Socio-technical architectural model of collaborative engineering design

By

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Declaration of authenticity and author's rights

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.

Signed: Date:

Tiffany Imron

To my beloved parents, Bapak and Mama

No two things have been combined together better than knowledge and patience

-Prophet Muhammad PBUH-

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Abstract

Collaborative engineering design may be considered a socio-technical process. However, literature suggested that the fundamental constitution of the social and technical in the collaborative engineering design process and their interrelationships are unclear. Furthermore, most the identified studies tended to focus on either the social or technical collaborative engineering design with relatively little focus on their combined effects. To address these issues, the study reported in this thesis have developed an architectural model of socio-technical CED adapting the Enhanced Entity Relationship (EER) information modelling language.

The model was incrementally developed in three phases: 1). Model development, 2) model review and refinement, 3) model evaluation. Five versions of the socio-technical architectural model (STAM) of collaborative engineering design were created, each adopting methods to elicit insight from different sources. At the model development stage, the social and technical elements and their inter-relationships were induced from a literature review (i.e. resulting in STAM-1) and interviews with 28 collaborative engineering design practitioners (resulting in STAM-2). The interviews were conducted in a UK company specialising in the design and manufacture of complex technical systems within the shipbuilding industry. The model was reviewed by a group of engineering design practitioners and academics through independent focus groups (resulting in STAM-3). To enhance the social perspective, an interview was conducted with an industrial psychology academic (yielding in STAM-4) and a review on the social collaboration literature was carried out (resulting in STAM-5).

The model was evaluated by industrial practitioners in three different companies, each with a different life phase and product focus. Preliminary evaluation was conducted in the first company using an interview method to assess the model's completeness. Findings from this interview support the completeness of the model. Learning from the evaluation approach in the first company, in the second and third company, independent focus groups and questionnaires were adopted. In addition to completeness, the evaluation was conducted to assess the model's correctness, relevance, usefulness, ease of understanding, and achievement of purpose. Findings from the two companies generally support the correctness, relevance, and usefulness of the model. The findings showed that the model may form a basis for customisation to suite a specific company's requirement. The findings also support the general aim of the model, i.e. to provide insights into collaborative engineering design from the socio-technical perspective. Nonetheless, the findings suggest that the model was not easy to understand due to its structural complexity and terminology differences used.

Finally, the study and its findings were assessed to identify their strengths, weaknesses, and recommendations for future research.

Contents

List of Figures

List of Tables

Nomenclature

Abbrevation	Meaning
B1	Recommended social reference, titled: "Reframing organizations: artistry, choice, and leadership" by Lee G. Bolman and Terrence E. Deal
B2	Recommended social reference, titled: "The secrets of successul team management: how to lead a team to innovation, creativity and success" by Michael A. West
CAD	Computer Aided Design
CED	Collaborative Engineering Design
CSCD	Computer Supported Collaborative Design
ED	Engineering Design
EER	Enhanced Entity Relationship
ERD	Entity Relationship Diagram
IP	Industrial practitioners
IP-1	Interviews participants from Company 1
IP-2	Workshop participants from Company 1
IP-3	Workshop participants from Company 2
IP-4	Workshop participants from Company 3
IP-5	Workshop participants from Company 4
W1	Workshop 1
W2	Workshop 2
STAM	Socio-technical Architectural Model

Symbol	Meaning
italic	Borrowed terms
underlined	Elements of the model
Human being	"Human being" theme of STAM
Communication	"Communcation" theme of STAM
Conflict	"Conflict" theme of STAM
Organisation	"Organisation" theme of STAM
Design process	"Design process" theme of STAM
Technical system	"Technical system" theme of STAM
Design information	"Design information" theme of STAM
Tools	"Tools" theme of STAM

1. Introduction

The study presented in this thesis was co-funded by a UK company specialising in the design and manufacture of complex technical systems within the shipbuilding industry (hereafter Company 1). A list of potential research topics was provided by the company for selection by the author. Given the author's educational background in engineering and innovation management, as well as industrial experience in the field of supply chain management and new product development, the topic of "collaborative working" was selected. Interviews with a senior engineer who had worked in the Company for more than 25 years and a systems engineering academic who had conducted several projects with the company yielded three conclusions: 1) there have been a major challenge in the company's engineering design process, i.e. high percentage of rework, 2) it was identified that this challenge was predominantly caused by the collaboration between multiple human beings, which adds to the complexity of the design process, and 3) despite the company's various efforts, the challenges persist, with relatively little positive change. Based on these conclusions, it was deemed necessary to conduct an in-depth investigation into the company's collaborative engineering design process. This became the initial motivation for the study on collaborative engineering design (CED).

To understand CED, one must first look at design in general. Design can be defined as an activity of creating something new or unknown, that bears social and technical implications to satisfy a specific purpose or foreseen needs (Hubka and Eder, 1987; Cross, 2008b). Engineering design is a branch of the design discipline that focuses on developing technological-related solutions (Hubka and Eder, 1987). The process utilises technical information and scientific principles to solve a design problem (Hubka and Eder, 1987; Cross and Cross, 1995; Van Gorp and Van de Poel, 2001; Ju *et al.*, 2006; Gonnet, Henning and Leone, 2007), and is often supported by various tools (Hubka and Eder, 1988; Slimani *et al.*, 2006; Red *et al.*, 2013). From this perspective, an engineering design process may be generally regarded as a technical process. However, throughout the design process, engineering designers typically work together with others, who often come from different disciplines (Bucciarelli, 2002; Ostrosi, Haxhiaj and Fukuda, 2012; Esparragoza *et al.*, 2015) for a broader perspective and faster results (Dieter and Schmidt, 2013; Esparragoza *et al.*, 2015). The act of working together may be generally defined as collaboration (Bedwell *et al.*, 2012) which is a social process (Cross and Cross, 1995; Feast, 2012). While engineering design is a technical process, the way it is often conducted (i.e. through collaboration) is a social process. As such, CED may be perceived as a socio-technical process (Lu *et al.*, 2007).

