasons. The lack of available data inhibited the use of best practices or average values at the industry level as reference factors. Surface areas of impact or affected human population were also discarded due to the uncertainties regarding the geographical scale of certain environmental impacts, as discussed in Section 7.1.1.1.

As a result of the lack of a normalisation technique, the findings of both the numerical example and the case studies only include single environmental indicator eco-intensity at the company level and at the supply chain level. The lack of a normalisation technique prevents the comparison of different environmental impacts and inferring about priorities among environmental categories in terms of operational improvement.

Consequently, the method was not fully evaluated with respect to global eco-intensity outputs, highlighting a future research direction. The lack of a global eco-intensity indicator determines that the method did not offer synthesised information about the overall environmental performance at the product level and at the supply chain level in such applications. This is a limitation, which partially affects other applications of the method.

A unique index aggregating the environmental impacts would be an additional layer of information for decision-makers, which could be more easily integrated with other key performance indicators, as recognised by the supply chain manager of FC2. This would particularly be particularly useful when eco-intensity indicators provide conflicting results in the benchmarking of different product supply chains. On the other hand, the issue is not as critical for supplier evaluation as internal normalisation can be adopted in certain instances for this application, as illustrated in CS2 (Section 6.2.6.1). Moreover, an aggregated index would also simplify the understanding of the environmental performance in an external reporting perspective, especially with non-experts, as it would provide a single value summarising the environmental performance.

Despite providing advantages in terms of decision-making and communication, an index obtained through the steps of normalisation, weighting and aggregation introduces certain methodological bias in the method (Ichimura et al., 2009), "as these steps inherently introduce a certain degree of subjectivity, which could influence the overall results" (Daystar et al., 2015). In fact, the results "undesirably are dependent on the specific weighting system employed alongside the aggregation method used for combining the various factors involved" (Ahi and Searcy, 2014). The increased number of assumptions determines a higher uncertainty in the results, as an additional layer of conceptualisation is introduced between the method and the underlying reality. The aggregated information also determines a partial loss of information in the outputs, as the level of granularity of single environmental impacts is hidden in an aggregated index format. Therefore, future research direction is required to identify a suitable normalisation technique to obtain global eco-intensity indicators, however these cannot be applied independently and need to be utilised in parallel with eco-intensity indicators for specific environmental indicators in order to achieve the full potential of the developed method.

7.1.2.3 Supplier evaluation and organisational external reporting

The eco-intensity indicators at the company level find a basic application for external reporting at the organisational level, potentially being incorporated as part of the corporate sustainability reports. Moreover, they can serve to define environmental targets of the organisation, given the suitability of the method for benchmarking over time (Section 7.1.2.4).

Additionally, they can be adopted as part of the supplier evaluation process. The key advantage of the method towards this application is that the method can indirectly achieve a multi-tier supplier selection and evaluation. The eco-intensity value passed by suppliers to their customers include the environmental backpack associated to their upstream supply chain. With this respect, customers do not simply evaluate alternative suppliers but supply chain branches instead, capturing the need "to spread sustainable supplier selection across multiple supply chain tiers" (Jabbour et al., 2018).

In a simplified application, the method can also be adopted to assess the eco-intensity performance of suppliers without their environmental backpack, should a focal company limit its assessment to its 1st tier suppliers. In this case, the internal eco-intensity values are to be forwarded downstream from the suppliers without any further adjustment.

The simplified version of supplier evaluation was tested in CS2 where two alternative parallel suppliers were evaluated. An internal normalisation technique was used in this instance to support the identification of the most environmentally sustainable supplier, however the introduction of a more robust external normalisation technique, as discussed in Section 7.1.2.2, would increase the application range of supplier evaluation as well, as it would allow comparing suppliers that do not necessarily have a similar business structure.

On the other hand, the evaluation of tentative suppliers, i.e. supplier selection, was not tested in this research. While the logic for supplier selection and evaluation is identical, the process of supplier selection may face further challenges. Most noticeably, the upstream supply chain may be non-existent as in the case of particularly innovative products (Knight et al., 2015). Moreover, in terms of applicability, the challenges associated to obtaining the information required before a business relation between supplier and customer is established are not to be neglected unless suppliers have already some sort of environmental reporting in place, which is aligned with the requirements of the method. With this respect, a drawback of the method is that it is not linked to any environmental legislative requirement or major reporting scheme, such as GRI, which can determine that new or tentative suppliers need to adapt their environmental reporting to the method, potentially slowing down the assessment process.

7.1.2.4 Benchmarking and external product reporting

The supply chain eco-intensity output has among its applications external reporting and benchmarking. External reporting of the product supply chain eco-intensity can be adopted to attract green consumers in a B2C context. The eco-intensity indicators can be included into labelling schemes and can be potentially communicated to customers adopting colours scheme, similarly to those used in this research to represent the hotspots, which were demonstrated to meet the favour of customers (Emberger-Klein and Menrad, 2018). Informing the customers about the product is considered a form of product responsibility as well, thus contributing also towards social sustainability.

The benchmarking of eco-intensity at the company level has been discussed in Section 7.1.2.3 by addressing the supplier evaluation application, therefore this section focuses on the benchmarking of the product supply chain eco-intensity. The benchmarking application of the method draws upon two pillars of the conceptual model, which are the eco-intensity concept and the system boundaries. The eco-intensity defines a unique reference factor for any product irrespective of the physical characteristics of the product and its final purpose. The benchmarking of different products is however only possible as long as they refer to common principles in terms of system boundaries, which is a pre-requisite to obtain comparability (Wiedmann et al., 2009).

The combination of these two aspects determine some advantageous features of the developed method for both cross-case and longitudinal benchmarking, as summarised in Table 7.3. For cross-case benchmarking, the selection of monetary units as the reference unit for environmental impacts allows the application of the method to any profit oriented company and the implementation of the method consistently across different industries, as the case studies demonstrated. Alternative reference units used to obtain relative indicators do not share this feature, as they are either product-specific, like in the case of product unit, weight or volume, or they are related to the performance the product fulfils, like in the case of the functional unit. The latter especially has been targeted with criticism, due to the subjective definition of system boundaries, which is affecting the comparability of results and its ambiguous definition on occasions (Croes and Vermeulen, 2015; Finnveden et al., 2009). As an example, the interpretation of the environmental impact of white bread and wholemeal bread supply chains through relative indicators could be based on different functional units, assessing the environmental impact per weight of bread or per nutrient intake, with results varying as much as 300% based on the selected functional unit (USDA, 2016). Eco-intensity thus removes the constraints imposed from alternative reference factors and broadens the opportunity for benchmarking of the environmental performance of product supply chain, adopting a unique reference factor, which theoretically allows even comparing a loaf of bread to an engine.

The adoption of eco-intensity is not only beneficial to the benchmarking of different product supply chain, but it also advantageous for longitudinal benchmarking. Products do not necessarily remain the same over time, i.e. electronic products, but they are constantly innovated with implications on the supply chain. In these instances, the benchmarking over product units assumes products are comparable over time, while using functional unit as the reference factors poses serious challenges in terms of system expansion (i.e. mobile phone and smartphone). The use of eco-intensity, having a different approach to benchmarking relaxes these constraints as well, simplifying longitudinal benchmarking applications. However, future work is required on the longitudinal benchmarking application of the method. The method needs to be practically validated with respect to this application, as this was not possible in this research due to time constraints posed by the research project. A future scenario evaluation was performed in both case studies to understand the potential impact of managerial decisions on the supply chain environmental performance, however both scenarios were affected by the amount of assumptions introduced, most noticeably the constant values for economic indicators. Environmental indicators were also assumed constant outside from the organisation(s) affected from the operational improvement scenario. As a result, scenario evaluation performed some sort of benchmarking between as-is scenario and potential future scenario, but this cannot be deemed equal to an actual longitudinal benchmarking application, as the number of assumptions introduced was too high.

Table 7.3: Comparison of main reference factors for product supply chain relative environmental indicators

Reference factor	Cross-case benchmarking		Longitudinal benchmarking
	Products with similar physical properties	Products with similar performance attributes	Products with similar physical properties
Functional unit	Only if they share the same function	Yes	Only if they share the same function
Unit of product/ Weight/ Volume	Yes, under the assumption products fulfil same performance attributes	No	Yes, under the assumption products fulfil same performance attributes
Monetary unit	Yes	Yes	Yes

The advantages for benchmarking derived from the adoption of eco-intensity outweigh its limitations, which however cannot be neglected. The selection of monetary units as the reference factor exposes the method to variation of the economic output, based on the variation of prices (Bernardi et al., 2012). While the fluctuations of prices internally within the supply chain in a micro-economic perspective was discussed in Section 7.1.1.1, a macro-economic perspective is taken in this section. At a higher level, prices may vary both over space and time (Finkbeiner, 2016), which are deeply intertwined, determining a variation of the value of money depending on these two variables. The variation of prices over space has an impact on cross-case benchmarking, whereas the variation of prices over time affects predominantly longitudinal benchmarking.

The variation of prices over space is essentially determined by the adoption of different currencies in different geographical areas. Currencies can be converted by either using exchange rates, which convert the nominal value of currencies, or purchasing power parity exchange rates, which convert the purchasing power value of producers and consumers within an economy (Eurostat, 2010). Under the current formulation of the method, the currencies are converted by exchange rates, however these are “unable to capture geographical differences in relative prices” (Finkbeiner, 2016). This is particularly critical in the case of developing countries, whose weakness of local currencies in the international market has been long established (Eurostat, 2010). At a theoretical level, the cross-case benchmarking of two organisations and/or supply chain under the assumption they have the same absolute environmental impact and the same economic output at purchasing power exchange rates, would favour the one located in a geographical area where the currency is stronger according to the current formulation of eco-intensity indicators. Future research is required to understand the impact of spatial variation of prices on the results of the method.

The variation of prices over time is instead determined both by variation in the supply and demand conditions (Finkbeiner, 2016), as discussed in Section 7.1.1.1, but also from the inflation rate, which is the variation in the general level of prices within an economy. As a result, longitudinal benchmarking applications need to encapsulate a common time reference for the economic indicators. The harmonisation of prices and turnovers could be achieved by introducing an inflation rate coefficient as part of the denominator of eco-intensity ratios (European Commission et al., 2014; European Environment Agency, 2016; Goedkoop et al., 2009; WCED, 1987).

The combined variation of prices over space and time needs also to be addressed. The exchange rates between different currencies are not fixed since the floating exchange rate regime became widespread around the globe in the 1970's. Exchange rates of currencies are prone to vary over time due to monetary policies of countries and macro-economic factors, beyond the control of any organisation. While the variation of prices in space and time were addressed individually, their combination needs to be carefully evaluated due to potential correlations arising between the two. As a result, more research is required in this direction.

Finally, it is necessary to point out that all above considerations are only valid under the assumption of the performance assessment being carried out referring to the same system boundaries. This means that cross-case benchmarking of product supply chain eco-intensity performance is significant in the case that the cradle-to-gate supply chain is assessed in accordance with the system boundaries identified in Section 4.1.2. This may not be the case for complex products due to incomplete data, as CS2 demonstrated. On the other hand, the issue of incomplete data does not affect longitudinal benchmarking as the system boundaries could be defined consistently across several years. The cross-case benchmarking in a practical context may also be challenging if companies do not publicly disclose information about their environmental performance, as it would require organisations to access to information from competitors.

7.1.2.5 Summary of outputs and applications

Sections 7.1.2.1 to 7.1.2.4 touched upon the main outputs obtained through the method and their most significant applications within the supply chain context. This section provides a brief summary of these, adopting the purposes of environmental performance assessment identified by Jasch (2000) as a reference. The purposes are listed in the first column of Table 7.4, with details of how the method does or does not achieve each purpose listed in the second column. The method outputs and its application are able to fulfil partially or completely all purposes listed by Jasch (2000), except the technical support for environmental management systems.

Table 7.4: Environmental performance assessment checklist

Purpose	Advantages and limitations of the developed method	
Communication for environmental reports	+	External reporting both at the company level and at the supply chain level
	-	Not linked to any existing legislation
Cross-case benchmarking of environmental performance	+	Cross-case benchmarking can be applied to any product, including products with similar physical characteristics and products fulfilling the same purpose.
	+	Applicable to supplier evaluation and multi-tier supplier evaluation (thanks to environmental backpack inclusion)
	-	Space variation of prices to be further explored
	-	Practically challenging to apply as requires data from competitors unless data publicly available
Longitudinal benchmarking of environmental performance	+	Longitudinal benchmarking can be applied to any product, including products with similar physical characteristics and products fulfilling the same purpose.
	-	Volatility of prices may influence results
	-	Inflation rate and variation of exchange rates (for international supply chains) not accounted
Derivation and pursuit of environmental target	+	Possibility to set environmental targets both at the company level and at the supply chain level
	-	Similarly to benchmarking, environmental targets are linked to the economic performance in a weak sustainability perspective
Highlighting of optimisation potentials	+	Identification of hotspots for each environmental indicator
	-	Hotspots to be analysed in combination with environmental backpack to identify highest optimisation potential at the supply chain level
	-	Detailed operational improvement within each black box not addressed (beyond the scope of the research)
Identification of market chances and cost reduction potentials	+	Method offers potential for identification of win-win solutions, especially regarding environmental inputs (cost reduction)
	-	No market chances identified
Technical support for Environmental Management Systems	-	Not available

7.1.3 Reflections on the practical applicability of the method

The method evaluation consisted of qualification, verification and validation in order to address objective 5 (O5). Moreover, the validation of the method in an operating context also contributed towards objective 4 (O4) and assumed particular importance not only for testing, but also for operationalisation and generalisation of the research, coherently with the deductive methodology adopted in this research.

The validation of the method was pursued through case study research, which highlighted additional advantages and limitations of the method compared to the theoretical reflection addressed in sections 7.1.1 and 7.1.2. Moreover, challenges to the applicability of the method were also identified during validation.

In terms of environmental data availability, the case studies proved that the environmental data to be collected are typically available in most organisations. Despite involving micro enterprises, CS1 covered five out of seven environmental impact areas, while CS2 covered six environmental impact areas. Both case studies did not cover the emissions to water, due to the lack of available data, while also material consumption environmental indicator was not available in CS1. The lack of environmental data in the emissions to water category aligns with the findings of the systematic literature review, where this category was included in the least number of paper with the lowest number of associated measurements, probably reflecting a lack of interest in both research and practice for this environmental aspect. Future work will require tackling emissions to water in a case study adopting primary data to demonstrate the applicability of the method also with this environmental category.

In terms of data quality, the values of the outputs of the method are affected by the data fed into the mathematical model as inputs, which are the environmental and economic indicators, like the turnover and the share of turnover generated by a product. These values were particularly critical in the case studies, where primary data sourced from actual practice were adopted. The material consumption eco-intensity of suppliers 2.2.1 and 2.2.2 showed several orders of magnitude in the value of the organisation-wide indicator. While a certain difference in the material eco-intensity profile was justified from the different production processes in place at the organisations, the magnitude of the difference could have been arisen due to some error at the stage of data collection, as confirmed by the supply chain manager of FC2 in the follow-up interview.

A definition of each environmental indicator was provided to participating organisations in order to have a common reference for the environmental indicators across both case studies, however this could not have necessarily been interpreted in the same way by the people filling the spreadsheet. Moreover, the researcher did not prescribe how the data should be collected, as this was outside the scope of this research and different organisations record such information according to their internal practices. Sources of data are quite broad and include, but are not limited to, documents from the purchasing department for the use of materials, utility bills for water consumption, energy consumption and waste, reading from meters. On the one hand, the wide variety of sources of data facilitates the data collection process at the organisations as it does not impact heavily on their operations, but on the other hand it does not achieve a completely standardised data recording across the companies part of the supply chain. Since each organisation is responsible for its internal self-assessment, a mechanism to verify the environmental data provided by suppliers needs to be identified in the future, potentially through an audit scheme or including a third party platform external to supply chain members.

Additional challenges to the practical application of the method refer to the effective coverage ratio of the supply chain achieved by the method, as this has an impact on the results and applications attainable. The supply chain coverage is intended both in terms of supply chain extent or supply chain depth, which is the number of tiers involved in the assessment, as well as in terms of supply chain breadth, which is here defined as the number of organisations within each tier involved in the assessment.