Rong *et al.*, (2008) argued that studying both social and technical collaborative design can provide different "paradigms". Fest (2012, p. 215) remarked, "… the development of support for collaborative design should target not only methods for solving design problems [i.e. technical aspects], but also informal social interactions [i.e. social aspects]…" In this sense, it can be concluded that to support a collaborative engineering design process, both social and technical aspects need to be considered (Pahl, Badke-Schaub and Frankenberger, 1999; Hammond *et al.*, 2005; Lu *et al.*, 2007; Ostergaard and Summers, 2009). Extensive studies have been conducted supporting the social (e.g. Stempfle and Badke-Schaub, 2002; Maier and Störrle, 2011; Kleinsmann *et al.*, 2012; Eckert, Stacey and Earl, 2013; McComb, Cagan and Kotovsky, 2015) and the technical (e.g. Boujut and Blanco, 2003; Shen, Ong and Nee, 2010; Walthall *et al.*, 2011; Austin-Breneman, Honda and Yang, 2012; Belkadi *et al.*, 2013; Singh and Casakin, 2015) elements of CED. However, relatively little work supporting both the social and technical was identified in the literature.

Duffy and O'Donnell (1999) suggest, to support something (e.g. a collaborative design process), a fundamental understanding of its phenomenon (e.g. activity, elements, relationship) needs to be developed. From this perspective, it was viewed that to support the socio-technical elements of collaborative engineering design, a fundamental understanding of its phenomena needed to be developed. A number of studies have discussed the phenomena of collaborative engineering design from the socio-technical perspective (e.g. Baird *et al.*, 2000; Lu and Cai, 2000; Hammond *et al.*, 2005; Hassannezhad and Montagna, 2016). However, three prominent shortcomings from these studies were identified. Firstly, they tended to discuss the socio-technical elements of collaborative engineering design within a specific context such as conflict management (e.g. Lu *et al.*, 2000), complexity management (e.g. Grogan and de Weck, 2016), and communication (e.g. Esparragoza *et al.*, 2015). In other words, the socio-technical perspective was used to perceive a specific part of the collaborative engineering design process only. The use of the socio-technical perspective to view the collaborative engineering design process in a holistic manner was not evident. Secondly, it was identified that authors tend to refer the terms "social" and "technical" differently. For example, Hammond *et al.* (2005) and Esparragoza *et al.*, (2015) referred social to "interaction" and technical to "tools" while Grogan and de Weck (2016) referred social to "teamwork" and technical to "design problem". Although these studies have discussed the socio-technical elements and their inter-relationships in the context of collaborative engineering design, the socio-technical elements that were discussed varied, depending on the authors' understanding of social and technical definitions.

Based on the aforementioned shortcomings, it can be inferred that there is a lack of : 1) socio-technical studies in the literature search on collaborative engineering design, 2) a holistic socio-technical perspective towards the collaborative engineering design process, and 3) a consensus on the fundamental consitution of socio-technical elements of collaborative engineering design and their inter-relationships. Furthermore, further investigation at Company 1 revealed that, regardless of the social collaboration issues (e.g. lack of communication, lack of personal relationship), the company's effort was mainly reserved for technical issues (e.g. develop new information platform) with relatively little consideration given to social elements (see Appendix 1: industrial challenges). In other words, there is a lack of awareness on the social elements of CED in Company 1.

In 2001, Lu et al remarked, "A more comprehensive view is required to clarify the relationships among various technical and social aspects of collaborative design" (Lu and Cai, 2001, p.4). Sixteen years later, the existence of such a comprehensive view is still not evident. This thesis aims to provide the comprehensive view. For the reasons mentioned above, a generic model describing the fundamental social and technical elements of collaborative engineering design and their inter-relationships was developed and presented in this thesis.

1.1 Scope of work

From the identified shortcomings on the knowledge of collaborative engineering design discussed above, the study reported in this thesis focusses on formalising collaborative engineering design from the socio-technical perspective. For this, the study includes the identification of social and technical elements, and their inter-relationships in a CED process. The scope of which the identification was conducted is explained in the following paragraphs.

As discussed above, the study presented in this thesis was initially motivated by issues identified in the practice of collaborative engineering design in Company 1. The company specialises in the design and manufacture of complex technical systems. A complex technical system can be characterised as having a number of elements that inter-relate in a complicated way, and thus, it is challenging to describe its structure and behaviour (Browning, 2013). Additionally, Company 1 can also be characterised as an "*engineer-to-order*" (ETO) company - a company that designs and manufactures their particular products based on the requirements from customers, and thus, "each product has a distinctive degree of customisation" (Adrodegari et al. 2015, p.911). In an ETO company, the CED process commences upon receipt of the customer requests and finishes upon receiving the customers' approval. Because of this, an ETO company typically deals with high uncertainty in the design as well as the design process (Adrodegari *et al.*, 2015).

Considering the above points, the study was conducted in the context of, although not limited to, the CED for complex technical systems in an ETO setting. The collaborative engineering design process for relatively simple technical systems such as general building construction and industrial products in non-ETO settings (i.e. mass production), was not within the concern of this study.

1.2 Aim and objectives

The study documented in this thesis aims to develop a socio-technical architectural model of collaborative engineering design, consisting of social and technical elements and their inter-relationships. The model was intended to provide insight into the phenomenon of collaborative engineering design from the socio-technical perspective.

To achieve this aim, the following objectives were defined:

O1. Identify issues on collaborative engineering design literature and practice to form the basis for defining the focus of the study

- O1.1 Review the collaborative engineering design literature to establish the current state of knowledge and shortcomings on the literature of CED.
- O1.2 Investigate the collaborative engineering design practice to identify challenges, improvement strategy, and suggestions for improvement on the practice of CED.

O2. Construct a socio-technical architectural model of collaborative engineering design to address the issues identified in O1

- O2.1 Develop the model based on the literature and industrial investigation to obtain multiple-perspectives.
- O2.2 Evolve the model using various review methods to obtain insights from a socio-technical perspective.

O3. Evaluate the model to assess the extent to which it appropriately represents the elements of collaborative engineering design from the socio-technical perspective.

O4. Discuss and critique the work to identify strengths, weaknesses, and areas for future work.

1.3 Thesis structure

The research methodology to conduct the research is outlined in Chapter 2, consisting of a discussion on the philosophical assumptions that underpin the study presented in this thesis, the description of methods adopted to collect and interpret data, and the overall procedure of the research. The remainder of the thesis is divided into five parts. The contents of each part are explained below.

Part 1: Research focus definition (Chapters 3 and 4)

Chapter 3 presents the definition of CED that underpins the study presented in this thesis.

Chapter 4 provides findings from a review of research on collaborative engineering design, which were categorised into social, technical, and socio-technical. The findings were then used to define the focus of the study. Additionally, from the literature review, the first versions of socio-technical architectural model of CED (STAM-1) was constructed.

Part 2: Model development (Chapter 5)

Chapter 5 presents the socio-technical elements and their inter-relationships derived from interviews with 28 engineering design practitioners of Company 1. Using this information, the first versions of the social and technical architectural model were refined and combined into one socio-technical architectural model (i.e. STAM-2).

Part 3: Model evolution (Chapters 6 and 7)

Chapter 6 provides feedback on the model, elicited through independent focus groups, with engineering design practitioners and academics. Based on the feedback, STAM-2 was refined into STAM-3.

Chapter 7 presents feedback on the model given by a social science academic, elicited through a semi-structured interview. This enhanced the social perspective of the model. Based on this feedback, STAM-3 was refined into STAM-4. A recommendation to review social literature was given by the social science academic to further enhance social perspective of the model. Findings from the literature review were used as the basis to refine STAM-4 into STAM-5.

Part 4: Model evaluation (Chapter 8)

Chapter 8 presents findings from evaluating the model in three different companies that practice collaborative engineering design (i.e. Company 2, Company 3, and Company 4), two of which focussing on different life phase or product (i.e. Company 3 and Company 4). The findings were elicited using the following methods: 1) an interview in Company 2, 2) focus groups in Company 3 and Company 4, and 3) questionnaires in Company 3 and Company 4. Based on the outcomes of the interviews, focus groups and questionnaires, STAM-5 was evaluated for its completeness in Company 2, Company 3, and Company 4, and for its correctness, relevance, usefulness, ease of understanding, and achievement of purpose in Company 3 and Company 4.

Part 5: Reflection (Chapters 9 and 10)

Chapter 9 discusses the strengths, weaknesses, and lessons learned in relation to the research findings, research methods, and overall research procedure. These led to the suggestions of areas for future work.

Chapter 10 concludes the thesis with the summary of work and knowledge contributions.

The thesis structure as afore explained is depicted by Figure 1.

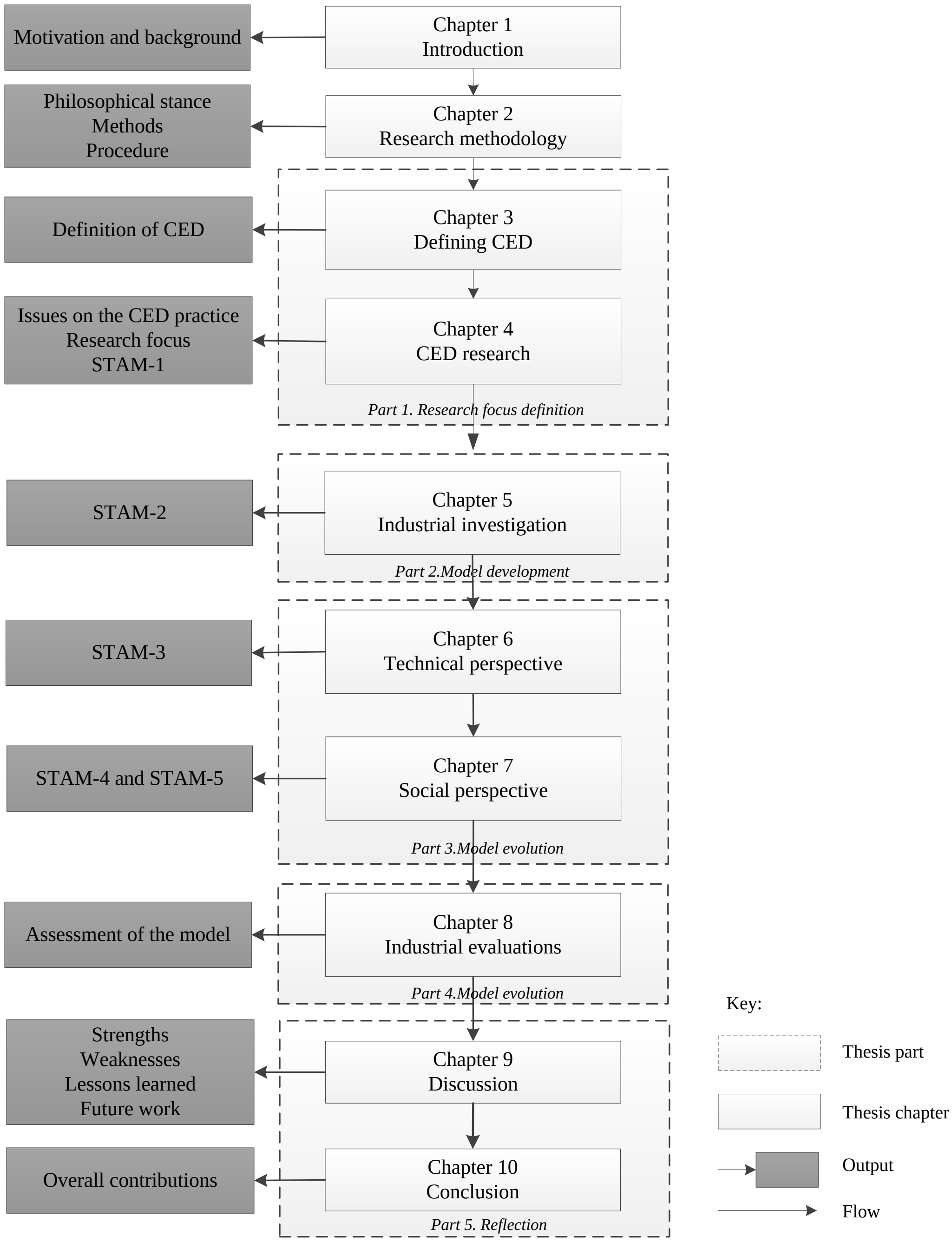


Figure 1 Thesis structure

2. Research methodology

Defining the research methodology can be viewed as an essential activity in the research process. According to Saunders et al. (2007) one of the characteristics of research is that the data is collected and interpreted systematically. Using a clearly defined research methodology, a systematic data collection and interpretation can be done to produce knowledge that can be considered reliable and valid (Wang, 2008).