Regarding the supply chain extent, it is possible that lowest tier suppliers cannot be involved in the assessment, due to the unsuccessful implementation of the indirect multi-tier SCM approach at any dyad along the supply chain either in the environmental pressure to obtain relevant documentation moving upstream or in the environmental performance communication moving downstream. Although the method does not require a collaborative supply chain to be applied, a minimal information exchange between the supply chain players is still required. Therefore, trust between supplier and customer in each dyadic relationship is crucial, since the environmental requirements are not mandatory by law. The influence of trust on the applicability of the method along the supply chain was confirmed by the cross-case comparison of enablers by both FC1 and FC2. Consequently, certain supply chain players may be unwilling to cooperate to the assessment, while other organisations might be unsuccessful in involving their own suppliers in the application of the recursive mechanism due to unfavourable balance of power along the supply chain as well as unavailability of data at some organisations. CS2 confirmed this as a supplier dropped out of the study due to its unwillingness to share environmental data. As a result, environmental data might not be available or collected for all supply chain tiers leading to an incomplete evaluation of the eco-intensity of the cradle-to-gate supply chain. This may be particularly the case of global supply chains, where a high number of intermediaries are involved and upstream tiers located in remote geographical areas may be difficult to be accessed (Wilhelm et al., 2016). This aspect was further reinforced by the findings from the cross-case comparison of the enablers to the applicability of the method, where both FC1 and FC2 recognised the significant influence of the capabilities of lower-tier suppliers to meet focal company's requirements as a key enabler. In the case studies presented in this thesis, CS1 depicted a three-tiers supply chain, consequently the extended supply chain was assessed, whereas CS2, showcasing a longer supply chain, did not manage to reach the raw material extraction stage, as such inputs are acquired on the commodity market, rather than being purchased from specific organisations. Assessing a limited extent of the supply chain compared to the system boundaries defined in Section 4.1.2 impacts mostly the cross-case benchmarking application which is not applicable consistently as different system boundaries do not allow comparing results (Wiedmann et al., 2009). On the other hand, hotspot identification and supplier evaluation remain possible, although decision-makers need to be alert of the incomplete evaluation when interpreting results, recognising that the different extent of supply chain branches may affect the results.

Regarding the supply chain breadth, the application of the method was complete in CS1 owing to the simplicity of the final product, whereas it was partial in CS2, due to the complexity of the final product involving around 1,000 components. As a result, a critical sub-system of the engine was assessed, taking into account the supply chain. This challenge may be common to other complex products where the bill of material of a product is particularly complex. A cut-off criterion may be necessary to be introduced to facilitate the operationalisation of the method in future work addressing complex products. This complexity may be further enhanced where multiple organisations are supplying the same intermediary products to a company. This challenge may be partially overcome by selecting a representative supplier for each intermediate product, assuming that the environmental profile of alternative parallel suppliers is similar. In this case, some applications of the method such as alternative supplier evaluation would not be available, whereas others, such as hotspot identification, would also be partially affected.

An additional challenge to the applicability of the method lies in the continuously changing structure of the supply chain, which determines an unstable supply base for certain organisations, especially for non-critical items. Such an occurrence was observed in CS2, where supply chain manager revealed the impossibility to access supplier 2.2.2 to double check the values of the material consumption environmental indicator, as the supplier had dropped out of the supply base in the meanwhile. This issue may become particularly critical for organisations that adopt a multiple-suppliers' procurement strategy, as the requirement to collect the data and feed them into an executable model may not be timely communicated along the supply chain down to the focal company to complete the evaluation of a product supply chain before the suppliers drop out of the supply base. Building on the considerations above, the method is best applicable to supply chains characterised by a stable supply base and a limited number of alternative suppliers supplying the same intermediary products.

7.2 Research methods

The previous section discussed the findings of this research, which were achieved thanks to the combined application of five research methods: systematic literature review, conceptual and mathematical modelling, semi-structured interviews, numerical example and multiple case studies. This section reflects on the research methods adopted in this research.

7.2.1 Systematic literature review

The method developed in this research stemmed from the gap identified in the literature. While a narrative literature review was conducted to cover the introductory topics to this research, the core of the literature investigation at the intersection of GSCM and performance assessment was conducted adopting a systematic approach. The systematic review was then complemented by a further round of state-of-the-art literature review regarding the topic of multi-tier GSCM, as this was deemed necessary from the identification of the main gap in the literature. Owing to time availability constraint, it was not possible to investigate systematically the multi-tier GSCM literature as well.

Systematic investigations of the literature minimise the bias in the selection of the reviewed materials, offering the opportunity to replicate the research and minimising the bias in the findings arising from the literature (Tranfield et al., 2003). The systematic literature review process does not only entail that data, in this case the sample of reviewed papers, are collected systematically, but it also involves a systematic interpretation of such data (Saunders et al., 2008). A rigorous process is therefore repeated at the stage of content analysis, enhancing the robustness of the literature investigation, as “a more systematic literature review process can help to justify/qualify the near/final research question which is posed” and to identify the gap in the literature (Tranfield et al., 2003).

Moreover, the systematic process to select the final sample of papers included in the review allows the adoption of statistical techniques to analyse the body of the knowledge and apply statistical significance checks (Gold et al., 2010), which would have not been otherwise possible due to the bias introduced at the stage of sample selection. Statistical techniques have been adopted in this work in the form of demographic statistics to describe the bibliographic details of papers published as well as in the form of contingency analysis to identify measures of association between environmental categories analysed. Contingency analysis provides a quantitative support at the stage of content analysis to detect relations between categories, thus further enhancing the evidence arising from the literature (Gold et al., 2010; Sauer and Seuring, 2017).

On the other hand, the systematic literature review approach has some disadvantages, despite the accuracy and rigour of the systematic process. The rigidity of the process throughout the stages of selecting the keywords, searching for the papers and applying inclusion/exclusion criteria may lead to the exclusion of relevant papers from the sample, thus overlooking work compatible with the review questions guiding the literature investigation. The size and content of the sample is affected by the database selection: other databases apart from Scopus and Web of Science may have offered the opportunity to consider additional publications as well as the consideration of documents from the practitioner community.

Moreover, the systematic approach at the stage of content analysis, despite providing a structured and summarised understanding of the body of research, suffers from constraints typical from any classification and thus may not adequately convey the complexity and the specific in-depth features of each paper. This was particularly observed in the environmental measurements evaluation, where some measures fell among multiple categories and required a decision about their classification, as well as in the supply chain extent evaluation, when the chain was described by the activities rather than the organisational entities involved. A careful analysis was required in these cases to assess the papers according to the categories adopted in the review and such decisions still required a degree of subjectivity, potentially affecting the final results.

Overall, a trade-off between meeting the criteria to make the review eligible to be considered systematic and the flexibility in the literature inquiry exists. An integration of a systematic approach with an extended snowball literature review at the intersection of GSCM and performance assessment may have overcome this observed trade-off but was limited by the time resources available to complete both investigation in parallel. Nevertheless, the adoption of a systematic approach for the investigation of the core of the literature is deemed an advantageous feature of the literature review process within this research. More systematic literature review process can better support a clear specification and qualification of the final research question generated as an output of the review process (Tranfield et al., 2003) and thus better inform the following research phases.

7.2.2 Conceptual and mathematical modelling

Conceptual and mathematical modelling were adopted to construct the method to quantitatively determine the environmental sustainability performance of multi-tier supply chains.

Two main elements were modelled, which are the environmental impact and the supply chain structure and dynamics. The modelling activities of both elements stemmed from the literature review findings, thus adopting only academic data sources to guide the development of the method. An early inclusion of data sources from the practitioners' community may have directed differently the development of the method. Regarding the environmental impact conceptualisation, the selection of the environmental indicator was based on the outcomes of the systematic literature review, therefore the inclusion of other data sources may have complemented the set of suggested indicators with an increased consideration of data availability, which was only considered in this research at the phase of method evaluation. However, no additional environmental indicator was identified during the method evaluation sub-phases thus allowing inferring on the appropriateness of the set of indicators initially selected. Regarding the supply chain structure, the critical distinction between the system and its surroundings was based on the definition of supply chain provided in this thesis. An alternative definition of supply chain may have resulted in a different consideration of the system boundaries.

Finally, despite the definition of system boundaries being necessary to limit the scope of the investigation and to provide comparability of results (Wiedmann et al., 2009), an extension of the system boundaries is generally considered to improve the overall quality of the assessment, as it broadens the scope of models and it enhances their reliability (Baldi, 2016). With this respect, the inclusion of usage and EOL lifecycle stages may have provided additional insights, although it would have introduced additional uncertainties as detailed in Section 7.1.1.2.

7.2.3 Semi-structured interviews

Semi-structured interviews research method was adopted to evaluate the usefulness and fitness for purpose of the conceptual model part of the method. The multi-tier GSCM performance assessment method presented in this research was developed stemming from the literature review phase, which was predominantly based on academic publications, therefore adopting a data source originating from the practitioners' community in the initial phase of evaluation broadened the *foci* of data sources.

The four interviewed experts have extensive experience in the field of sustainability working for Scottish Enterprise. While the fact that both I1 and I2 were conducted with experts belonging to the same organisation can be considered a disadvantage of the conducted interviews, it also entails that interviewed experts work for an economic development agency meaning that they have extensive cross-industrial experience. This is functional to address the multi-faceted aspects of sustainability within different industries and matches the generic supply chain domain of use identified for the multi-tier GSCM performance assessment method developed in this research.

The temporal misalignment of the interviews is also considered an advantageous feature of the conducted interviews, contributing to the purpose of evaluating and refining the method coherently with its different stages of development. With this respect, the opportunity for interviewees to elaborate on issues they believe important was key to identify and add the fifth pillar of transport to the conceptual model, as this pillar was not included in the initial versions v1 and v2 of the conceptual model.

Moreover, semi-structured interview research method was also adopted to evaluate the applicability of the method in an operating supply chain as part of the validation sub-phase. However, semi-structured interviews were embedded in the multiple case studies design; therefore, the discussion over the advantages and limitations related to the use of semi-structured interviews as a follow-up to the application of the method in the two case studies is presented in Section 7.2.5.

7.2.4 Numerical examples

A numerical example consisting of four fictitious supply chain was adopted in order to evaluate the accuracy of the mathematical model part of the method. The numerical example offered several key advantages. First, it allowed verifying the solution accuracy of the mathematical model in a controlled environment with the opportunity to run multiple times the model with different level of complexity of the fictitious supply chains, in order to reach a “reasonable confidence” in the accuracy of data (Defra, 2013). Second, it provided evaluation quickly, in contrast to the lengthy process required to access to primary data from industry. Third, the numerical example gave the opportunity to simulate more complex supply chain structures compared to the ones that were identified through the case studies, in order to verify the accuracy of the mathematical model under more challenging scenarios. The review process at the journal provided an additional verification both in terms of transformational accuracy and of solution accuracy.

On the other hand, a drawback of the numerical example is that it did not include the assessment of the environmental performance of transport, as mathematical model v2 was used for the numerical example. The inclusion of transport among the five pillars of the conceptual model was derived from I2, which led to the developed of mathematical model v3, which was then adopted for the case studies. Furthermore, the adoption of secondary data, including randomly generated values for the water consumption indicator, did not allow inferring about the meaning of the numerical outputs obtained through the numerical example, a shortcoming that was tackled by applying the method in operating supply chains, through multiple case studies.

7.2.5 Multiple case studies

Two case studies served the purpose of evaluating the applicability of the method. In contrast with the numerical example, the case studies provided an evaluation of the numerical outputs by comparing them with other another case available in the literature (CS1) and information available at the focal company (CS2) thanks to the adoption of primary data in the form of actual environmental and economic data. Moreover, a within-method triangulation was achieved thanks to the adoption of case study method in different occasions, enhancing the justification of the findings. This was further complemented by collecting data from multiple sources within each case, as the collection of environmental and economic data to feed the mathematical model was followed by semi-structured interviews with the managers of focal companies to evaluate the applicability of the overall method within operating supply chains.

Certain advantages and limitations of the adoption of multiple case studies stem from the key features of the case studies. The two case studies differ significantly in terms of key features, such as size of focal company, industrial sector, manufacturing production strategy, supply chain geographical scope and supply chain structure. The focal companies of CS1 and CS2 stand at the extreme positions of the spectrum of the size of organisations, being respectively a micro enterprise and a large enterprise. Originally, a third case study was planned to cover also a medium sized focal company to enhance the representativeness of the sample. However, the focal company ultimately dropped out from the research project due to unwillingness or inability of identified suppliers to share environmental data, which is identified as an obstacle to the applicability of the method introduced in this research. Regardless of this, the research covers the extreme points of the spectrum of the size of focal companies and it is therefore a reasonable assumption that the method is able to be adequately operationalised also in small and medium enterprises as well. Furthermore, another advantage of the adoption of multiple case studies research lies in the fact that the multi-tier GSCM performance assessment method was applied within two different industries, thus enhancing the generalisability over the applicability of the method. Furthermore, CS2 presented an international supply chain, demonstrating that the application of the method is not constrained by geographical distances. However, all organisations in both case studies were located in developed countries. This can be considered a limitation as the majority of sustainability related incidents are reported in developing countries (Dou et al., 2017; Grimm et al., 2016; Hartmann and Moeller, 2014; Miemczyk et al., 2012), the environmental regulations are less stringent in such countries (Dou and Sarkis, 2010; Lee et al., 2014) and suppliers are less prone to disclose environmental data (Jabbour et al., 2018) or environmental data may not be available at all. Finally, neither SC1 or SC2 showed such a complex supply chain structure as those appearing in the numerical example, therefore the mathematical model in its latest version (version 4), which includes the assessment of the environmental impact of transport, was not applied to the potential most complex structure of supply chains.

This differences among the case studies, especially in terms of focal firm size and industry, allowed gaining further insights on the key enablers to the applicability of the method within different operating context, highlighting similarities and differences. The cross-case comparison exemplified a multi-sector comparative research within multi-tier GSCM and allowed shedding light upon those enablers that are considered critical to apply the method in any supply chain and upon those that may acquire importance in specific industrial sectors or due to the size of the focal company.

Finally, during both case studies, the method was implemented in its executable mathematical model by the researcher rather than by supply chain managers and/or sustainability managers, who are the intended users of the method within organisations. This would have required dedicated time from organisation to understand the functioning of the executable model, which would have been impractical to achieve. Future research may adopt participatory method to explore this aspect. Moreover, the implementation of the executable model by the relevant people within focal companies would have enhanced their understanding of the overall method with a further benefit towards their evaluation of its applicability. Despite the extended explication about the pillars of the conceptual model provided to relevant people in the focal companies as well as an overview of the mathematical model, it is acknowledged that their overall evaluation of the method depends on their understanding of it. It is likely that owner of FC1 and supply chain manager of FC2 do not share the same knowledge about the multi-tier GSCM performance assessment method as the researcher and that this may have influenced their conclusions regarding the applicability of the method. Nevertheless, both interviewees belong to focal companies, which are the primary intended users of the method presented in this research, and were thus deemed the most appropriate source of information to evaluate the applicability of the method. Future research may include additional perspectives of relevant managers of 1st tier suppliers and 2nd tier suppliers to complement the analysis and incorporate their views on the applicability of the method.

7.3 Research approach

The research methods discussed in Section 7.2 were functional to answer the research question and address the research objectives coherently with the research design illustrated in Section 3.5 and accordingly to the overall research approach, which is discussed in this section.

Informed from the critical realism ontological positioning and embracing a post-positivism epistemological stance, this research adopted a deductive methodology. A key advantage of this methodology lies in its structured approach, ensuring reliability and replicability of the research. The features of testing, operationalisation and generalisation of deductive methodology were all achieved by applying the multi-tier GSCM performance assessment method in two operating supply chains with different characteristics through multiple case studies, as explicated in Section 5.4.

The post-positivist epistemology also advocates the use of triangulation as a mean to strengthen the validity and reliability of the research (Creswell, 2014; Wang and Duffy, 2009). Triangulation is also usually linked to mixed-method research, which is adopted in this research. As a result, triangulation was extensively used in this research, which is considered an advantage of this work, as triangulation is deemed to increase the overall researchers' understanding of an area (Hay, 2015; Wang and Duffy, 2009). Four types of triangulation exist: data triangulation, investigator triangulation, theory triangulation and methodological triangulation, which can further be distinguished into between-method triangulation and within-method triangulation (Wang and Duffy, 2009).

Between-method triangulation was adopted to address objective 4 (O4), adopting semi-structured interviews, numerical example and multiple case studies for method evaluation. Moreover, the three research methods adopted for evaluation further strengthened the validity and reliability of the findings by including a blend of qualitative (interviews, case studies) and quantitative (numerical example, case studies) data as a way to seek convergence across different methods. Within-method triangulation was realised for semi-structured interviews and case studies as these methods were adopted in different occasions (I1/I2 and CS1/CS2 respectively). Finally, data triangulation was adopted during both case studies as the environmental and economic quantitative information were complemented by opinions of decision-makers as data sources.

On the other hand, investigator triangulation was limited throughout this research, which may be considered a disadvantage. This was achieved only at the stages of abstract screening, title screening and environmental metrics clustering within the systematic literature review process and at the stage of conducting semi-structured interviews, where two researchers were involved. All other research phases and sub-phases were conducted independently by the author, meaning that the findings may suffer from a certain degree of bias in their interpretation. Finally, theory triangulation was the only type of triangulation not performed in this research, as each set of data was interpreted according to a single perspective coherently with the mixed-method research.