This chapter primarily focuses on presenting the research methodology adopted in the study presented in this thesis. Generally speaking, "research methodology" can be defined as an overall strategy on how research would be conducted (Saunders, Lewis and Thornhill, 2007). As such, research methodology may also be regarded as "research strategy", as identified in Denscombe (2014). In a more detailed sense, research methodology may consist of "…procedures that span the steps from broad assumptions to detailed methods of data collection, analysis, and interpretation" (Creswell 2014, p.3). From this perspective, a research methodology may consist of three elements: 1) assumptions, 2) methods, and 3) procedures. Based on this perspective, the research methodology used in the study is outlined in this chapter. Each element is briefly described below and how they inter-relate is depicted by Figure 2.

Assumptions

The term "assumptions" used above refers to "philosophical assumptions". Philosophical assumptions may be defined as the basic set of assumptions on the nature of reality and knowledge that researchers bring into their study which in turn guide their actions (Guba and Lincoln, 1994; Reich, 1994; Saunders, Lewis and Thornhill, 2007; Blessing and Chakrabarti, 2009; Creswell, 2014). These assumptions affect the way researchers view the relationship between "knowledge and the process by which it is developed…their views on what is important…and what is useful" (Saunders et al. 2007, p.102). Because of this, when the researcher defines their methodology, they are directed by their philosophical assumptions (Guba and Lincoln, 1994). As Saunders et al. (2007, p.101) remarked, "These [philosophical] assumptions will underpin your research strategy [research methodology], and the methods you choose as part of that strategy [methodology]." As such, to define an appropriate research methodology for a study, it is considered important to first identify the philosophical assumptions that the researcher brings into the study (Lincoln and Guba, 2011; Creswell, 2014). Furthermore, Blessing and Chakrabarti (2009) remarked that anything that has directed the researcher needs to be explicitly presented. Accordingly, Section 2.1

presents the researcher's philosophical assumptions for the study documented in this thesis, regarded as the research philosophy.

Methods

The second element of research methodology is "methods". This term refers to "techniques or procedures used to obtain and analyse data" (Saunders et al. 2007, p.3). In a more general view, Denscombe (2014, p.3) referred to methods as "tools" and equated their role with that of "a microscope for a scientist" or "a thermometer for a medic". According to Reich (1994, p.264), research methodology consists of "a collection of methods for doing research and their interpretations". From this perspective, it can be concluded that to define the research methodology of a study, its constituents (research methods) need to be defined first. Easterby-Smith et al. (2012) believe that methods need to be selected by the researchers depending on the questions that they intend to answer (i.e. research question or research aim and objectives). Furthermore, the practicality factors such as time and resource availability (Saunders, Lewis and Thornhill, 2007) also need to be considered. Additionally, the selection of research methods is also dependent on the researcher's philosophical assumptions (Creswell, 2013). The selected methods to define the research methodology of the study presented in this thesis are described in Section 2.2.

Procedures

The underpinning assumptions and selected methods are elaborated as a procedure that guides the process of the research. This is recognised as research design (Saunders, Lewis and Thornhill, 2007; Creswell, 2014). The research design for the study documented in this thesis is presented in Section 2.3.

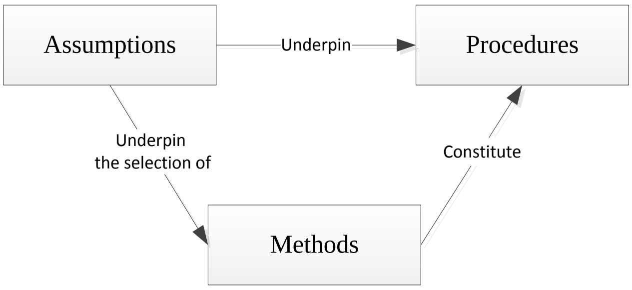


Figure 2 The elements of research methodology (adapted from Creswell 2014)

This chapter concludes with a summary of work, provided in Section 2.4.

2.1 Research philosophy

Acknowledging the significance of philosophical assumptions to the process of research as mentioned above, in this section, the philosophical assumptions that underpin the study are described. To aid the description, the types of philosophical assumption identified in the literature are presented in Section 2.1.1. These assumptions are used as the basis to identify and describe the philosophical assumptions of this study, provided in Section 2.1.2.

2.1.1 Philosophical assumptions

Philosophical assumptions were also identified in the literature under different terms, such as "paradigm" (Guba, 1990; Guba and Lincoln, 1994; Saunders, Lewis and Thornhill, 2007; Blessing and Chakrabarti, 2009; Lincoln and Guba, 2011; Easterby-Smith, Thorpe and Jackson, 2012) and "worldview" (Reich, 1994; Creswell, 2013). Thus, in this thesis, these terms are perceived as synonyms and may be used interchangeably.

The study presented in this thesis is focused on collaboration in an engineering design context. From this perspective, the study can be categorised as an "engineering design study". However, collaboration involves interaction between human beings; a study dealing with human beings and their interactions can also be found within the social science study. Thus, the research reported in this thesis is an engineering design study that utilises findings, where appropriate, from the social science literature.

In the domain of engineering design research, *positivism* and *post-positivism* can be perceived as predominant paradigms (e.g. Wang and Duffy 2009; Horváth and Duhovnik 2005). Kumar (2014) remarked that *positivism* and *naturalism* are major paradigms in the social science research field. In the field of management research, Saunders et al. (2007) identified three predominant paradigms, namely *positivism*, *realism* and *interpretivism*, while Easterby-Smith et al. (2012) identified *positivism* and (*social*) *constructionism*. Upon reviewing these paradigms, it was found that several paradigms have different terminologies for the same characteristics. The similarities are between: 1) *post-positivism* and *realism*, and 2) *interpretivism, naturalism,* and *constructionism*. Addressing the first group of paradigms; as the term *realism* also represents a type of ontology in the literature (e.g. Saunders et al. 2007), to avoid confusion, the term *post-positivism* will be used throughout this thesis. For the second group of paradigms, *naturalism* was identified as a form of *constructionism* (Guba and Lincoln, 1994). However the term *constructionism* is often used inconsistently in the literature (e.g. *constructionism* was also labelled as *constructivism* as can be seen in Lincoln and Guba (2011) and Creswell (2013)). Again, to avoid confusion, the term *interpretivism* will be used throughout this thesis. Consequently, three paradigms are explored in this section, i.e. *positivism*, *post-positivism*, and *interpretivism*.

According to Guba and Lincoln (1994), a "paradigm" is fundamentally characterised by three interrelated aspects: *ontology¸ epistemology,* and *methodology* (Easterby-Smith et al. 2012; Creswell 2013; Rubin and Rubin 2012; Guba 1990). In this section, the descriptions of the different types of paradigms are focussed upon with reference to the three aforementioned aspects. Each aspect can be briefly described as follows:

- *Ontology* relates to the nature of reality (Saunders, Lewis and Thornhill, 2007; Easterby-Smith, Thorpe and Jackson, 2012) and its characteristics (Creswell, 2013).
- *Epistemology* refers to the way knowledge is captured (Easterby-Smith, Thorpe and Jackson, 2012; Creswell, 2013) and the relationship between the researchers and the knowledge during the study (Lincoln and Guba, 1985).
- *Methodology* is concerned with the way knowledge is created or obtained (Reber, 2011).

Positivism

Ontology: Positivists believe that there is a fixed, universal, single truth of reality (Rubin and Rubin, 2012) that is divisible and fragment-able, and therefore measurable (Lincoln and Guba, 1985; Anderson and Ozanne, 1988). Reality may consist of physical or natural (e.g. climate change) and social (e.g. the behaviour of human beings) world (Easterby-Smith, Thorpe and Jackson, 2012). However, positivists believe that a "social world" exists outside the reality (Easterby-Smith, Thorpe and Jackson, 2012). According to positivists, reality functions "according to cause and effect, free-context law" (Reich 1994, p.265). In other words, they embrace a "deterministic philosophy, in which, causes determine effects or outcomes" (Creswell 2014, p.7).

Epistemology: Positivists claim that knowledge can be captured through empirical research and it is only significant if it is based on objective observations, which do not result from judgement, interpretation, or subjective opinion (Hughes and Sharrock, 1997; Horváth and Duhovnik, 2005). In other ontological terms, positivists believe in objectivity where the truth should correspond with observed facts, not opinion. As such, positivists believe that reliable data can only be produced if the data source can be observed (Saunders, Lewis and Thornhill, 2007) and knowledge can be obtained only from what can be observed and measured (Remenyi *et al.*, 1998; Horváth and Duhovnik, 2005; Easterby-Smith, Thorpe and Jackson, 2012). Positivists also assume that researchers are capable of separating themselves from their study (i.e. not influencing their study) (Guba and Lincoln, 1994). Positivism researchers position themselves as a "neutral recorder" during a study to minimise interventions (Rubin and Rubin 2012, p.16). Consequently, in positivism, researchers are independently related to their research (Lincoln and Guba, 1985; Remenyi *et al.*, 1998).

Methodology: The focus of the methodology is on theory testing or theory verifying (Guba and Lincoln, 1994; Easterby-Smith, Thorpe and Jackson, 2012) through empirical tests (e.g. experiments) that follow a scientific procedure (Anderson and Ozanne, 1988). A positivist approach typically begins with deriving hypotheses from existing studies or theories (Saunders, Lewis and Thornhill, 2007; Rubin and Rubin, 2012). Positivists accept deduction as a valid reasoning approach to draw conclusions (Lincoln and Guba, 2011).

Post-positivism

Ontology: Post-positivists believe that reality exists regardless of what is known (Easton, 2010). However, instead of separating social world from the reality, post-positivists accept that the social world is a part of, and therefore influences reality (Sayer, 1992). Although post-positivists accept the existence of reality, they believe that identifying the absolute truth of reality is not possible (Guba, 1990; Creswell, 2014). Post-positivists acknowledge that their observation is imperfect (Guba and Lincoln, 1994). As such, they hold the view that "reality must be subjected to the widest possible critical examination to facilitate apprehending reality as closely as possible" (Guba and Lincoln 1994, p.110). Differing from the assumptions of a positivist, post-positivists reject the strict cause-effect operations of reality (Creswell, 2013). Instead, they perceive cause-effect as a possibility that "may or may not occur" (Creswell 2013, p.24).

Epistemology: Although post-positivists embrace objectivism, they acknowledge that researchers influence their study, and thus, maintaining dualism (i.e. an interdependent relationship between the knowledge and the researchers) is not possible (Guba and Lincoln, 1994). Post-positivists believe that knowledge comes from the accumulation of facts, which continuously develop and change (Sayer, 1992).

Methodology: Similarly to positivism, the methodology starts with the formulation of a hypothesis from existing theory (Creswell, 2014). However, instead of focusing on verifying the formulated hypothesis, post-positivists tend to focus on falsifying the hypothesis (Guba and Lincoln, 1994; Creswell, 2013). Post-positivists embrace the value of obtaining multiple perspectives through the involvement of multiple data sources (Easterby-Smith, Thorpe and Jackson, 2012) and the utilisation of multiple data collection methods.

Interpretivism

Ontology: In contrast to positivists, interpretivists claim that reality can be accessed through the subjective interpretations, opinions, and judgement of people (Easterby-Smith, Thorpe and Jackson, 2012; Creswell, 2014), and thus, reality can change and multiple versions of reality are accepted (Rubin and Rubin, 2012). As such, interpretivists reject the ontological view of positivists that there is a single absolute truth (Easterby-Smith, Thorpe and Jackson, 2012).