7.4 Summary

This chapter presented a reflective discussion over the research reported in this thesis. First, the research findings were discussed and critiqued (Section 7.1), then advantages and limitations of adopted research method (Section 7.2) and of the overall research design (Section 7.3) were discussed. Drawing on the limitations of the current work, directions for future research are also outlined throughout sections 7.1 to 7.3.

Building on the elements emerged from the discussion presented in this chapter, the next chapter (Chapter 8) concludes this thesis by reviewing the research question and research objectives and providing a summary of main novelty and contributions to the knowledge of the research documented in this thesis as well as its implications for practitioners and policy makers. A summary of limitations of the research and future research directions is also presented.

8 Conclusions

According to the research design (Figure 3.4), the reflections over research findings, research methods and research approach (Chapter 7) constituted the reporting of the discussion research phase, which is the penultimate research phase before the consolidation of the research through this thesis. Therefore, this chapter ends this thesis by summarising the main elements emerged from this research.

First, the research objectives are reviewed (Section 8.1), then the key knowledge contribution of this research is illustrated (Section 8.2), highlighting the main contributions to the fields of both multi-tier GSCM and GSCM performance assessment, which are the two areas this research lies at the intersection of. Section 8.3 identifies the main implications for practitioners, while Section 8.4 summarises implications for policy makers. Then the advantages and limitations of the multi-tier GSCM environmental performance assessment method developed in this research are outlined in Section 8.5, while the limitations of the broader research are listed in Section 8.6. Building on sections 8.5 and 8.6, Section 8.7 identifies future work and research directions. Finally, Section 8.8 briefly reiterates the main novelty and contribution to the knowledge of this research. The concluding remarks (Section 8.9) and the summary of this chapter (Section 8.10) conclude this thesis.

8.1 Review of research objectives

The research presented in this thesis was guided by the following research question: *How can the environmental sustainability performance of multi-tier supply chains be quantitatively assessed?* The research question was answered by developing an eco-intensity based method that relates the environmental performance of the supply chain to its economic output and adopts an indirect approach to respect the multiple-organisation and non-collaborative nature of supply chains.

This work was intended to address the lack of methods in the existing literature that simultaneously:

- Assess multi-tier supply chains environmental sustainability performance;
- Provide a comprehensive evaluation of environmental aspects;
- Use primary data sourced from actual practice to assess the environmental performance;
- Respect the multiple organisation and non-collaborative nature of the majority of real-life supply chains.

In order to answer to the research question, five objectives were outlined, whose achievement is discussed in the following paragraphs.

O1. Identify quantitative methods developed to assess the environmental performance of supply chains and evaluate their key features

The literature at the intersection of GSCM and performance assessment was investigated by the mean of a systematic literature review, as outlined in Chapter 2, more specifically from Section 2.5 onwards. The methods were evaluated according to their environmental aspects assessed, the supply chain extent covered, the type of supply chain addressed, the methodological approaches adopted and the main scope of the work. Analytical models were identified as the dominant methodological approach for GSCM performance assessment, while three sub-streams of assessment methods were identified based on the primary scope of the work, which are 'Supply chain design and performance optimisation', 'Supplier selection and evaluation' and 'Assessment of the supply chain'. The combined evaluation of the environmental aspects coverage and supply chain extent coverage of methods highlighted the lack of existing methods, which progress sufficiently along both dimensions, urging the development of a method to bridge this gap.

O2. Understand the key mechanisms regulating sub-supplier management and multi-tier supply chains, with a particular focus on GSCM

The multi-tier GSCM literature was investigated by the mean of a state-of-the-art literature review as outlined in Chapter 2, more specifically in Section 2.3.4 and 2.3.5. Several approaches to manage sub-suppliers in a multi-tier GSCM perspective were identified based on the number of tiers considered and the lens adopted by authors. The most comprehensive classification identifies 'Direct', 'Indirect', 'Third Party' and 'Don't bother' as the possible options faced by focal companies to deal with lower-tier suppliers, while 'Hybrid' approaches have been later recognised and added to this taxonomy.

O3. Construct a method to quantitatively determine the environmental sustainability performance of multi-tier supply chains

The method, outlined in Chapter 4, is built by a conceptual and a mathematical model. Informed by the findings emerged from the literature review, the environmental impact of the supply chain as well as its structure and dynamics were abstracted through a conceptual model, shaped around five pillars: eco-intensity concept; cradle-to-gate and transformed resources system boundaries; black-box approach; indirect multi-tier SCM approach; transport. The conceptual model was then transformed into relevant mathematical formulations through a mathematical model, which allow the operationalisation of the entire method in an operating supply chain. The mathematical model is shaped around several mathematical equations and offers three main outputs, which are the single environmental indicator company eco-intensity, single environmental indicator supply chain eco-intensity and the environmental backpack of products for each environmental indicator.

O4. Apply the method to operating supply chains

The developed method to assess the environmental sustainability performance of multi-tier supply chains was applied to two operating supply chains, adopting multiple case studies research. The two case studies differed in terms of industrial sector, size of the focal company, manufacturing production strategy, supply chain geographical scope and supply chain structure thus enhancing the generalisability over the domain of use of the method. The findings emerging from the applications of the method, which are reported in Chapter 6, illustrate the numerical outputs generated through the method as well as the multiple applications for practitioners arising from its implementation. These include support for environmental hotspot identification, supplier selection and evaluation, external reporting and evaluation of the environmental impact of future scenarios.

O5. Evaluate the utility, accuracy and applicability of the method

The method was evaluated against the criteria of utility, accuracy and applicability adopting three different research methods. Each evaluation research sub-phase fed back to the method development research phase, leading to a progressive refinement of the constructed method. Semi-structured interviews with sustainability experts evaluated the conceptual model part of the method, evaluating the usefulness and fitness for purpose, i.e. the utility, of the method, based on its conceptual building pillars. A worked example, in the form of a numerical example, served to verify the accuracy of the mathematical model part of the method. Finally, multiple case studies were functional to evaluate the applicability of the method in an operating supply chain. Findings regarding the evaluation of the utility and accuracy are presented in Chapter 5, whereas those regarding the applicability of the method are split between Chapter 5 and Chapter 6.

8.2 Knowledge contribution

This research lies at the intersection of two fields, namely multi-tier GSCM and performance assessment, as illustrated in Figure 8.1. Therefore, the knowledge contribution of this research is found in both fields: contributions to the multi-tier GSCM filed are detailed in Section 8.2.1, whereas those for GSCM performance assessment field are outlined in Section 8.2.2.

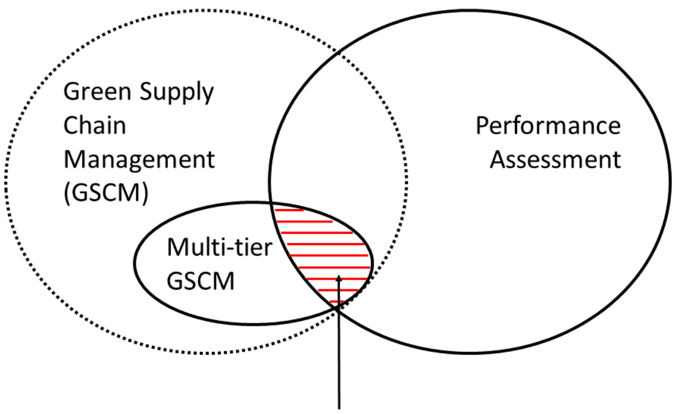

Figure 8.1: Knowledge contribution fields

8.2.1 Knowledge contribution to multi-tier GSCM field

The multi-tier GSCM performance assessment method introduced in this work expands the body of the literature in the emerging area of multi-tier supply chain management for sustainability. The research in this field has mostly focused on governance mechanisms to manage sustainability for multi-tier sustainable supply chains, most noticeably through the work of Mena et al., (2013), Tachizawa and Wong (2014) and Wilhelm et al. (2016), marking a clear separation to the more strictly technical stream of research on environmental performance assessment and LCA, which does not consider "the dynamics arising from the multi-tiered structure and the interactions along the supply chain" (Adhitya et al., 2011). This work merges these streams of research and sets the foundations in the specific area of multi-tier GSCM performance assessment, by introducing a method to assess the environmental sustainability performance of multi-tier supply chains. This is realised by moving away from the more theoretical approaches of governance mechanism-focused works towards developing a practically oriented method, while at the same time respecting the multiple-organisation nature of the supply chain.

This work advances the multi-tier GSCM literature in three ways. First, as assessment, along with collaboration, was recognised as one of the two options faced by focal companies to manage sub-suppliers (Grimm et al., 2016), it introduces an assessment method specifically designed for multi-tier supply chains. The method is theoretically rooted in the indirect multi-tier SCM approach and accordingly adopts "cascadic assessment" of the environmental performance combined with first-party audit, i.e. self-assessment processed by the supplier and forwarded to the customer (Grimm et al., 2016; Schöggl et al., 2016). Second, it provides evidence an exploratory application of the method into an operating context through two case studies (Chapter 6), demonstrating its suitability in achieving a decentralised assessment in a non-collaborative supply chain even without visibility of the lower-tier suppliers. Third, thanks to the evaluation of the method through case studies in different industrial sectors (Section 6.1 and Section 6.2) and the cross-case applicability evaluation of the method (Section 6.3), it addresses the lack of studies carrying out "multi-sector, comparative research in multi-tier sustainable supply chains" (Jabbour et al., 2018).

8.2.2 Knowledge contribution to GSCM performance assessment field

Building on the call by Brandenburg et al. (2014) on the need for more SSCM quantitative models focusing on extended supply chains and on the findings emerged from the systematic literature review, this work advances the knowledge in the field of performance assessment for GSCM.

First, the developed method expands the number of tiers typically assessed in the GSCM literature beyond the traditional tier-1 level and obtains an effective cradle-to-gate assessment of the eco-intensity of products. Second, the method expands the number of environmental aspects considered in the GSCM literature for multi-tier supply chains by including multiple environmental impacts, tackling overall seven environmental impact areas. This choice overcomes the current tendency in the literature to decrease the spectrum of the measures adopted when the level of analysis increases beyond the dyadic supply chain (Miemczyk et al., 2012). Focusing on a single environmental performance, i.e. using emissions as a proxy of the performance as highlighted in the systematic literature review, or focusing on a limited set of environmental aspects limits an accurate evaluation of the supply chain and may provide an incomplete assessment of the overall environmental performance. The presented method is thus innovative as it achieves a holistic environmental performance assessment of multi-tier supply chain, by simultaneously addressing multi-tier supply chains in a cradle-to-gate approach while covering multiple environmental aspects, leading the way for an effective supply chain-wide environmental assessment.

Additionally, the method achieves this extension of the coverage in terms of environmental aspects and supply chain extent coverage while relying on primary environmental data sourced from actual practice, except for the assessment of the environmental impact associated to transport. This differentiates the presented method from methods adopting consistently secondary data from database sources such as LCA-based approaches and thus achieving a more detailed level of granularity in the assessment of the environmental performance, which is particularly important in the comparison of supply chains showing similar design features. The blending of data collection at the company level with an assessment of the supply chain at the product level further differentiates this method from LCA based method which adopts a product-centric perspective neglecting the wider organisational environment where production processes take place.

8.3 Implications for practitioners

The outputs obtained through the multi-tier GSCM performance assessment method presented in this research offer a wide set of applications for organisations, which were extensively discussed individually in Section 7.1.2.

The single company eco-intensity indicators measure the yearly performance of a company by considering different environmental impacts and offer an overall snapshot of the organisation-wide environmental performance. These indicators find potential applications for external reporting in an organisational context, but can most noticeably be adopted for longitudinal benchmarking of the environmental performance at the company level. As the data is collected on a yearly basis, single company eco-intensity indicators can be used to draw upon the historical environmental profile of an organisation. However, they have also forward-looking applications, as managers can define environmental targets to be reached adopting the eco-intensity indicators as relevant KPIs.

The single company eco-intensity indicators could also find a supply chain-oriented application as part of the green supplier selection and evaluation process. The figures provide quantitative support to the procurement decisions and can be integrated in vendor ratings or other tools requiring quantitative values. The quantitative values limit the subjectivity and uncertainty introduced by supplier selection and evaluation methods based on judgements of experts or decision makers (Shokravi and Kurnia, 2014; Tsoulfas and Pappis, 2008). However, the eco-intensity values would need to be integrated with traditional green supplier selection and evaluation methods, as they do not inform decision makers about environmental practices in place at suppliers' facilities and other key requirements such as environmental management systems or certifications.

The eco-intensity indicators at the supply chain level offer several additional applications to practitioners and stakeholders. First, indicators help practitioners to understand the environmental impact of the supply chain, given the limited knowledge of managers of what happens beyond 1st tier suppliers. When the recursive mechanism is applied throughout the lower-tier suppliers of the supply chain, it reveals information about each branch of the supply chain. On these grounds, the method can assist them to decide whether to implement environmental actions to improve their performance or extend the pressure from green customers to their upstream business partners. The recursive mechanism allows in this way to recognise the environmental hotspots along the supply chain and to prioritise actions to improve the environmental performance.

Decision makers in the focal firm are likely to be the most interested to track the environmental performance of the supply chain as customers hold these organisation responsible for the behaviour of the supply chain. Focal firm managers may want to pay attention to a specific eco-intensity indicator or a subset of indicators to improve the environmental performance of the supply chain, a process that is facilitated by the level of granularity offered by the proposed method. Furthermore, additional environmental indicators, reflecting specific industry requirements or environmental impacts, can be incorporated within the method, thus contributing to the flexibility in the application of the method. Every industrial sector has different features and challenges, thus posing different pressures on the natural capital: machinery industry (CS2) is typically considered an energy-intensive sector; therefore, energy consumption eco-intensity might be the most relevant indicator to tackle, whereas land occupation might be more critical in the food industry (CS1).

Moreover, the eco-intensity indicators show a potential application also in green marketing. The eco-intensity outputs are easy to understand by non-experts and can be adopted for external reporting of the environmental performance of products, potentially being incorporated into labelling schemes of products combined with a colour scale, similarly to the one introduced for the identification of hotspots in this research. The indicators are likely to be an effective way to influence the purchasing decisions in the lucrative business segment of sustainable consumers (Ormond and Goodman, 2015; Zhao and Zhong, 2015). The simplicity of the indicators, combined with their applicability to virtually any type of product, offer additional benefits to benchmark different products, removing the constraints to comparative studies typical of methods based on functional unit definition or reference units based on physical features of products, as discussed in Section 7.1.1.1.

8.3.1 Operationalisation of the method

The enablers for the applicability of the method were discussed in Chapter 6. Therefore, this section expands the discussion on the operationalisation of the method in an actual supply chain, as the method was implemented in its executable mathematical model by the researcher rather than by the intended users of the method in the case studies, as detailed in Section 7.2.5.

In terms of practical applicability of the method, each organisation requires to collect few environmental and economic data. The environmental data adopted are typically already readily available in most organisations facilitating the applicability in real life supply chains as "the data collection burden for the organization has to be as small as possible" (Wiedmann et al., 2009) and workload for environmental assessment has to be minimised (Schöggl et al., 2016). Multiple sources for environmental data can be adopted as illustrated in Section 7.1.3. Moreover, data collection at the company level aims to highlight unsustainable behaviours of any player in the chain should this happen, mitigating reputational risk for focal companies, as organisations are held responsible for their selection of the upstream suppliers as a whole rather than at a product level (Gimenez and Tachizawa, 2012).

The environmental data are largely those appearing in the final formulation of the environmental indicators, with the only exception of 'Energy consumption' and 'Emissions to air' categories. The former environmental indicator aggregates the energy consumption associated to electricity consumption, distinguishing between electricity acquired from the network and self-produced renewable electricity, and the energy consumption associated to the consumption of fossil fuels. The latter aggregates emissions generated from electricity consumption and from fossil fuels consumption. Appendix A.6 and A.7 detail the methodological steps followed to come up with the final formulations of these two environmental indicators. These steps can be easily performed with a calculation spreadsheet, like the one adopted for the executable version of the mathematical model. On the other hand, the economic data required are the turnover, prices and quantities of intermediary products purchased and of final products sold.

Finally, an additional information may be required, which is the ratio between the inputs, i.e. intermediary products purchased, and the outputs, i.e. final products. This ratio, which is typically detailed in the bill of materials, is needed in the case of divergent supply chain structures, with a single intermediary product used for multiple final products. Since the intermediary product may be acquired in larger quantities from the same supplier(s), its coefficient of utilisation in the final product needs to be known to allocate to the product supply chain the correct share of environmental backpack passed on by the supplier(s). This information is however widely available in organisations as it is central to the production know-how.