Epistemology: Interpretivists recognise the differences between natural world and social world and believe that they need to be studied differently (Bryman, 2016). Interpretivists also recognise that researcher is an integrated part of their study (as the main collector and interpreter of knowledge) and accept that they have influence over the study (Lincoln and Guba, 1985; Rubin and Rubin, 2012). Interpretivists accept that knowledge gained from different individuals can be fairly different, as knowledge is context- and interpretation-dependent (Anderson and Ozanne, 1988; Rubin and Rubin, 2012; Creswell, 2013).

Methodology: Differing from positivism and post-positivism, in interpretivism, the focus of the methodology is on “meaning generation” (Creswell, 2013), or as Guba and Lincoln referred it, “construction” generation (Guba and Lincoln, 1994). Interpretivism also suggests that meaning can be obtained through the interaction between researchers and participants (Guba and Lincoln, 1994). As interpretivists believe in multiple versions of reality, they hold the view that it is necessary to obtain multiple perspectives from the utilisation of multiple methods and/or the involvement of multiple participants (Easterby-Smith, Thorpe and Jackson, 2012). The research design tends to change; adapting to the evolving understanding towards reality (Anderson and Ozanne, 1988). Meanings are concluded from the result of these multiple perspectives (Creswell, 2013).

2.1.2 Adopted philosophical assumption

Having recognised the different types of paradigm above, *interpretivism* is argued as the main philosophical assumption that underpins the study presented in this thesis for the following reasons.

Firstly, in this study, CED may be viewed as a socio-technical activity. In this sense, the reality (i.e. CED activity) consists of two variants, i.e. the social and the technical variant. This perception echoes the basic ontological assumptions of *interpretivism* aforementioned, that 1) reality can be accessed through the interpretation of individuals (i.e. the researcher and the data sources), and 2) there are multiple perceptions (i.e. variants) of reality (i.e. social and technical collaborative design activity).

Secondly, the aim of the study is to develop a social-technical model of CED activity. In this activity, human beings may be perceived as the key element (see Chapter 3). To develop the model, it is therefore essential to consider the perspectives of the human beings. As generally recognised, the perspective of each human being is naturally different. Therefore, the opinions of one human being cannot be taken as the opinions of all human beings. *Interpretivism* recognises these different views and accepts them when the knowledge is created.

2.2 Research methods

The study presented in this thesis aims to develop a socio-technical architectural model of collaborative engineering design to address the lack of socio-technical descriptions, and ultimately, to gain a better understanding on the CED phenomenon (Chapter 1). The study to better understand the nature of a phenomenon that has been lacking or not properly understood (Saunders et al. 2007, p.133) may be categorised as an *exploratory study*. An exploratory study is often approached with qualitative study as they both seek to explore and understand a phenomenon. As Creswell (2013, p.47) mentioned, qualitative study is needed when “a problem or issue needs to be explored…”.

In addition to the above, as discussed in Section 2.1.2, *interpretivism* was argued as the main philosophical assumption that underpins this study. In *interpretivism*, reality is perceived to exist in the human beings’ interpretation, and thus, to collect the knowledge about reality, human beings may be considered the main source of information. Furthermore, within the *interpretivism* philosophical assumption, the researcher (i.e. a human being) is seen as the main instrument to collect and interpret information (Section 2.1.1). Lincoln and Guba (1985) argued that human beings tend to favour methods that extend their natural activity, e.g. speaking, listening, and observing, which are the main methods identified in qualitative study. Based on these points, qualitative study was deemed appropriate to accommodate both *exploratory study* and the *interpretivism* paradigm, and thus, it was adopted in the study.

In qualitative studies, there are various data collection and data interpretation methods identifiable in the literature (Angrosino and Mays de Perez, 2003; Fontana and Frey, 2003; Silverman, 2011; Creswell, 2013). The adopted data collection methods are outlined in Section 2.2.1, while the adopted data interpretation approaches are described in Section 2.2.2.

2.2.1 Data collection

Four data collection methods were adopted based on the considerations of: 1) the aim and objectives of the study (Chapter 1), and/or 2) the practicality factors such as the time and resource availability. The methods were: 1) literature review, 2) interview, 3) focus group, and 4) questionnaire. The adoption of these methods is explained below:

Literature review

According to Saunders et al. (2007, p.61), "…reviewing the literature will provide the foundation on which your research is built". As such, literature reviews were conducted to identify the current state of research on the collaborative engineering design domain (i.e. O1 - Chapter 1). This review resulted in knowledge of prominent issues within the domain (Chapter 4). This knowledge was used as the basis to define the focus of the study. The review also resulted in knowledge of collaborative engineering design (Chapter 3 and Chapter 4). Based on this knowledge, the solution for the defined research problem (i.e. a socio-technical architectural model of CED) was developed at its earliest stage. Developing the solution was a part of the second objective of the study. In this sense, in addition to O1, the literature review also used to achieve O2 (Chapter 1). In addition to this, reviewing the literature was also used to review and refine the model from the social perspective (i.e. O3). It resulted in knowledge of collaboration from the social perspective. Based on this knowledge, the architectural model was evolved (Chapter 7).

Interview

Best (2014, p.76) defined an interview as "A form of conversation… initiated by the researcher for the purpose of collecting data that can be used to support the aims of a research project." In other words, an interview may be generally defined as a conversation with purpose (Kvale, 2007). Interviews were considered suitable for an explorative study to understand the nature of a phenomenon, as they provide the opportunity to obtain detailed understanding of "how things work, how factors are inter-connected or how systems operate" (Denscombe 2014, p.186).