8.3.2 Domain of use

The method was applied through case study research in two different supply chains, showing differences in terms of size of focal company, industrial sector, manufacturing production strategy and supply chain geographical scope, thus allowing inferring on the generalisability of the applicability of the method to a wide typology of forward supply chains in the future. The method demonstrated the potential to be consistently applied to most generic commercial supply chains falling within the boundaries defined by the scope of the work (Section 1.3), without requiring further tailoring or modifications in its key concepts and mechanisms.

Additionally, CS1 demonstrated the applicability of the method also for SMEs, which do not typically have dedicated resources to sustainability management (Yusuf et al., 2013). The method can be used as long as the organisations part of the supply chain are able to collect relevant environmental data and track the economic indicator necessary for the correct operation of the recursive mechanism.

However, the domain of use of the method is limited by certain methodological features. First, the definition of the system boundaries according to the transformed resources concept limits the domain of use to physical products. Second, the domain of use is confined to commercial supply chains due to the selection of the monetary unit both to allocate the environmental impact from the company level to the product mix and to obtain relative environmental indicators. This excludes from the domain of use non for-profit supply chains, such as humanitarian supply chains. Third, the recursive mechanism adopted requires the final product to be sold to the final customer according to the current formulation, thus determining a transfer in the ownership of the product. As a result, the method requires further adaptations and evaluations to be applicable to product-service systems, product leasing, product renting or other arrangements regarding the final product between the focal company and the customer, which are different from sale. The transfer of ownership of the product to the final customer also implies that any product which does not reach the gate of the focal company is not allocated any environmental impact despite potentially causing environmental impacts. Instances may include products blocked by legal barriers or products being tested. Their environmental impact of such products is shared among the remaining product mix, coherently with the amount of turnover they generate.

Finally, the method was specifically designed for operating supply chains, meaning it cannot assess the environmental performance of supply chain at the design stage. At the same time, the method is also designed for forward supply chains and it cannot be applied to closed-loop supply chains due to the inability of the method to capture the environmental impact associated to the usage phase, as explicated in Section 7.1.1.2. The application to reverse supply chain is theoretically possible, as 3Rs activities are increasingly generating profits with a market-oriented approach since the emergence of circular economy principles. However, the extension of the domain of use to reverse supply chain needs still to be demonstrated given the complexity of reverse chains and the ultimate source of inputs, which are partially or fully not withdrawn from the natural capital, thus requiring a re-scoping of the cradle-to-gate system boundary.

8.4 Implications for policy makers

Although the method was developed having industry and more specifically focal companies as its intended users, some basic insights can be drawn also for policy makers. The external reporting potential to support the development of environmental product labelling and the benchmarking potential of the method to support the development of environmental taxation may be of interest to policy makers.

The consistent system boundaries along with the recursive mechanism systematically applied along the supply chain form a stable platform to generate consistent product supply chain reporting, as discussed in Section 7.1.2.4. This could serve as a starting point for policy makers towards the development of environmental labelling of products based on the extended supply chain. As an example, it is already a requirement within certain countries of European Union that processed food products display information regarding the geographical origin of raw products, thus asking producers for extended supply chain traceability to guarantee product responsibility (European Parliamentary Research Service, 2018). A similar mechanism may be put in place also for environmental impacts as part of the labelling requirements, in order to inform consumers about the sustainability level of their purchases.

Furthermore, the product supply chain eco-intensity indicators are also able to reach a consistent cross-case environmental benchmarking among products, taking into account their supply chain, and can provide a quantitative support to policy makers for the development of environmental consumption taxation policies, similarly to the case of plastic consumer bags introduced in Ireland (European Environment Agency, 2016)

8.5 Advantages and limitations of the multi-tier GSCM performance assessment method

The developed method to assess the environmental performance of multi-tier supply chains is the main contribution of the research presented in this thesis. An extensive reflection over the features of the method and the implications for its application is presented in Chapter 7. This section thus introduces a synthesis of main advantages and disadvantages of the method, both at a theoretical level and concerning aspects pointing towards the application of the method in operating contexts.

The main advantages of the method are listed below:

- Wide domain of use: method can be applied to any generic commercial forward supply chain with a physical product as the final product, thus offering cross-industrial applicability.
- Modularity: environmental indicators can be added or removed without affecting the functioning of the method. Environmental indicators can be selected based on data availability, preferences of the users or specific industry requirements.
- Visibility and traceability of the multi-tier supply chain not required to carry out the performance assessment.
- Supply chain liability effect of focal companies incorporated: environmental performance assessment is kicked-off from the focal company and is completed when eco-intensity indicators are cascaded downstream to the focal company, coherently with the prominent role of the organisation within the supply chain and environmental chain liability associated to the focal company by stakeholders.
- Simple data collection at the company level, boosting applicability of the method also for SMEs.
- Complete allocation of organisational environmental impacts to products with mutually exclusive portions of environmental impacts assigned to each product.
- Double-layer of outputs at the supply chain level: both relative (in the form of eco-intensity indicators) and absolute (in the form of environmental backpack) environmental performance of a product supply chain are calculated.
- Extensive opportunities for comparability of the outputs of the method thanks to eco-intensity indicators, which are independent of the size of the system under analysis. Opportunities both in the form of cross-case benchmarking and longitudinal benchmarking. Cross-case benchmarking is achievable at the company level in the form of supplier evaluation and at the product supply chain level. Longitudinal benchmarking can support the assessment of environmental performance retrospectively or the definition of environmental targets in a prospective orientation.
- Multiple applications of the outputs, including guidance for operational improvement thanks to the identification of environmental hotspots and communication for external reporting, including potential use for green labelling.

On the other hand, the limitations of the method are the following:

- No location-specific information captured for any supply chain organisation both in terms of environmental and economic indicator adopted.
- Volatility of prices prone to influence the economic denominator and the values of the overall eco-intensity indicators: variation of prices over time not considered (e.g. inflation).

- Synthesised information about the eco-intensity performance at the company level and at the supply chain level still to be finalised due to the lack of an adequate normalisation technique.
- Usage and EOL stages outside of the system boundaries, with a potential significant underestimation of the lifecycle environmental impact of certain products, whose major share of impacts arise in such lifecycle phases (e.g. ships).
- Allocation mechanism based on the economic output generated by each product prone to overestimate or underestimate the environmental performance imputable to the product.
- No information provided about the operational improvement to undertake within each black box, i.e. organisational boundaries
- Consistent application of the recursive mechanism along the upstream supply chain influenced by supply chain dynamics, and especially from the level of influence each organisations has on its supply chain partners, i.e. relative power balance.
- Challenges in accessing data in the multi-tier supply chain hindering certain applications of the method, especially cross-case benchmarking.
- Potentially challenging operationalisation in industries characterised by a continuously changing design of supply chain.

8.6 Limitations of the research

On top of the limitations of the developed method to assess the environmental performance of multi-tier supply chains, additional limitations are related to the wider research and are listed below:

- Lack of a theoretical underpinning of the research, given the emergent status of multi-tier green supply chain management.
- Conceptual and mathematical modelling stemmed from the literature review findings, thus using academic data sources without the consideration of data sources from the practitioners' community, which is the intended user of the method. While practitioners were involved at the method evaluation stage, the development of the method was guided only from academic sources.
- Model qualification was performed with experts belonging to the same organisation. Despite their cross-industrial experience and suitability for the purpose of qualification, this may have introduced some bias in the findings of this evaluation stage.
- Case studies application of the method did not stretch beyond 2nd tier suppliers, thus the method could be further validated in longer supply chains.
- Organisations involved in the case studies are located in developed countries, whereas the majority of sustainability related incidents arise in developing countries, where environmental data collection is also more challenging.
- Longitudinal benchmarking application could not be tested due to time constraints imposed by the research project.

- The case studies applicability evaluation follow-up was performed with managers from the focal companies only. While such organisations are the designated primary users of the method, the application of the method requires inputs from other companies in the supply chain, therefore extending the applicability evaluation follow-up to other organisations within the supply chains would have enhanced these findings.

8.7 Future work and research directions

Based on the advantages and disadvantages of the multi-tier GSCM performance assessment method identified in Section 8.5 and on the research findings discussed in Section 7.1, future work is recommended in the following directions:

- Introduction of location-specific factors within the method to take into account spatially differentiated impact for certain environmental categories.
- Identification of a suitable normalisation technique to be integrated within the method in order to obtain global eco-intensity indicators at the company level and at the supply chain level to complement the insights offered by single environmental indicator eco-intensity indicators.
- Identification of actual improvement plans within the organisational boundaries of the companies identified as environmental hotspots.
- Application of the method in a supply chain over multiple years to implement longitudinal benchmarking and understand the impact of operational improvement actions on supply chain performance.
- Application of the method in more complex supply chains, including suppliers beyond tier-2 and/or a more elaborate supply chain design, to understand the extensibility of the indirect multi-tier approach and to validate the method in a more complex scenario.
- Application of the method in supply chains involving organisations located in developing countries, to validate the method also in geographical contexts where the availability of environmental data is scarcer.
- Evaluation of the applicability of the method with managers belonging to organisations different from the focal company to understand the views of the upstream players regarding the method.
- Advancement of the theory in the area of multi-tier supply chain sustainability to provide more robust theoretical underpinning for the research in the field
- Integration of the social dimension of sustainability within the current method, in order to obtain a socio-eco-intensity index synthesising the triple-bottom-line sustainability performance of a supply chain.

Table 8.1 complements this section by linking limitations of the developed method to assess the environmental performance of multi-tier supply chains (Section 8.5) and of the wider research (Section 8.6) to the future research directions.

Table 8.1: Overview of the limitations of the developed method and of the wider research and link to future research directions

Limitation	Future research directions
Limitations of the multi-tier GSCM performance assessment method	
No location-specific environmental and economic information for supply chain organisations	Introduction of location-specific factors within the method to take into account spatially differentiated impact for certain environmental categories
Volatility of prices prone to influence overall eco-intensity indicators	
Synthesised information about the eco-intensity performance at the company and at the supply chain level still to be finalised	Identification of a suitable normalisation technique to be integrated within the method in order to obtain global eco-intensity indicators at the company level and at the supply chain level
Usage and EOL stages outside of the system boundaries with potential underestimation of the lifecycle environmental impact of certain products	
Potential overestimation or underestimation of the environmental impact imputable to products due to allocation mechanism based on economic output	
No information about the operational improvement within each black box, i.e. organisational boundaries	Identification of actual improvement plans within the organisational boundaries of the companies identified as environmental hotspots
Relative power balance along the supply chain affecting the application of the recursive mechanism application along the upstream supply chain	
Challenges in accessing data in the multi-tier supply chain hindering certain applications of the method, such as cross-case benchmarking	
Potentially challenging operationalisation in industries characterised by a continuously changing design of supply chain	
Method not considering the social dimension of sustainability	Integration of the social dimension of sustainability within the method, in order to obtain a socio-eco-intensity index synthesising the 3BL sustainability performance of a supply chain

Limitations of the research	
Lack of a theoretical underpinning of the research, given the emergent status of multi-tier green supply chain management	Advancement of the theory in the area of multi-tier supply chain sustainability to provide more robust theoretical underpinning for the research in the field
Conceptual and mathematical modelling based solely on academic data sources. Practitioners' data sources sought only at the later evaluation stage	
Potential bias in the model qualification stage due to interviewees belonging to the same organisation	
Case studies application of the method until 2^{nd} tier suppliers, thus the method could be further validated in longer supply chains.	Application of the method in more complex supply chains, including suppliers beyond tier-2 and/or a more elaborate supply chain design, to understand the extensibility of the indirect multi-tier approach and to validate the method in a more complex scenario
Organisations involved in the case studies located in developed countries, whereas the majority of sustainability related incidents arise in developing countries	Application of the method in supply chains involving organisations located in developing countries, to validate the method in geographical contexts where the availability of environmental data is scarcer
Longitudinal benchmarking application could not be tested due to time constraints imposed by the research project.	Application of the method in a supply chain over multiple years to implement longitudinal benchmarking and understand the impact of operational improvement actions on supply chain performance
Case studies applicability evaluation follow-up performed with managers from the focal companies only.	Evaluation of the applicability of the method with managers belonging to organisations different from the focal company to understand the views of the upstream players regarding the method

8.8 Contribution to the knowledge and novelty of the research

The aim of the research reported in this thesis was to *facilitate quantitative assessment of the environmental sustainability performance of multi-tier supply chains*.

The main knowledge contribution of this work is the developed method to assess the environmental performance of multi-tier supply chains, presented in Chapter 4. The method was constructed informed by the findings of the systematic literature review and evaluated through semi-structured interviews with sustainability experts, a worked example in the form of a numerical example and two case studies. The method contributes to the knowledge by setting the foundations in the specific area of multi-tier GSCM performance assessment. Previous research in the field has either focused on governance mechanisms to manage sustainability for multi-tier sustainable supply chains or adopted a strictly technical perspective to assess the performance of the supply chain without consideration of the dynamics and interactions along the chain. This work advances the knowledge by merging these streams of research, moving away from the theoretical approaches of governance mechanism-focused work towards developing a practically oriented method, while at the same time respecting the multiple-organisation nature of the supply chain.

Based on the above, the method is novel as it is the first to allow assessing the environmental sustainability performance of supply chains and to simultaneously achieve the following:

- Extend the supply chain coverage to include multi-tier supply chains in order to obtain a cradle-to-gate assessment, thus expanding the number of tiers assessed beyond the traditional tier-1 level of the GSCM literature.
- Extend the environmental aspects coverage for multi-tier supply chains providing a comprehensive consideration of environmental inputs and outputs through seven environmental impact areas, thus expanding the number of environmental aspects considered compared to the existing GSCM literature.
- Adopt primary data sourced from actual practice to assess the environmental performance, capturing differences between similar organisations and supply chains with a similar design.
- Respect the multi-organisation nature and non-collaborative characteristics of the majority of real-life supply chain as well as the limited visibility of focal companies about their upstream supply chain.

By simultaneously addressing the above mentioned aspects, the method paves the way for an effective supply chain-wide environmental assessment.

Moreover, secondary contributions to the knowledge are identified as follows:

- A mapping of the existing GSCM performance assessment methods and a classification of their key characteristics, including environmental metrics adopted (Table 2.6), supply chain extent covered (Figure 2.12) and methodological approaches used (Table 2.9), addressed both individually and in combination (Table 2.11, Figure 2.17). This work first evaluates such features in combination, supporting the mapping with contingency analysis based statistics. Moreover, the mapping first examines in detail which supply chain tiers are effectively considered in GSCM performance assessment (Figure 2.12), thus clarifying the scope of the supply chain dimension in GSCM performance assessment research.

- A real-life application of an indirect multi-tier supply chain approach for GSCM performance assessment in two operating contexts, namely a food supply chain (Section 6.1) and in a machinery supply chain (Section 6.2). This work first applies the indirect GSCM multi-tier supply chain approach to an operating supply chain while using primary data sourced from actual practice and covering multiple environmental aspects, thus demonstrating the applicability of an indirect approach for GSCM performance assessment and its suitability in achieving a decentralised assessment in a non-collaborative supply chain even without visibility of the entire network.

8.9 Concluding remarks

Rising global environmental challenges have determined an increased interest of society over the activities of organisations. This scrutiny has been lately expanding to the wider supply chains of companies due to the significant environmental impact arising beyond organisational boundaries, combined with increased adoption by companies of outsourcing and offshoring practices. As a result, focal companies have been pressured to improve their supply chain environmental performance and have been kept liable for the behaviour of their upstream suppliers at the same time, calling for an approach to assess the wider supply chain environmental performance.

Nevertheless, a trade-off was observed in the literature between the range of environmental aspects and the extent of the supply chain considered with no existing method suitable for a holistic evaluation of the environmental supply chain performance identified in the literature (Chapter 2). Intending to bridge this gap in the literature, the aim of the research reported in this thesis was to facilitate quantitative assessment of the environmental sustainability performance of multi-tier supply chains. This was achieved by developing a novel eco-intensity based method that relates the environmental performance of the supply chain to its economic output (Chapter 4). The method was evaluated against three criteria: utility, accuracy and applicability. Utility was evaluated through industrial studies in the form of semi-structured interviews, while accuracy was evaluated through worked examples in the form of a numerical example (Chapter 5). Finally, applicability was evaluated through case studies by applying the method to two multi-tier supply chains, belonging to the food and to the machinery industries respectively (Chapter 6). The entire research work was then critiqued in order to identify advantages and limitations, leading to future research directions (Chapter 7).

The research presented in this thesis has the potential to change the way organisations approach their environmental sustainability by facilitating understanding of the wider supply chain impact. The method to assess the multi-tier supply chain environmental performance serves as an initial step towards the development of more environmentally sustainable supply chains by capturing the ‘as-is’ status of the supply chains and ultimately contributing to sustainable development.

8.10 Summary

This chapter concluded this thesis by reviewing the research objectives (Section 8.1), identifying the key contributions to the knowledge (Section 8.2) and the implications for practitioners (Section 8.3) and policy makers (Section 8.4). Moreover, the key advantages and limitations of the main contribution of this research, which is the developed method to assess the environmental performance of multi-tier GSCM, are summarised in Section 8.5, while the limitations of the research as a whole are listed in Section 8.6. Drawing upon limitations identified in sections 8.5 and 8.6, Section 8.7 identifies directions for future research. Finally, the novelty of the work and its contribution to the knowledge are briefly reiterated in Section 8.8, before the concluding remarks end this thesis (Section 8.9).

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A.1 Systematic literature review additional material

Table A.1.1: Distribution of reviewed papers by journal

Journal	# of Articles	Authors
Journal of Cleaner Production	17	(Baboulet and Lenzen, 2010; Brent and Visser, 2005; Govindan et al., 2013; Jakhar, 2015; Joa et al., 2014; Kannan et al., 2015, 2013; Kannegiesser and Günther, 2015; Lee, 2011; Manzardo et al., 2014; Mintcheva, 2005; Nagel, 2003; Nikolaou et al., 2013; Schmidt and Schwegler, 2008; Schmidt, 2015; Tajbakhsh and Hassini, 2015; Tsoulfas and Pappis, 2008)
International Journal of Production Economics	6	(Bai and Sarkis, 2010; Hashemi et al., 2015; Mahdiloo et al., 2015; Sarkis and Dhavale, 2015; Sundarakani et al., 2010; Zakeri et al., 2015)
International Journal of Production Research	5	(Azadnia et al., 2015; Marcus Brandenburg, 2015; Lenny S.C. Koh et al., 2012; Lu et al., 2007; Yakovleva et al., 2012)
Environmental Science and Technology	3	(Adhitya et al., 2011; De Soete et al., 2014b; Dewulf et al., 2005)
Resources, Conservation and Recycling	3	(De Soete et al., 2014a; Krikke, 2011; Shen et al., 2013)
ACS Sustainable Chemistry and Engineering	2	(Gao and You, 2015; Garcia and You, 2015)
Applied Energy	2	(Kravanja and Čuček, 2013; Rocco et al., 2014)
Ecological Indicators	2	(Alvarez and Rubio, 2015; Efroymson and Dale, 2015)
International Journal of Life Cycle Assessment	2	(Krikke, 2010; Röhrlich et al., 2000)
Production Planning & Control	2	(Dey and Cheffi, 2013; Tseng et al., 2013)
Supply Chain Management: An International Journal	2	(McIntyre et al., 1998; Varsei et al., 2014)
Sustainability	2	(Salvado et al., 2015; Shokravi and Kurnia, 2014)

Other journals with a single paper	30	(Accorsi et al., 2015; Ahi and Searcy, 2014; Bernardi et al., 2012; Bojarski et al., 2009; Bouchery et al., 2012; Boukherroub et al., 2014; Caro et al., 2013; Charmondusit et al., 2014; De Soete et al., 2013; Dotoli et al., 2006; Du et al., 2015; Fahimnia et al., 2015; Gerbens-Leenes et al., 2003; Giarola et al., 2012; Jakhar, 2014; Jamshidi et al., 2012; Lee and Cheong, 2012; Mellor et al., 2002; Michelsen et al., 2006; Ortiz Gutiérrez et al., 2013; Pålsson et al., 2013; Ren et al., 2015, 2013; Shi et al., 2015; Trappey et al., 2012; Tuzkaya et al., 2009; Yazan et al., 2011; Yue et al., 2014; Zamboni et al., 2011; Zhang et al., 2014)

Table A.1.2: Distribution of reviewed papers by GICS industry group and GICS industry

GICS Industry Group	GICS Industry	Total	Application	Industry specific
General	*General*	**29**		
Energy	*Oil, Gas & Consumable Fuels*	**12**	**2**	**10**
Consumer Durables		**9**	**7**	**2**
	Household Durables	5	4	1
	Leisure Equipment & Products	2	2	0
	Textiles, Apparel & Luxury Goods	2	1	1
Automobiles & Components		**7**	**6**	**1**
	Automobiles	4	3	1
	Auto components	3	3	0
Materials		**7**	**2**	**5**
	Paper & Forestry Products	3	0	3
	Chemicals	2	0	2
	Metals & Mining	2	2	0
Technology Hardware & Equipment		**6**	**2**	**4**
	Computer & Peripherals	3	1	2
	Electronic Equipment & Components	2	1	1
	Office Electronics	1	0	1
Pharmaceuticals, Biotechnology & Life Sciences	*Pharmaceuticals*	**3**	**0**	**3**
Food, Beverage & Tobacco	*Food Products*	**3**	**1**	**2**
Household & Personal Products	*Personal Products*	**1**	**0**	**1**
Commercial Professional & Services	*Commercial Services & Supplies*	**1**	**0**	**1**
Total		**78**	**20**	**29**

A.2 Multi-tier GSCM literature additional material

The multi-tier GSCM was presented in Section 2.3.4 and further expanded in Section 2.3.5 to understand the key mechanisms regulating sub-supplier management in multi-tier GSCM. Table A.2.1 presents an overview of the state-of-the-art literature in the area of multi-tier GSCM, introducing main studies contributing to the field. A summary of the problems addressed and main findings of the studies is provided as well as a mapping of the methodologies adopted.

Table A.2.1: Multi-tier GSCM literature landscape

Source	Problem	Methodology	Main findings
(Aßländer et al., 2016)	Relationship between 1st and 2nd tier suppliers	Single case study	• Evaluation of buyer-supplier relationship in the particular context of 1st tier supplier-2nd tier supplier under the lens of principal-agent relationship and stewardship theory • Evaluation of the relationship according to the criteria of autonomy, motivation, identification, authority, stakeholder orientation and timeline of collaboration
(Awasthi et al., 2018)	Multi-tier supplier selection	Fuzzy AHP-VIKOR model	• Framework for sustainable global supplier selection taking into account sustainability risks from sub-suppliers • Evaluation based on five weighted criteria: economic, quality, environmental, social and global risk
(Dou et al., 2017)	GSCM multi-tier enablers	DEMATEL-based multiple case studies	• Top-management support at the focal company and buyer power are the most foundational enablers • Top-management support at the focal company and close geographical proximity between supply chain members are the most prominent enablers • Trust between supply chain members and key 1st tier supplier critical to achieve a hybrid direct-indirect approach
(Fritz et al., 2017)	Sustainability assessment data exchange	Literature review, interviews and survey	• List of 36 sustainability aspects to exchange sustainability data • Differences in the sustainability aspects exchanged between organisations and other stakeholders

Source	Problem	Methodology	Main findings
(Gong et al., 2018)	Multi-tier supply chain learning of sustainability	Multiple case studies	• Resources are orchestrated internally and externally to achieve multi-tier supply chain learning of sustainability • Focal companies orchestrate resources in breadth by internally setting up new functional departments and externally working with third parties • Focal companies orchestrate resources in depth working directly with their extreme upstream suppliers adopting varied governance mechanisms on lower-tier suppliers along the project lifecycle • The resource orchestration in breadth and depth and along the project lifecycle results in changes of supply chain structure
(Grimm et al., 2014)	Sub-suppliers compliance with corporate sustainability standards (identification of critical success factors)	Multiple case studies	• Identification of 14 critical factors for the success of sub-suppliers' compliance with corporate sustainability standards • Classification of critical success factors into four categories: focal-firm related, relationship-related, supply chain partner-related, context related
(Grimm et al., 2016)	Sub-suppliers compliance with corporate sustainability standards (management of)	Multiple case studies	• Management of sub-suppliers based on two dimensions: assessment and collaboration • CSS of sub-suppliers positively affected both by a greater direct engagement of the focal company and by the mediating role of third parties involved • The greater a focal firm's channel power, the greater its engagement in managing sub-suppliers • Involvement of 1st tier supplier vital

Source	Problem	Methodology	Main findings
(Grimm et al., 2018)	Sub-suppliers compliance with corporate sustainability standards (interrelationship among critical success factors)	DEMATEL-based single case study	• Long-term relationship between the direct supplier and the sub-supplier, the involvement of the direct supplier and the focal firm's buyer-power over the direct supplier are critical success factors; • Differences in the perception of the critical success factor can be aligned through contractual agreements
(Hartmann and Moeller, 2014)	Responsibility attribution for unsustainable supplier behaviour	Vignette-based survey	• Chain liability effect increased if environmental incidents are the result are more severe or arise due to a company decision or misbehaviour • Responsibility attributions do not differ with organisational distance from the supplier, firm size, strategic importance of the supplied product, or the existence of environmental management systems. • Chain liability effect increases reputational risks for the focal firm
(Jabbour et al., 2018)	Multi-tier supply chain modelling	Systematic literature review	• Identification of 16 gaps in the literature in the areas of: knowledge development and transfer, interdisciplinary research, research in emerging economies, variety of modelling approaches, truly sustainable supply chains, truly multi-tiered supply chains and diversity of economic sectors • Four lessons learned: relevance of decision-making models and science-based multi-tier sustainable supply chains; insertion of sustainability into key-decisions of multi-tier supply chains; extension of sustainable supplier selection across multiple supply chain tiers; shared responsibilities across multiple tiers and stakeholders towards effective sustainable supply chains

Source	Problem	Methodology	Main findings
(Jia et al., 2018)	Leadership in multi-tier supply chains	Multiple case studies	• Three leadership styles identified: transformational leadership on 1st tier suppliers, transformational leadership on extreme upstream suppliers, transactional leadership on middle tier suppliers • Combined effect of supply chain leadership and governance mechanisms affects supply chain structure and supply chain learning
(Lee et al., 2014)	Transfer of environmental requirements along the supply chain	Single case study	• Definition of the “green-bullwhip” effect • Strict time constraints increase the “green-bullwhip” effect • Demands for better environmental performance are passed upstream through successive tiers with significant variation • Four managerial strategies (effect: replace, accommodate, negotiate and collaborate) can amplify or attenuate the “green-bullwhip”
(Meinlschmidt et al., 2018)	Management of lower-tier suppliers sustainability by focal firms	Multiple case studies	• Eight approaches for lower-tier suppliers sustainability management approaches identified falling within three categories: direct, indirect and neglect • Contextual factors to lower-tier suppliers sustainability management: stakeholder salience, structural supply network complexity, product and industry salience, past supply base incidents, socio-economic and cultural distance and lower tier supplier dependency • Choice of approaches by focal firm based on contextual factors, leading to perceived sustainability risk

Source	Problem	Methodology	Main findings
(Mena et al., 2013)	Management of lower-tier suppliers sustainability by focal firms	Multiple case studies	• Triadic supply chain structures definition • Product characteristics are better influenced adopting a closed triadic approach • Growing sense of interdependence moving from an open to a closed triad
(Sauer and Seuring, 2018)	Sub-suppliers compliance with multi-tier SSCM objectives	Conceptual paper	• Sub-supplier's environment has an implication on the achievement of multi-tier sustainable supply chain management objectives • Three dimensional SSCM framework, based on: institutional distance between supply chain and supplier space, supply uncertainty and demand uncertainty
(Schöggl et al., 2016)	Supply chain sustainability assessment	Literature review and focus-group	• Definition of requirements for supply chain-wide sustainability assessment • Three approaches for supply chain sustainability information exchange: cascadic assessment, direct assessment, generic data • Framework for supply chain sustainability assessment
(Tachizawa and Wong, 2014)	Multi-tier supply chain management conceptualisation	Literature review	• Framework including four approaches for multi-tier supply chain management (beyond triadic supply chains): don't bother, direct, indirect and work with third party • Identification of contingency variables to the management of multi-tier supply chains: power, dependency, distance, industry, knowledge resources, stakeholder pressure, material criticality

Source	Problem	Methodology	Main findings
(Villena and Gioia, 2018)	Lower-tier supply chain risk	Multiple case studies	• Many lower-tier suppliers address their environmental and social sustainability issues passively due to low risk of being penalised • Lower-tier suppliers constitute the riskiest suppliers in a supply network • Lower-tier suppliers operating in supply chains serving focal companies recognised as sustainability leaders are more likely to adopt 3BL sustainability practices • Tier-one suppliers with higher growth rates will have greater difficulty allocating resources to their social and environmental initiatives and to those initiatives involving their own suppliers
(Wilhelm et al., 2016a)	Role of 1st tier suppliers	Multiple case studies	• Importance for focal firms to incentivise each 1st tier supplier separately and to reduce information asymmetries, particularly at the second-tier level (agency factors) • Contingency factors influencing the effective action of 1st tier suppliers: resource availability at the 1st tier supplier, focal firm's focus on the 3BL, focal firm's use of power and focal firm's internal alignment of the sustainability and purchasing function • Focal firm pressure for sustainability as the sole institutional factor influencing 1st tier suppliers

Source	Problem	Methodology	Main findings
(Wilhelm et al., 2016b)	Management of lower-tier suppliers sustainability by focal firms	Multiple case studies	• Supply chain complexity, sustainability management capabilities of first-tier suppliers and type of sustainability in focus (i.e., environmental or social sustainability) influence selection of strategy to manage sub-suppliers • High level of horizontal complexity call for third party or indirect multi-tier approaches • Strong supplier sustainability management with 1st tier suppliers facilitate delegation of responsibilities and generation of open triads • Non-compliance regarding environmental sustainability easier to detect than non-compliance regarding social sustainability

A.3 CS1 conversion factors and data processing

In the specific case of “Il patto della farina” supply chain (CS1), certain data required conversion of their units of measurement. Some data required conversion because the collected data was reported in a unit of measurement which differs from the unit of measurement of the environmental indicators adopted, such as in the case of fossil fuels, whose consumption was converted into energy consumption and GHG emissions. Other data were reported adopting different units of measurement at different organisations and required conversion to obtain homogenous values along the supply chain, such as in the case of solid waste that was reported either by volume or weight at different organisations. This process allowed obtaining homogenous units of measurement along the entire supply chain, which are those appearing in the environmental indicators shown in Chapter 6. Following data required conversion factors in CS1:

<u>Diesel consumption (La Fattoria)</u>
Data was reported in hectolitres [hl] at the company. Original reported figure was 80 hl. Data needed to be converted to kilowatt-hour [kWh] to measure the energy consumption and to kilograms of CO_2 equivalent [kg CO_2e] to measure the direct GHG emissions to air.

- To energy consumption [kWh]:
    1. Diesel consumption converted from hectolitres [hl] to litres [l] multiplying the original value by a factor of 100, resulting in 8,000 l;
    2. Diesel consumption converted from litres to the International System of Units (SI) unit of measurement, which is cubic metres [m^3], by dividing the value by a factor of 1,000, resulting in 8 m^3;
    3. Diesel consumption converted from volume [m^3] to weight [kg] thanks to the diesel density coefficient, which equals to 832 kg/m^3 (Edwards et al., 2007), resulting in 6,656 kg;
    4. Diesel consumption converted from weight [kg] to its energy content [MJ] thanks to the energy density coefficient. Energy density of diesel fuel equals to 43.1 MJ/kg (Edwards et al., 2007), resulting in 286,873 MJ;
    5. Conversion of energy content of diesel fuel from mega-joule [MJ] to kilowatt-hour [kWh] by multiplying the value by a factor of 0.277778;
    6. Calculation of the final value of the indicator in the standardised unit of measurement, equalling **79,687 kWh**.
- To GHG emissions to air (kg CO_2e):
    1. Diesel consumption converted from hectolitres [hl] to litres [l] multiplying the original value by a factor of 100, resulting in 8,000 l;
    2. Diesel consumption converted from litres to the International System of Units (SI) unit of measurement, which is cubic metres [m^3], by dividing the value by a factor of 1,000, resulting in 8 m^3;

3. Diesel consumption converted from volume [m^3] to weight [kg] thanks to the diesel density coefficient, which equals to 832 kg/m^3 (Edwards et al., 2007), resulting in 6,656 kg;
4. Diesel consumption converted from kilograms [kg] to tonnes [t] to be integrated in the emissions coefficient, by dividing the value by a factor of 1,000, thus equalling 6.656 t;
5. Calculation of the CO_2, N_2O and CH_4 emissions is based on relevant diesel air pollutant emission factors specific to non-road mobile machinery for agricultural use, retrieved from Winther and Dore (2017); coefficients are displayed in Table A.3.1;
6. Conversion of the N_2O and CH_4 emissions from grams [g] to kilograms [kg] by dividing the value by a factor of 1,000;
7. Application of the relevant coefficients to convert N_2O and CH_4 emissions [kg] to the adopted unit of measurement for the GHG emissions indicator [kg CO_2e]. The coefficients based on 100-year global warming potential (GWP) are adopted and displayed in Table A.3.1 (U.S. Environmental Protection Agency, 2014);
8. Sum of CO_2, N_2O and CH_4 emissions measured in kilograms of CO_2 equivalent [kg CO_2e] to calculate the overall GHG emissions to air.
9. Calculation of the final value of the indicator in the standardised unit of measurement, equalling **21,317 kg CO_2e**.