Similar with the literature review, interviews were adopted to achieve two different objectives of the study. The first objective was to evolve the architectural model from the social and the technical perspectives (i.e. O2.2 – Chapter 1). For this objective, two interview runs were conducted with different sources: 1) industrial practitioners to obtain a technical perspective, which resulted in the second version of the architectural model (Chapter 5), and 2) a social science academic to obtain a social perspective, which resulted in the fourth version of the architectural model (Chapter 7). Interviews with the industrial practitioners also resulted in knowledge of salient issues within the industrial collaborative engineering design practice (Appendix 1: Industrial challenges). This knowledge, in conjunction with the knowledge obtained from the first literature review, was used as the basis to define the focus of the study presented in this thesis (Chapter 4). The second objective was to evaluate the architectural model (i.e. O3) through a case study. For this, an interview was conducted with a collaborative engineering design practitioner (Chapter 8, Section 8.1). The result was used as one of the bases to evaluate the architectural model for its representativeness within collaborative engineering design practice.

Focus group

A focus group may be defined as a form of qualitative data collection where a group of participants are asked to discuss a topic provided by a moderator (i.e. researcher) to elicit information (Denscombe, 2014). According to (Kamberelis and Dimitriadis 2011, p.560) "…[a] focus group allows for the proliferation of multiple meanings and perspectives, as well as interactions between and among them [the participants]". Denscombe (2014) remarked that through the interactions, the reason underlying the participants' response (e.g. opinion) may be understood. This cannot be obtained through individual interviews (Denscombe, 2014). Additionally, as focus groups involve multiple people at once, it is considered effective for obtaining insight from different points of view in a relatively short period of time (Saunders, Lewis and Thornhill, 2007).

Focus groups were adopted to review (i.e. O2.1 – Chapter 1) and to evaluate (i.e. O3 – Chapter 1) the architectural model. For these, four focus groups were conducted involving different groups of participants for multiple perspectives. To review the model, the focus groups involved two groups of participants, consisting of one group of industrial practitioners and one group of engineering design academics (Chapter 6). To evaluate the model, the focus groups also involved two groups of participants. The participants were solely industrial practitioners, coming from two independent companies (Chapter 8). The result was used as a basis to evaluate the architectural model, particularly its applicability within the different practices of collaborative engineering design.

Questionnaire

A questionnaire may be defined as the technique of data collection whereby people are asked to answer a set of fixed, predetermined questions (Bernard and Ryan 2010; De Vaus 2005). It is considered effective in providing direct answers (De Vaus 2005) and efficient at collecting information from a large number of participants (Saunders, Lewis and Thornhill, 2007; Denscombe, 2014). Due to this effectiveness and efficiency, questionnaires were adopted to elicit opinions from industrial practitioners on the model's quality (i.e. O3 – Chapter 1). Questionnaires were employed as part of a set of activities for model evaluation, after the final two focus groups with industrial practitioners (Chapter 8). The result was used to complement the result of the focus groups, as the basis to evaluate the model.

2.2.2 Data interpretation

Two general approaches to data interpretation can be identified: an inductive and a deductive approach. In an inductive approach, the data collected is interpreted with strictly-limited, or without pre-defined theories and/or assumptions (Lincoln and Guba, 1985; Thomas, 2006). It allows findings to emerge "…from the frequent, dominant, or significant themes inherent in raw data…" (Thomas 2006, p.238). In contrast to the inductive approach, is a deductive approach, the interpretation of the data collected is done with pre-defined theories and/or assumptions, and the conclusion is derived to test the said theories and/or assumptions (Thomas, 2006). Both inductive and deductive approaches were adopted in the study presented in this thesis.

An inductive approach was primarily adopted across the model development phase (Chapter 5). During this stage, the data collected was coded and categorised to elicit socio-technical elements of collaborative engineering design and their inter-relationships. The model was then developed by inferring the identified elements and inter-relationships. A deductive approach was adopted during model development (Chapter 5), model review and refinement (from Chapter 6 to Chapter 7) as well as during the model evaluation (Chapter 8) phases, in the sense that the interpretation was done with pre-defined theories and assumptions obtained from the model development phase.

2.3 Research design

Having identified the philosophical assumption (i.e. *interpretivism*) underpinning the study (Section 2.1) and the methods (i.e. literature review, interviews, focus groups, and questionnaires) adopted (Section 2.2), the overall procedure of study (i.e. research design) is provided in this section.

The research design can be divided into four phases: 1) research focus definition, 2) solution generation, 3) evaluation, and 4) documentation, depicted by Figure 3. These are explained in Section 2.3.1, 2.3.2, and 2.3.3, respectively.

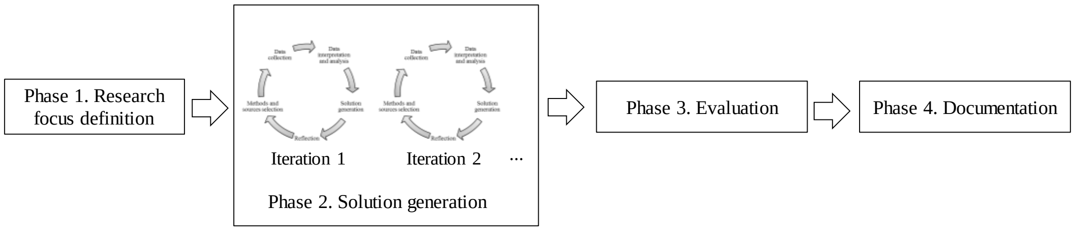


Figure 3 Research design

2.3.1 Research focus definition

The aim of this first phase was to define the focus of the study through the identification of the research focus (Chapter 4) and underpinning the formulation of the aim and objectives (Chapter 1). These were based on the current state of the research (i.e. state-of-the-art), derived from collaborative engineering design literature identified during the literature review (Chapter 3 and Chapter 4). The procedure of the research focus definition is illustrated by Figure 4.