Table A.3.1: CS1 conversion factors to calculate GHG emissions to air arising from fuel consumption

Conversion factor			
	CO_2 [kg/t fuel]	**N_2O [g/t fuel]**	**CH_4 [g/t fuel]**
Air pollutant emission factor	3,160	136	87
	CO_2	**N_2O**	**CH_4**
100-year GWP factor	1	298	25

Electricity consumption (Molino Tuzzi and Panificio Iordan)

Data was reported in kilowatt-hour [kWh] at the companies. Original reported figures were 3,200 kWh at Molino Tuzzi and 21,887 kWh at Panificio Iordan. Data needed to be converted to kilograms of CO_2 equivalent [kg CO_2e] to account for indirect GHG emissions to air. Since reported electricity is consumed from the national Italian grid, the average Italian CO_2 equivalent conversion factor was calculated from the most recent available annual report by the International Energy Agency (year 2015). The factor equals to 1.068 kg CO_2 e/kWh based on the Italian electricity mix (International Energy Agency, 2016). The converted values therefore equal **3,418 kg CO_2 e for Molino Tuzzi** and **23,375 kg CO_2 e for Panificio Iordan**.

Solid waste (Panificio Iordan)

Solid waste was reported by volume at Panificio Iordan, adopting litres [l] as unit of measurement. Original reported figures were 2,860 l for mixed paper – old corrugated containers flattened, 1,320 l for aluminium cans, 1,320 l for plastic waste and 953 l for non-recyclable commercial dry waste. All data were reported on a monthly basis. Data needed to be converted to kilograms [kg] to obtain a homogenous representation of the solid waste indicators along the supply chain according to the following steps:

1. Solid waste generated was converted from the reported value to yearly values by multiplying by a factor 12;
2. Solid waste generated was converted from litres [l] to the SI unit of measurement for volumes, which is the cubic metre [m^3], by dividing the value by a factor of 1,000;
3. Solid waste generated was converted from cubic metres [m^3] to cubic yards [yd^3], by multiplying the value by a factor of 1.30795; this conversion was required as volume-to-weight conversion factors suitable for the study adopted units of measurement different from SI unit of measurement;
4. Conversion of the values according to appropriate volume-to-weight conversion factors in order to convert the solid waste generated from cubic yards [yd^3] to pounds [lb]; the conversion factors, displayed in Table A.3.2, were retrieved from the U.S. Environmental Protection Agency (2016) and are specific to each type of waste;
5. Conversion of the solid waste values from pounds [lb] to kilograms [kg] by multiplying the values by a factor of 0.45359237;
6. Calculation of the final value of the indicator in the standardised unit of measurement, equalling 2,158 kg of paper waste, 432 kg of aluminium waste and 380 kg of plastic waste and 495 kg of non-recyclable waste.
7. Sum of the “Paper”, “Aluminium” and “Plastic” solid waste generated values as they are all recycled in the area of operation of the company in order to account for a unique environmental indicator labelled “**Solid waste - recycled**”, equalling **2970 kg**; on the other hand, “**Solid waste – non-recycled**” did not require further processing and totals **495 kg**;

Table A.3.2: CS1 solid waste volume-to-weight conversion factors

Type of waste	**Old Corrugated Containers Flattened**	**Aluminium Cans Uncompacted**	**Plastic Mixed Bottles and Containers Loose**	**Municipal Solid Waste – Commercial Dry Waste**
Conversion factor [lb/yd^3]	106	46	40.4	73

A.4 CS2 conversion factors and data processing

Case study 2 supply chain (CS2) data required a limited amount of unit of measurement conversion as a standardised spreadsheet was circulated among the supply chain members. This facilitated the collection of data in a homogenous unit of measurement, which is the final unit of measurement appearing on the absolute environmental performance indicators. Few exceptions still existed due to data availability and different reporting standards adopted by some companies thus requiring some data processing.
Moreover, conversion factors were still required to calculate the GHG emissions caused both by fossil fuels consumption and by electricity consumption as well as to calculate the energy consumption associated to the fossil fuels consumption. The conversion factors and data processing required for CS2 are listed in this section.

Electricity consumption to GHG emissions to air
Data was reported in kilowatt-hour [kWh] or multiples of at all companies. Original reported figures are displayed in Table A.4.1. Data needed to be converted to kilograms of CO_2 equivalent [kg CO_2e] to account for indirect GHG emissions to air. The conversion is required for electricity consumed from the grid only and is not applied to recyclable energy produced on site by the organisations. Since CS2 supply chain is international, different CO_2 equivalent conversion factors were adopted, reflecting the differences in terms of energy mix between different countries. All conversion factors were retrieved from the most recent available annual report by the International Energy Agency, which is year 2015 (International Energy Agency, 2016). The converted values are also displayed in Table A.4.1: CS2 electricity consumption to GHG emissions to air conversionTable A.4.1.

Table A.4.1: CS2 electricity consumption to GHG emissions to air conversion

Company	Electricity consumed from the grid [kWh/year]	CO_2 equivalent conversion factor	Country	GHG emissions [kg CO_2 e/year]
2.2.1	50,000,000	1.274	Germany	**63,700,000**
2.2.2	25,000,000	1.274	Germany	**31,850,000**
2.3.1	420,245,603	0.510	Finland	**214,325,258**
2.1	795,000,000	1.833	Poland	**1,457,235,000**
2.2	1,212,450	1.068	Italy	**1,294,897**
2.3	4,382,340	1.053	Hungary	**4,614,604**
FC2	21,512,372	1.068	Italy	**22,975,213**

Fossil fuels to GHG emissions to air
Several fossil fuels were adopted at the different tiers of the supply chain, including natural gas, diesel, heavy fuel oil, light fuel oil and lignite coal.

Natural gas

Data was reported in cubic metres [m^3] at five organisations (2.2.1, 2.2.2, 2.1, 2.2 and 2.3), whereas it was stated in tonnes [t] at FC2. Data needed to be converted to kilograms of CO_2 equivalent [kg CO_2e] to account for the direct GHG emissions to air associated to natural gas consumption. A simple application of the emission factor was required to convert the data: this equals to 2.097 kg CO_2e/m^3 or 2814 kg CO_2e/t (UK Government, 2017), as displayed in Table A.4.2.

Table A.4.2: CS2 natural gas consumption to GHG emissions to air conversion

Company	Natural gas consumption		Emission factor	GHG emissions [kg CO_2 e/year]
2.2.1	1,700,000	m^3	2.097 kg CO_2e/m^3	**3,564,431**
2.2.2	675,000	m^3	2.097 kg CO_2e/m^3	**1,415,289**
2.1	59,607,737	m^3	2.097 kg CO_2e/m^3	**124,980,984**
2.2	23,714	m^3	2.097 kg CO_2e/m^3	**49,722**
2.3	700,799	m^3	2.097 kg CO_2e/m^3	**1,469,382**
FC2	4,467	t	2,814 kg CO_2e/t	**12,569,047**

Diesel

Data was reported in litres [l] at 2.2.2, with original figure accounting 44,000 l/year. Data needed to be converted to kilograms of CO_2 equivalent [kg CO_2e] to account for the direct GHG emissions to air associated to diesel consumption. The following steps were required:

1. Diesel consumption converted from litres to the International System of Units (SI) unit of measurement, which is cubic metres [m^3], by dividing the value by a factor of 1,000, equalling 44 m^3;
2. Diesel consumption converted from volume [m^3] to weight [kg] thanks to the diesel density coefficient, which equals to 832 kg/m^3 (Edwards et al., 2007), resulting in 36,608 kg;
3. Diesel consumption converted from kilograms [kg] to tonnes [t] to be integrated in the emissions coefficient, by dividing the value by a factor of 1,000, equalling 36.608 t;
4. Calculation of the CO_2, N_2O and CH_4 emissions is based on relevant air pollutant emission factors specific to diesel non-road mobile machinery for industrial use, retrieved from Winther and Dore (2017); coefficients are displayed in Table A.4.3;
5. Conversion of the N_2O and CH_4 emissions from grams [g] to kilograms [kg] by multiplying the value by a factor of 1,000;
6. Application of the relevant coefficients to convert N_2O and CH_4 emissions [kg] to the adopted unit of measurement for the GHG emissions to air indicator [kg CO_2e]. The coefficients based on 100-year global warming potential are adopted and displayed in Table A.4.3 (U.S. Environmental Protection Agency, 2014);
7. Sum of CO_2, N_2O and CH_4 emissions measured in kilograms of CO_2 equivalent [kg CO_2e] to calculate the overall GHG emissions to air;

8. Calculation of the final value of the indicator in the standardised unit of measurement, equalling **117,230 kg CO_2e**.

Table A.4.3: CS2 conversion factors to calculate GHG emissions to air arising from diesel consumption

Conversion factor			
	CO_2 [kg/t fuel]	**N_2O [g/t fuel]**	**CH_4 [g/t fuel]**
Air pollutant emission factor	3,160	135	83
	CO_2	**N_2O**	**CH_4**
100-year GWP factor	1	298	25

Fuel oils

Data was reported in tonnes [t] at 2.3.1 and FC2, as shown in Table A.4.4. Data needed to be converted to kilograms of CO_2 equivalent [kg CO_2e] to account for the direct GHG emissions to air associated to the fuel oils consumption.

Table A.4.4: CS2 consumption of fuel oils

Organisation	**2.3.1**	**FC2**
Heavy fuel oil (HFO) consumption [t/year]	9,340	2,541.6
Light fuel oil (LFO) consumption [t/year]	1,192	1,527.1

Following steps were required:

1. Fuel oil consumption converted from tonnes [t] to kilograms [kg], by multiplying the reported value by a factor of 1,000;
2. Fuel oil consumption converted from weight [kg] to its energy content [MJ] thanks to the energy density coefficient. Energy density of heavy fuel oil (HFO) equals to 42.6 MJ/kg (FAO, 1990), while energy density of light fuel oil (LFO) equals to 43.5 MJ/kg (FAO, 1990);
3. Application of the emission factors, which equals to 0.074 kg CO_2e/MJ for HFO and 0.081 kg CO_2e/MJ for LFO (Juhrich, 2016);
4. Calculation of the final value of the indicators in the standardised units of measurement, which are displayed in Table A.4.5.

Table A.4.5: CS2 fuel oils consumption to GHG emissions to air conversion

Organisation	**2.3.1**	**FC2**
Heavy fuel oil (HFO)-associated GHG emissions [kg CO_2e /year]	**29,443,416**	**8,012,140**
Light fuel oil (LFO)- associated GHG emissions [kg CO_2e /year]	**4,215,568**	**5,400,666**

Lignite coal

Data was reported in kilograms [kg] at 2.2.2, with original figure accounting 14,800 kg/year. Data needed to be converted to kilograms of CO_2 equivalent [kg CO_2e] to account for the direct GHG emissions to air associated to the lignite coal use. The following steps were required:

1. Lignite coal use converted from kilograms [kg] to tonnes [t] dividing the original value by a factor of 1,000;
2. Lignite coal use converted from tonnes [t] short tonnes [US t], by multiplying the value by a factor of 1.10231; this conversion was required as lignite coal emission factors suitable for the study adopted units of measurement different from SI unit of measurement;
3. Calculation of the CO_2, N_2O and CH_4 emissions is based on relevant air pollutant emission factors specific lignite coal use, retrieved from the U.S. Environmental Protection Agency emission factors for greenhouse gas inventories (2014); coefficients are displayed in Table A.4.6;
4. Conversion of the N_2O and CH_4 emissions from grams [g] to kilograms [kg] by dividing the value by a factor of 1,000;
5. Application of the relevant coefficients to convert N_2O and CH_4 emissions [kg] to the adopted unit of measurement for the GHG emissions indicator [kg CO_2e]. The coefficients based on 100-year global warming potential are adopted and displayed in Table A.4.6 (U.S. Environmental Protection Agency, 2014);
6. Sum of CO_2, N_2O and CH_4 emissions measured in kilograms of CO_2 equivalent [kg CO_2e] to calculate the overall GHG emissions to air.
7. Calculation of the final value of the indicator in the standardised unit of measurement, equalling **22,836 kg CO_2e**.

Table A.4.6: CS2 conversion factors to calculate GHG emissions to air arising from lignite coal consumption

Conversion factor			
	CO_2 [kg/short t fuel]	**N_2O [g/short t fuel]**	**CH_4 [g/short t fuel]**
Air pollutant emission factor	1389	23	156
	CO_2	**N_2O**	**CH_4**
100-year GWP factor	1	298	25

<u>Fossil fuels to energy consumption</u>

Several fossil fuels were adopted at the different tiers of the supply chain, including natural gas, diesel, heavy fuel oil, light fuel oil and lignite coal.

Natural gas

Data was reported in cubic metres [m^3] at five organisations (2.2.1, 2.2.2, 2.1, 2.2 and 2.3), whereas it was stated in tonnes [t] at FC2. Therefore, two natural gas energy density conversion factors were used to determine the consumed energy associated to the consumption of fossil fuels (The Engineering Tool Box, 2018):

- Energy density per cubic metre: 36.6 [MJ/m^3]
- Energy density per tonne: 47.1 [MJ/t]

Following the application of the conversion factor, the energy content of diesel from all five organisations was converted to from mega-joule [MJ] to kilowatt-hour [kWh] by multiplying the value by a factor of 0.277778, leading to the final values displayed in Table A.4.7.

Table A.4.7: CS2 natural gas to energy consumption conversion

Company	Natural gas consumption		Energy consumption [kWh/year]
2.2.1	1,700,000	m^3	**17,283,347**
2.2.2	675,000	m^3	**6,862,505**
2.1	59,607,737	m^3	**606,012,478**
2.2	23,714	m^3	**241,093**
2.3	700,799	m^3	**7,124,796**
FC2	4,467	t	**58,438,063**

Diesel

Data was reported in litres [l] at 2.2.2. Original reported figure was 44,000 l. Data needed to be converted to kilowatt-hour [kWh] to measure the energy consumption. Following steps were required:

1. Diesel consumption converted from litres to the International System of Units (SI) unit of measurement, which is cubic metres [m^3], by dividing the value by a factor of 1,000, equalling to 44 m^3;
2. Diesel consumption converted from volume [m^3] to weight [kg] thanks to the diesel density coefficient, which equals to 832 kg/m^3 (Edwards et al., 2007), resulting in 36,608 kg;
3. Diesel consumption converted from weight [kg] to its energy content [MJ] thanks to the energy density coefficient. Energy density of diesel fuel equals to 43.1 MJ/kg (Edwards et al., 2007), thus energy content of consumed diesel equals to 1,577,805 MJ;
4. Conversion of energy content of diesel fuel from mega-joule [MJ] to kilowatt-hour [kWh] by multiplying the value by a factor of 0.277778;
5. Calculation of the final value of the indicator in the standardised unit of measurement, equalling **438,279 kWh**.

Fuel oils

Data was reported in tonnes [t] at 2.3.1 and FC2, as shown in Table A.4.4. Data needed to be converted to kilowatt-hour [kWh] to measure the energy consumption. Following steps were required:

1. Fuel oil consumption converted from tonnes [t] to kilograms [kg], by multiplying the reported value by a factor of 1,000;
2. Fuel oil consumption converted from weight [kg] to its energy content [MJ] thanks to the energy density coefficient. Energy density of heavy fuel oil (HFO) equals to 42.6 MJ/kg (FAO, 1990), while energy density of light fuel oil (LFO) equals to 43.5 MJ/kg (FAO, 1990);

3. Conversion of energy content of diesel fuel from mega-joule [MJ] to kilowatt-hour [kWh] by multiplying the value by a factor of 0.277778;
4. Calculation of the final value of the indicators in the standardised units of measurement, which are displayed in Table A.4.8.

Table A.4.8: CS2 energy consumption associated to fuel oils consumption

Organisation	2.3.1	FC2
Heavy fuel oil (HFO)-associated energy consumption [kWh/year]	**110,523,422**	**30,075,624**
Light fuel oil (LFO)-associated energy consumption [kWh/year]	**14,403,345**	**18,452,473**

Lignite coal

Data was reported in kilograms [kg] at 2.2.2, with original figure accounting 14,800 kg/year. Data needed to be converted to kilowatt-hour [kWh] to measure the energy consumption. The simple application of the energy density conversion factor was necessary, which is in the specific case of lignite coal equal to 8.22 kWh/kg (The Engineering Tool Box, 2018). The final value of the indicator in the standardised unit of measurement was thus equal to **121,656 kWh**.

<u>Solid waste</u>

Solid waste sent to landfill was reported by volume at company 2.3, adopting cubic metres [m^3] as unit of measurement. Original reported figure was 545 m^3/year for solid waste sent to landfill and thus not-recycled. Data needed to be converted to kilograms [kg] to harmonise it with the other solid waste indicators reported along the supply chain. Following steps were performed:

1. Solid waste generated was converted from cubic metres [m^3] to cubic yards [yd^3], by multiplying the value by a factor of 1.30795; this conversion was required as volume-to-weight conversion factors suitable for the study adopted units of measurement different from SI unit of measurement;
2. Conversion of the values according to volume-to-weight conversion factors in order to convert the solid waste generated from cubic yards [yd^3] to pounds [lb]; the conversion factors, displayed in Table A.4.9, were retrieved from the U.S. Environmental Protection Agency (2016) and are specific to each type of waste;
3. Conversion of the solid waste values from pounds [lb] to kilograms [kg] by multiplying the values by a factor of 0.45359237;
4. Calculation of the final value of the indicator in the standardised unit of measurement, equalling **44,620 kg** of solid waste sent to landfill on a yearly basis.

Table A.4.9: CS2 solid waste volume-to-weight conversion

Type of waste	Commercial -all waste, uncompacted
Conversion factor [lb/yd^3]	138

A.5 Summary of conversion factor

Appendixes A.1 and A.4 provided the information about the conversion factors and the process followed to convert data in the each of two case studies. This section provides a summary of all conversion factors adopted in both case studies, which are listed in Table A.5.1, along with the sources they were retrieved from.

Table A.5.1: Summary of conversion factors and coefficients

			Source	**CS1**	**CS2**
CH_4 100-year GWP factor	25		(U.S. Environmental Protection Agency, 2014)	✓	
CO_2 100-year GWP factor	1		(U.S. Environmental Protection Agency, 2014)	✓	
Diesel density coefficient	832	kg/m^3	(Edwards et al., 2007)	✓	✓
Emission factor – Aggregated GHG emissions to air – Electricity from the grid, Finland	0.510	kg CO_2 e/kWh	(International Energy Agency, 2016)		✓
Emission factor – Aggregated GHG emissions to air – Electricity from the grid, Germany	1.274	kg CO_2 e/kWh	(International Energy Agency, 2016)		✓
Emission factor – Aggregated GHG emissions to air – Electricity from the grid, Hungary	1.053	kg CO_2 e/kWh	(International Energy Agency, 2016)		✓

			Source	CS1	CS2
Emission factor – Aggregated GHG emissions to air – Electricity from the grid, Italy	1.068	kg CO_2 e/kWh	(International Energy Agency, 2016)	✓	✓
Emission factor – Aggregated GHG emissions to air – Electricity from the grid, Poland	1.833	kg CO_2 e/kWh	(International Energy Agency, 2016)		✓
Emission factor – Aggregated GHG emissions to air - Heavy fuel oil (HFO)	0.074	kg CO_2e/MJ	(Juhrich, 2016)		✓
Emission factor – Aggregated GHG emissions to air - Light fuel oil (LFO)	0.081	kg CO_2e/MJ	(Juhrich, 2016)		✓
Emission factor – Aggregated GHG emissions to air – Natural gas, by volume	2.097	kg CO_2e/m^3	(UK Government, 2017)		✓
Emission factor – Aggregated GHG emissions to air – Natural gas, by weight	2814	kg CO_2e/t	(UK Government, 2017)		✓
Emission factor - CH_4 emissions to air – Lignite coal	156	g/short t fuel	(U.S. Environmental Protection Agency, 2014)		✓
Emission factor - CH_4 emissions to air – Diesel, specific to non-road mobile machinery for industrial use	83	g/t fuel	(Winther and Dore, 2017)		✓

			Source	CS1	CS2
Emission factor - CH_4 emissions to air – Diesel, specific to non-road mobile machinery for agricultural use	87	g/t fuel	(Winther and Dore, 2017)	✓	
Emission factor – CO_2 emissions to air – Lignite coal	1389	kg/short t fuel	(U.S. Environmental Protection Agency, 2014)		✓
Emission factor – CO_2 emissions to air – Diesel, specific to non-road mobile machinery for industrial use	3160	kg/t fuel	(Winther and Dore, 2017)		✓
Emission factor – CO_2 emissions to air – Diesel, specific to non-road mobile machinery for agricultural use	3160	kg/t fuel	(Winther and Dore, 2017)	✓	
Emission factor – N_2O emissions to air – Lignite coal	23	g/short t fuel	(U.S. Environmental Protection Agency, 2014)		✓
Emission factor – N_2O emissions to air – Diesel, specific to non-road mobile machinery for industrial use	135	g/t fuel	(Winther and Dore, 2017)		✓
Emission factor – N_2O emissions to air – Diesel, specific to non-road mobile machinery for agricultural use	136	g/t fuel	(Winther and Dore, 2017)	✓	

			Source	CS1	CS2
Energy density coefficient – Lignite coal	8.22	kWh/kg	(The Engineering Tool Box, 2018)		✓
Energy density coefficient – Diesel	43.1	MJ/kg	(Edwards et al., 2007)	✓	✓
Energy density coefficient – Heavy Fuel Oil (HFO)	42.6	MJ/kg	(FAO, 1990)		✓
Energy density coefficient – Light Fuel Oil (LFO)	43.5	MJ/kg	(FAO, 1990)		✓
Energy density coefficient – Natural gas – by volume	36.6	MJ/m^3	(The Engineering Tool Box, 2018)		✓
Energy density coefficient – Natural gas – by weight	47.1	MJ/t	(The Engineering Tool Box, 2018)		✓
N_2O 100-year GWP factor	298		(U.S. Environmental Protection Agency, 2014)	✓	
Solid waste volume-to-weight factor – aluminium cans uncompacted	46	lb/yd^3	(U.S. Environmental Protection Agency, 2016)	✓	

			Source	CS1	CS2
Solid waste volume-to-weight factor – Commercial -all waste, uncompacted	138	lb/yd^3	(U.S. Environmental Protection Agency, 2016)		✓
Solid waste volume-to-weight factor – Municipal solid waste – commercial dry waste	73	lb/yd^3	(U.S. Environmental Protection Agency, 2016)	✓	
Solid waste volume-to-weight factor – Old corrugated containers flattened	106	lb/yd^3	(U.S. Environmental Protection Agency, 2016)	✓	
Solid waste volume-to-weight factor – Plastic mixed bottles and containers loose	40.4	lb/yd^3	(U.S. Environmental Protection Agency, 2016)	✓	

A.6 CS1 aggregation of environmental sub-indicators

The environmental profile of organisations, as appearing in Chapter 6, is a high-level snapshot of the absolute environmental performance of organisations. However, each environmental indicator is the result of multiple sub-indicators towards that specific indicator. The summarising tables for CS1 are outlined in this section. In the case of CS1, three environmental indicators required summations of different sub-indicators contributions. These are:

- Energy consumption (Table A.6.1);
- GHG emissions (Table A.6.2);
- Solid waste (Table A.6.3);

Table A.6.1: CS1 energy totals

Energy consumption [kWh/year]	**La Fattoria**	**Molino Tuzzi**	**Panificio Iordan**
Electricity consumption from the network		3,200	21,887
Energy consumption from diesel consumption	79,687		
Total energy consumption [kWh/year]	**79,687**	**3,200**	**21,887**

Table A.6.2: CS1 GHG emissions to air totals

GHG emissions [kg CO_2e/year]	**La Fattoria**	**Molino Tuzzi**	**Panificio Iordan**
GHG emissions from electricity consumption		3,418	23,375
GHG emissions from diesel consumption	89,392		
Total GHG emissions [kg CO_2e/year]	**89,392**	**3,418**	**23,375**

Table A.6.3: CS1 solid waste totals

Solid waste [kg/year]	**Weight**	**La Fattoria**	**Molino Tuzzi**	**Panificio Iordan**
Recycled waste	*1*	300	1,950	2,970
Non-recycled waste	*2*			495
Hazardous waste	*3*			
Total solid waste - unweighted [kg/year]		**300**	**1,950**	**3,465**
Total solid waste - weighted [kg/year]		**300**	**1,950**	**3,960**

A.7 CS2 aggregation of environmental sub-indicators

The environmental profile of organisations, as appearing in Chapter 6, is a high-level snapshot of the absolute environmental performance of organisations. However, each environmental indicator is the result of multiple contributions towards that specific indicator. The summarising tables for CS2 are outlined in this section. In the case of CS2, four environmental indicators required summations of different sub-indicators contributions. These are:

- Materials consumption (Table A.7.1);
- Table A.7.2);
- GHG emissions (Table A.7.3);
- Solid waste (Table A.7.4);

Table A.7.1: CS2 material consumption totals

Material consumption [kg/year]	***Weight***	**2.1**	**2.2.1**	**2.2.2**	**2.2**	**2.3.1**	**2.3**	**FC2**
Recycled material consumption	*1*	1,323,000,000	40,100,000			83,100,000	8,305,575	
Renewable material consumption	*2*		10,050,000					75,513
Non-renewable material consumption	*3*	42,000	17,800,000	910,000		4,986,510,066	673,425	28,153,868
Total material consumption *unweighted* [kg/year]		**1,323,040,000**	**67,950,000**	**910,000**	**0**	**5,069,610,066**	**8,979,000**	**28,229,381**
Total material consumption *weighted* [kg/year]		**1,323,126,000**	**113,600,000**	**2,730,000**	**0**	**15,042,630,198**	**10,325,850**	**84,612,630**

Table A.7.2: CS2 energy consumption totals

Energy consumption [kWh/year]	**2.1**	**2.2.1**	**2.2.2**	**2.2**	**2.3.1**	**2.3**	**FC2**
Electricity consumption from the network	795,000,000	50,000,000	25,000,000	1,212,450	420,245,603	4,382,340	21,512,372
Self-produced electricity from renewable sources				4,956			7,121,665
Energy consumption from natural gas consumption	606,012,478	17,283,347	6,862,505	241,093		7,124,796	58,438,063
Energy consumption from HFO consumption					110,523,422		30,075,624
Energy consumption from LFO consumption					14,403,345		18,452,473
Energy consumption from diesel consumption			438,279				
Energy consumption from lignite coal consumption			121,656				
Total energy consumption [kWh/year]	**1,401,012,478**	**67,283,347**	**32,422,441**	**1,458,499**	**545,172,370**	**11,507,136**	**135,600,198**

Table A.7.3: CS2 GHG emissions totals

GHG emissions [kg CO_2e/year]	**2.1**	**2.2.1**	**2.2.2**	**2.2**	**2.3.1**	**2.3**	**FC2**
GHG emissions from electricity consumption	1,457,235,000	63,700,000	31,850,000	1,294,897	214,325,258	4,614,604	22,975,213
GHG emissions from natural gas consumption	124,980,984	3,564,431	1,415,289	49,722		1,469,382	12,569,047
GHG emissions from HFO consumption					29,443,416		8,012,140
GHG emissions from LFO consumption					4,215,568		5,400,666
GHG emissions from diesel consumption			117,230				
GHG emissions from lignite coal consumption			22,836				
Total GHG emissions [kg CO_2e/year]	**1,582,215,984**	**67,264,431**	**33,405,355**	**1,344,618**	**247,984,241**	**6,083,986**	**48,957,066**

Table A.7.4: CS2 solid waste totals

Solid waste [kg/year]	***Weight***	**2.1**	**2.2.1**	**2.2.2**	**2.2**	**2.3.1**	**2.3**	**FC2**
Recycled waste	*1*	175,000,000	20,962	60,000	539,000	2,115,000	2,543,506	5,675,781
Non-recycled waste	*2*	0	3,520	0	1,526	105,143,000	44,620	985,382,023
Hazardous waste	*3*	20,000,000	4,090	1,800,000	450	1,470,000	57,158	2,225,418
Total solid waste *unweighted* [kg/year]		**195,000,000**	**28,572**	**1,860,000**	**540,976**	**108,728,000**	**2,645,284**	**993,283,222**
Total solid waste *weighted* [kg/year]		**235,000,000**	**40,272**	**5,460,000**	**543,402**	**216,811,000**	**2,804,221**	**1,983,116,081**

A.8 CS1 Transport environmental impact

The environmental impact of transport was calculated by EcoTransIT in terms of both energy consumption and GHG emissions to air, in accordance to the European Standard EN 16258:2012.

The geographical locations of the supply chain members of CS1 are as follows:

- La Fattoria: Premariacco Orsaria, Italy;
- Molino Tuzzi: Dolegna del Collio, Italy;
- Panificio Iordan: Capriva del Friuli, Italy;

The outputs of the EcoTransIT software calculations for CS1 are displayed in this section. The tank-to-wheel (TTW) outputs were used in the case study for both the energy consumption and the GHG emissions to air, as defined in Chapter 4. The environmental impact was calculated for two transportation links:

- From 2nd tier supplier La Fattoria to 1st tier supplier Molino Tuzzi (Figure A.8.1);
- From 1st tier supplier Molino Tuzzi to focal company Panificio Iordan (Figure A.8.2);

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General Information

Creation Date:	20.11.2018
Origin:	[City district] [it] Premariacco Orsaria
Destination:	[City district] [it] Dolegna del Collio
Cargo weight:	2.9375 ton (t/TEU: 10)

Detailed description of the calculated transport services

Transport service Truck - 18.34 km

Origin: [City district] [it] Premariacco Orsaria

Truck (26-40 t,diesel,EURO 5,LF: 60.0%,ETF: 20%) - 18.34 km

Destination: [City district] [it] Dolegna del Collio

Energy consumption and greenhouse gases (GHG) in accordance with EN 16258

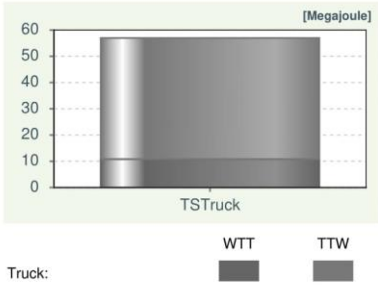
Energy consumption

WTW [Megajoule]

	TSTruck
Truck	57
Sum	57

TTW [Megajoule]

	TSTruck
Truck	46
Sum	46



Well-to-Wheel (WTW) = Well-to-Tank (WTT) + Tank-to-Wheel (TTW)

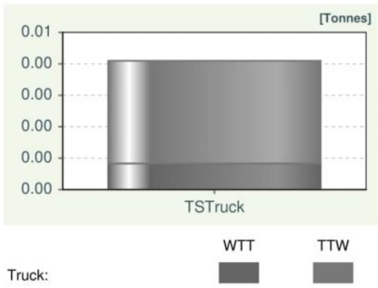
GHG emissions (calculated as CO2 equivalents)

WTW [Tonnes]

	TSTruck
Truck	0.004
Sum	0.004

TTW [Tonnes]

	TSTruck
Truck	0.003
Sum	0.003



Well-to-Wheel (WTW) = Well-to-Tank (WTT) + Tank-to-Wheel (TTW)

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Figure A.8.1: EcoTransIT output – CS1 Environmental impact of transport from La Fattoria to Molino Tuzzi

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General Information

Creation Date:	20.11.2018
Origin:	[City district] [it] Dolegna del Collio
Destination:	[City district] [it] Capriva del Friuli
Cargo weight:	2.4 ton (t/TEU: 10)

Detailed description of the calculated transport services

Transport service Truck - 15.07 km

Origin: [City district] [it] Dolegna del Collio

Truck (26-40 t,diesel,EURO 5,LF: 60.0%,ETF: 20%) - 15.07 km

Destination: [City district] [it] Capriva del Friuli

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Energy consumption and greenhouse gases (GHG) in accordance with EN 16258

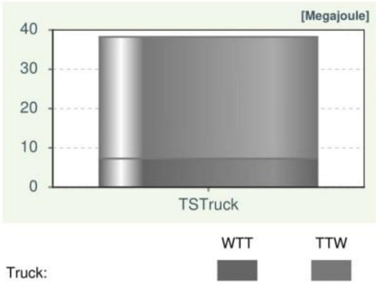
Energy consumption

WTW [Megajoule]

	TSTruck
Truck	38
Sum	38

TTW [Megajoule]

	TSTruck
Truck	31
Sum	31



Well-to-Wheel (WTW) = Well-to-Tank (WTT) + Tank-to-Wheel (TTW)

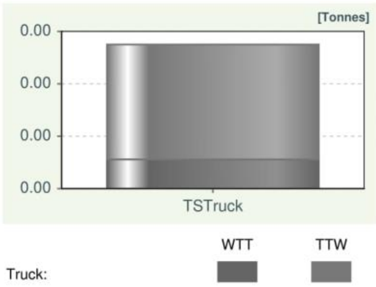
GHG emissions (calculated as CO2 equivalents)

WTW [Tonnes]

	TSTruck
Truck	0.003
Sum	0.003

TTW [Tonnes]

	TSTruck
Truck	0.002
Sum	0.002



Well-to-Wheel (WTW) = Well-to-Tank (WTT) + Tank-to-Wheel (TTW)

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Figure A.8.2: EcoTransIT output – CS1 Environmental impact of transport from Molino Tuzzi to Panificio Iordan

A.9 CS2 Transport environmental impact

The environmental impact of transport was calculated by EcoTransIT in terms of both energy consumption and GHG emissions to air, in accordance to the European Standard EN 16258:2012.

The exact geographical locations of the supply chain members of CS2 have been anonymised after the calculations of the results of the transport environmental impact in order to preserve the confidentiality of information and avoid the recognisability of organisations involved, therefore only the country of companies is given, as follows:

- 2.1: Location 2.1, Poland;
- 2.2: Location 2.2, Italy;
- 2.2.1: Location 2.2.1, Germany;
- 2.2.2: Location 2.2.2, Germany;
- 2.3: Location 2.3, Finland;
- 2.3.1: Location 2.3.1, Hungary;
- FC2: Location 2, Italy;

The outputs of the EcoTransIT software calculations for CS2 are displayed in this section. The tank-to-wheel (TTW) outputs were used in the case study for both the energy consumption and the GHG emissions to air, as defined in Chapter 4. The environmental impact was calculated for five transportation links:

- From 2.2.2 to 2.2 (Figure A.9.1);
- From 2.2.1 to 2.2 (Figure A.9.2);
- From 2.3.1 to 2.3 (Figure A.9.3);
- From 2.1 to FC2 (Figure A.9.4);
- From 2.2 to FC2 (Figure A.9.5);
- From 2.3 to FC2 (Figure A.9.6);

EcoTransIT World

EcoTransIT World (Ecological Transport Information Tool for Worldwide Transports) calculates the environmental impacts for any freight transport service. EcoTransIT World provides energy consumption and GHG Emissions for trucks, trains, ships and airplanes in accordance with the European standard EN 16258:2012. Additionally carbon dioxide (CO2) and the most important air pollutants (nitrogen oxide, non-methane hydrocarbons, sulfur dioxide and particulates) can be calculated with EcoTransIT World. Below you will find all information about your transport service selected and data sources used as well as the results of your calculation.

General Information

Creation Date:	01.06.2018
Origin:	[City district] Location 2.2.1
Destination:	[City district] Location 2.2
Cargo weight:	2374.32 ton (t/TEU: 10)

Detailed description of the calculated transport services

Transport service Truck - 968.16 km

Origin: [City district] Location 2.2.1

Truck (26-40 t,diesel,EURO 5,LF: 60.0%,ETF: 20%) - 968.16 km

Destination: [City district] Location 2.2

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Energy consumption and greenhouse gases (GHG) in accordance with EN 16258

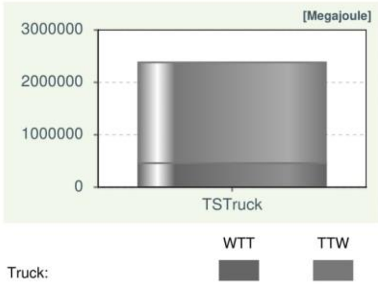
Energy consumption

WTW [Megajoule]

	TSTruck
Truck	2,380,926
Sum	2,380,926

TTW [Megajoule]

	TSTruck
Truck	1,921,280
Sum	1,921,280



Well-to-Wheel (WTW) = Well-to-Tank (WTT) + Tank-to-Wheel (TTW)

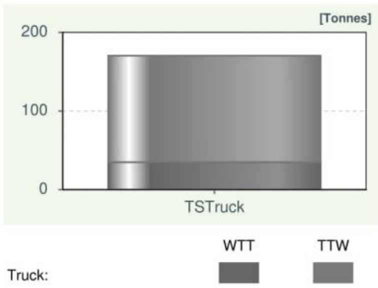
GHG emissions (calculated as CO2 equivalents)

WTW [Tonnes]

	TSTruck
Truck	170
Sum	170

TTW [Tonnes]

	TSTruck
Truck	135
Sum	135



Well-to-Wheel (WTW) = Well-to-Tank (WTT) + Tank-to-Wheel (TTW)

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Figure A.9.1: EcoTransIT output – CS2 Environmental impact of transport from 2.2.1 to 2.2

EcoTransIT World

EcoTransIT World (Ecological Transport Information Tool for Worldwide Transports) calculates the environmental impacts for any freight transport service. EcoTransIT World provides energy consumption and GHG Emissions for trucks, trains, ships and airplanes in accordance with the European standard EN 16258:2012. Additionally carbon dioxide (CO2) and the most important air pollutants (nitrogen oxide, non-methane hydrocarbons, sulfur dioxide and particulates) can be calculated with EcoTransIT World. Below you will find all information about your transport service selected and data sources used as well as the results of your calculation.

General Information

Creation Date:	04.06.2018
Origin:	[City district] Location 2.2.2
Destination:	[City district] Location 2.2
Cargo weight:	2374.32 ton (t/TEU: 10)

Detailed description of the calculated transport services

Transport service Truck - 536.05 km

Origin: [City district] Location 2.2.2

Truck (26-40 t,diesel,EURO 5,LF: 60.0%,ETF: 20%) - 536.05 km

Destination: [City district] Location 2.2

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Energy consumption and greenhouse gases (GHG) in accordance with EN 16258

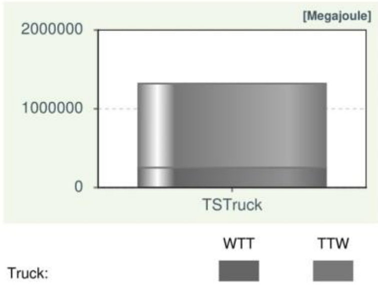
Energy consumption

WTW [Megajoule]

	TSTruck
Truck	1,320,339
Sum	1,320,339

TTW [Megajoule]

	TSTruck
Truck	1,067,016
Sum	1,067,016



Well-to-Wheel (WTW) = Well-to-Tank (WTT) + Tank-to-Wheel (TTW)

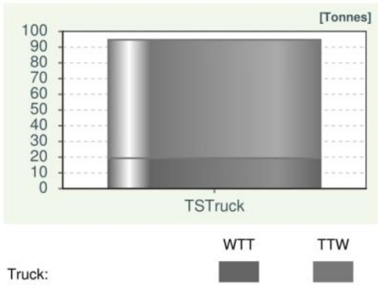
GHG emissions (calculated as CO2 equivalents)

WTW [Tonnes]

	TSTruck
Truck	95
Sum	95

TTW [Tonnes]

	TSTruck
Truck	75
Sum	75



Well-to-Wheel (WTW) = Well-to-Tank (WTT) + Tank-to-Wheel (TTW)

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Figure A.9.2: EcoTransIT output – CS2 Environmental impact of transport from 2.2.2 to 2.2

EcoTransIT World

EcoTransIT World (Ecological Transport Information Tool for Worldwide Transports) calculates the environmental impacts for any freight transport service. EcoTransIT World provides energy consumption and GHG Emissions for trucks, trains, ships and airplanes in accordance with the European standard EN 16258:2012. Additionally carbon dioxide (CO2) and the most important air pollutants (nitrogen oxide, non-methane hydrocarbons, sulfur dioxide and particulates) can be calculated with EcoTransIT World. Below you will find all information about your transport service selected and data sources used as well as the results of your calculation.

General Information

Creation Date:	01.06.2018	
Origin:	[City district]	Location 2.3.1
Destination:	[City district]	Location 2.3
Cargo weight:	1806.49 ton (t/TEU: 10)	

Detailed description of the calculated transport services

Transport service Truck - 2,634.61 km

Origin: [City district] Location 2.3.1

Truck (26-40 t,diesel,EURO 5,LF: 60.0%,ETF: 20%) - 2,634.61 km

Destination: [City district] Location 2.3

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Energy consumption and greenhouse gases (GHG) in accordance with EN 16258

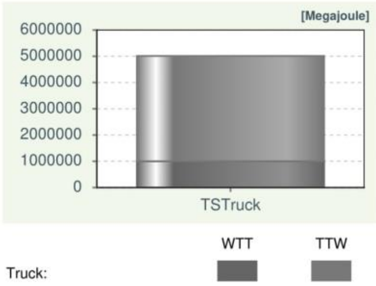
Energy consumption

WTW [Megajoule]

	TSTruck
Truck	5,011,043
Sum	5,011,043

TTW [Megajoule]

	TSTruck
Truck	4,008,424
Sum	4,008,424



Well-to-Wheel (WTW) = Well-to-Tank (WTT) + Tank-to-Wheel (TTW)

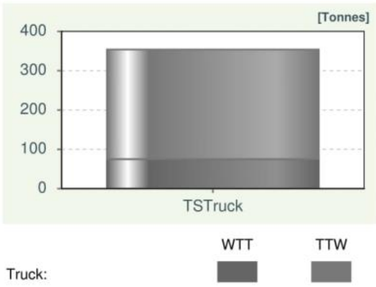
GHG emissions (calculated as CO2 equivalents)

WTW [Tonnes]

	TSTruck
Truck	354
Sum	354

TTW [Tonnes]

	TSTruck
Truck	279
Sum	279



Well-to-Wheel (WTW) = Well-to-Tank (WTT) + Tank-to-Wheel (TTW)

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Figure A.9.3: EcoTransIT output – CS2 Environmental impact of transport from 2.3.1 to 2.3

EcoTransIT World

EcoTransIT World (Ecological Transport Information Tool for Worldwide Transports) calculates the environmental impacts for any freight transport service. EcoTransIT World provides energy consumption and GHG Emissions for trucks, trains, ships and airplanes in accordance with the European standard EN 16258:2012. Additionally carbon dioxide (CO2) and the most important air pollutants (nitrogen oxide, non-methane hydrocarbons, sulfur dioxide and particulates) can be calculated with EcoTransIT World. Below you will find all information about your transport service selected and data sources used as well as the results of your calculation.

General Information

Creation Date:	20.07.2018
Origin:	[City district] Location 2.1
Destination:	[City district] Location 2
Cargo weight:	387 ton (t/TEU: 10)

Detailed description of the calculated transport services

Transport service Truck - 1,075.91 km

Origin: [City district] Location 2.1

Truck (26-40 t,diesel,EURO 5,LF: 60.0%,ETF: 20%) - 1,075.91 km

Destination: [City district] Location 2

Energy consumption and greenhouse gases (GHG) in accordance with EN 16258

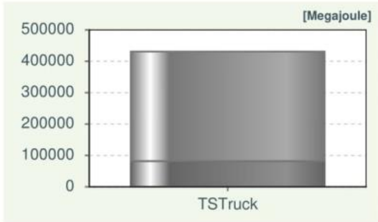
Energy consumption

WTW [Megajoule]

	TSTruck
Truck	431,044
Sum	431,044

TTW [Megajoule]

	TSTruck
Truck	348,959
Sum	348,959



	WTT	TTW
Truck:		

Well-to-Wheel (WTW) = Well-to-Tank (WTT) + Tank-to-Wheel (TTW)

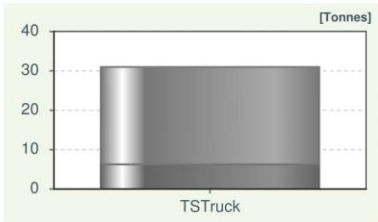
GHG emissions (calculated as CO2 equivalents)

WTW [Tonnes]

	TSTruck
Truck	31
Sum	31

TTW [Tonnes]

	TSTruck
Truck	25
Sum	25



	WTT	TTW
Truck:		

Well-to-Wheel (WTW) = Well-to-Tank (WTT) + Tank-to-Wheel (TTW)

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Figure A.9.4: EcoTransIT output – CS2 Environmental impact of transport from 2.1 to FC2

EcoTransIT World

EcoTransIT World (Ecological Transport Information Tool for Worldwide Transports) calculates the environmental impacts for any freight transport service. EcoTransIT World provides energy consumption and GHG Emissions for trucks, trains, ships and airplanes in accordance with the European standard EN 16258:2012. Additionally carbon dioxide (CO2) and the most important air pollutants (nitrogen oxide, non-methane hydrocarbons, sulfur dioxide and particulates) can be calculated with EcoTransIT World. Below you will find all information about your transport service selected and data sources used as well as the results of your calculation.

General Information

Creation Date: 01.06.2018
Origin: [City district] Location 2.2
Destination: [City district] Location 2
Cargo weight: 2135.28 ton (t/TEU: 10)

Detailed description of the calculated transport services

Transport service Truck - 233.18 km

Origin: [City district] Location 2.2
Truck (26-40 t,diesel,EURO 5,LF: 60.0%,ETF: 20%) - 233.18 km
Destination: [City district] Location 2

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Energy consumption and greenhouse gases (GHG) in accordance with EN 16258

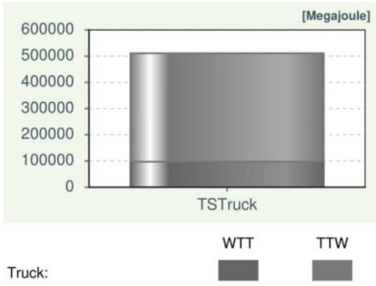
Energy consumption

WTW [Megajoule]

	TSTruck
Truck	511,333
Sum	511,333

TTW [Megajoule]

	TSTruck
Truck	413,959
Sum	413,959



Well-to-Wheel (WTW) = Well-to-Tank (WTT) + Tank-to-Wheel (TTW)

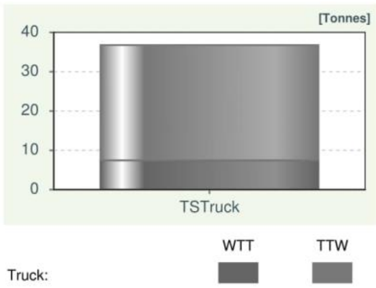
GHG emissions (calculated as CO2 equivalents)

WTW [Tonnes]

	TSTruck
Truck	37
Sum	37

TTW [Tonnes]

	TSTruck
Truck	29
Sum	29



Well-to-Wheel (WTW) = Well-to-Tank (WTT) + Tank-to-Wheel (TTW)

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Figure A.9.5: EcoTransIT output – CS2 Environmental impact of transport from 2.2 to FC2

EcoTransIT World

EcoTransIT World (Ecological Transport Information Tool for Worldwide Transports) calculates the environmental impacts for any freight transport service. EcoTransIT World provides energy consumption and GHG Emissions for trucks, trains, ships and airplanes in accordance with the European standard EN 16258:2012. Additionally carbon dioxide (CO2) and the most important air pollutants (nitrogen oxide, non-methane hydrocarbons, sulfur dioxide and particulates) can be calculated with EcoTransIT World. Below you will find all information about your transport service selected and data sources used as well as the results of your calculation.

General Information

Creation Date:	01.06.2018
Origin:	[City district] Location 2.3
Destination:	[City district] Location 2
Cargo weight:	1726.26 ton (t/TEU: 10)

Detailed description of the calculated transport services

Transport service Lkw - 613.11 km

Origin: [City district] Location 2.3

Truck (26-40 t,diesel,EURO 5,LF: 60.0%,ETF: 20%) - 613.11 km

Destination: [City district] Location 2

Energy consumption and greenhouse gases (GHG) in accordance with EN 16258

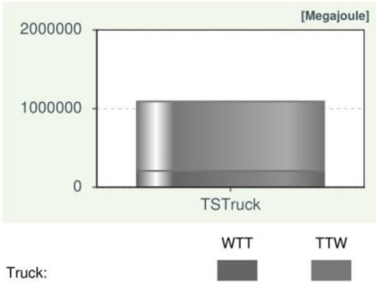
Energy consumption

WTW [Megajoule]

	TSTruck
Truck	1,091,185
Sum	1,091,185

TTW [Megajoule]

	TSTruck
Truck	883,389
Sum	883,389



Well-to-Wheel (WTW) = Well-to-Tank (WTT) + Tank-to-Wheel (TTW)

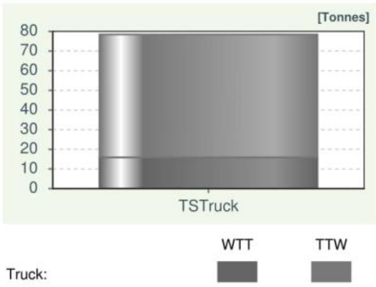
GHG emissions (calculated as CO2 equivalents)

WTW [Tonnes]

	TSTruck
Truck	78
Sum	78

TTW [Tonnes]

	TSTruck
Truck	63
Sum	63



Well-to-Wheel (WTW) = Well-to-Tank (WTT) + Tank-to-Wheel (TTW)

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Figure A.9.6: EcoTransIT output – CS2 Environmental impact of transport from 2.3 to FC2