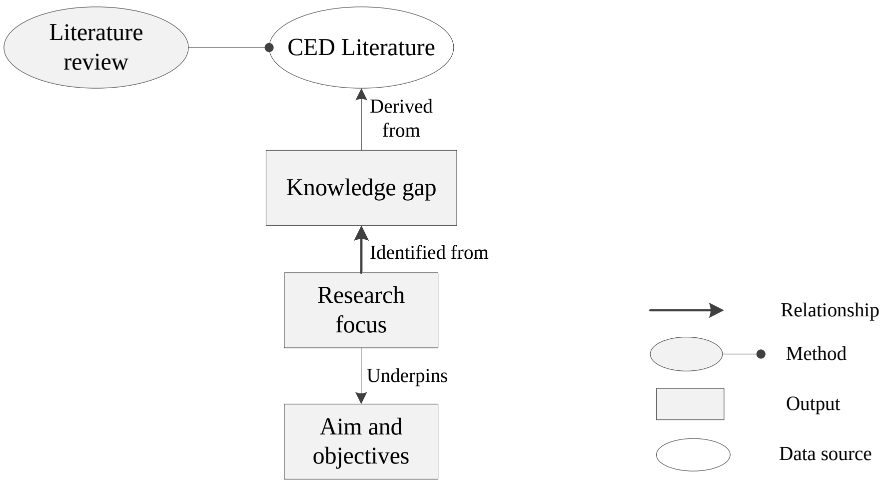


Figure 4 Research focus definition procedure

2.3.2 Solution generation

Based on the formulation of the research problem and the definition of research focus, the solution (i.e. model) was generated. The model was generated by adapting the *Scrum Framework* (hereafter "*Scrum*"). *Scrum* applies an iterative, incremental approach based on the believe of "knowledge comes from experience and making decisions based on what is known" (Schwaber and Sutherland 2016, p.3). Hence, instead of delivering one final model at the end of the research, through the scrum framework, a model is delivered at the end of each iteration, allowing the model to evolve in an incremental manner. *Scrum* accepts the use of various processes with various approaches (Ota, 2010). In scientific research, this variety of processes and approaches may be generally regarded as *triangulation*. In a more detailed sense, triangulation may be defined as the method to obtain multiple perspectives (Stake, 1995) through the combination of the data sources, the investigators, the methods/approaches, and/or the theories to address potential misinterpretation and bias during the study (Blessing and Chakrabarti, 2009).

The various processes and approaches are grouped into two sub-phases of solution generation: 1) development and 2) review and refinement. Each sub-phase consists of a recursion(s) of method and sources selection - data collection – data interpretation and analysis – solution generation (model development) – reflection (Figure 5).

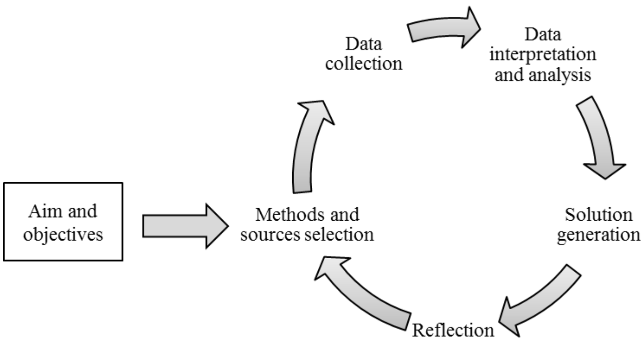


Figure 5 Solution generation iteration

As mentioned in Section 2.2, the methods were primarily selected based on the aim and objectives of the study, and practicality factors. The data was then collected using the selected methods that related to the selected resources. The data collected was interpreted and analysed. The results of the interpretation and analysis were used as the basis to generate the solution (i.e. model). Through reflection, lessons learned were derived, leading to a plan for the next iteration of solution generation. As such, in addition to aim and objectives and practicality factors, the methods were also selected based on the lessons learned from the previous iteration.

The sub-phases of solution generation procedures are explained as follows:

Sub-phase 1 Development

In addition to research focus, the literature review conducted within the research focus definition phase yielded the first version of socio-technical architectural model of CED (i.e.

STAM-1) (Chapter 4). As such, the literature review process was considered a part of the model development sub-phase. STAM-1 was then used as a basis to develop STAM-2, in conjunction with the result of the industrial investigation (Chapter 5) through interviews with industrial practitioners (IP-1). Additionally, as the literature review was conducted as a prescedence of the industrial investigation, it was regarded as a preliminary investigation.

Sub-phase 2 Review and refinement

After the model was developed, it was reviewed and refined, to a level whereby the *theoretical saturation point* was reached. That is, the point where the theory (i.e. model) can be considered well established (Bowen, 2008). According to Strauss and Corbin (1998), one of the parameters that can be used to determine the theoretical saturation point is when new themes can no longer be identified (or refined). For this reason, the model iteration was terminated when no new themes were identified or refined. This resulted in three iterations of review and refinement.

The first iteration involved two sets of data sources (i.e. from IP-2 and engineering design academics) to review the model. The first iteration was labelled as "technical perspective" review. In this review, a focus group method was employed. Based on the feedback elicited from the groups, STAM-2 was refined, resulting in STAM-3 (Chapter 6). The second iteration was labelled as "social perspective" review 1. In this review, an interview method was employed to elicit feedback from a social science academic. Based on the feedback, STAM-3 was refined, leading to STAM-4 (Chapter 7, Section 7.1). Lastly, the third iteration involved a social literature study, as suggested by the social science academic, regarded as social perspective review 2. Findings from the literature study were used as the basis to review and refine STAM-4, resulting in the final version of the model, i.e. STAM-5 (Chapter 7, Section 7.2).

2.3.3 Evaluation

At this phase, STAM-5 was assessed for its completeness, correctness, relevance, usefulness, ease of understanding and achievement of purpose through independent evaluation at three different companies. In the first company (hereafter Company 2) an interview method was employed for practicality reason. The interviewee was regarded as IP-3. In the second (hereafter Company 3) and third company (hereafter Company 4), based on the lesson learned from the evaluation in Company 2, focus groups and questionnaires methods were used. The group of participants from Company 3 were regarded as IP-4 while from Company 4 were regarded as IP-5. Findings from this phase were derived (Chapter 8), led to the identification of strengths and weaknesses, used as considerations for future work (Chapter 9).

Based on the explanation above, the process of solution generation and evaluation was created, depicted by Figure 6.

2.3.4 Documentation

The process of the study and the findings derived from the study were consolidated and documented as a thesis. The process of writing the thesis was considered the final stage of the study.

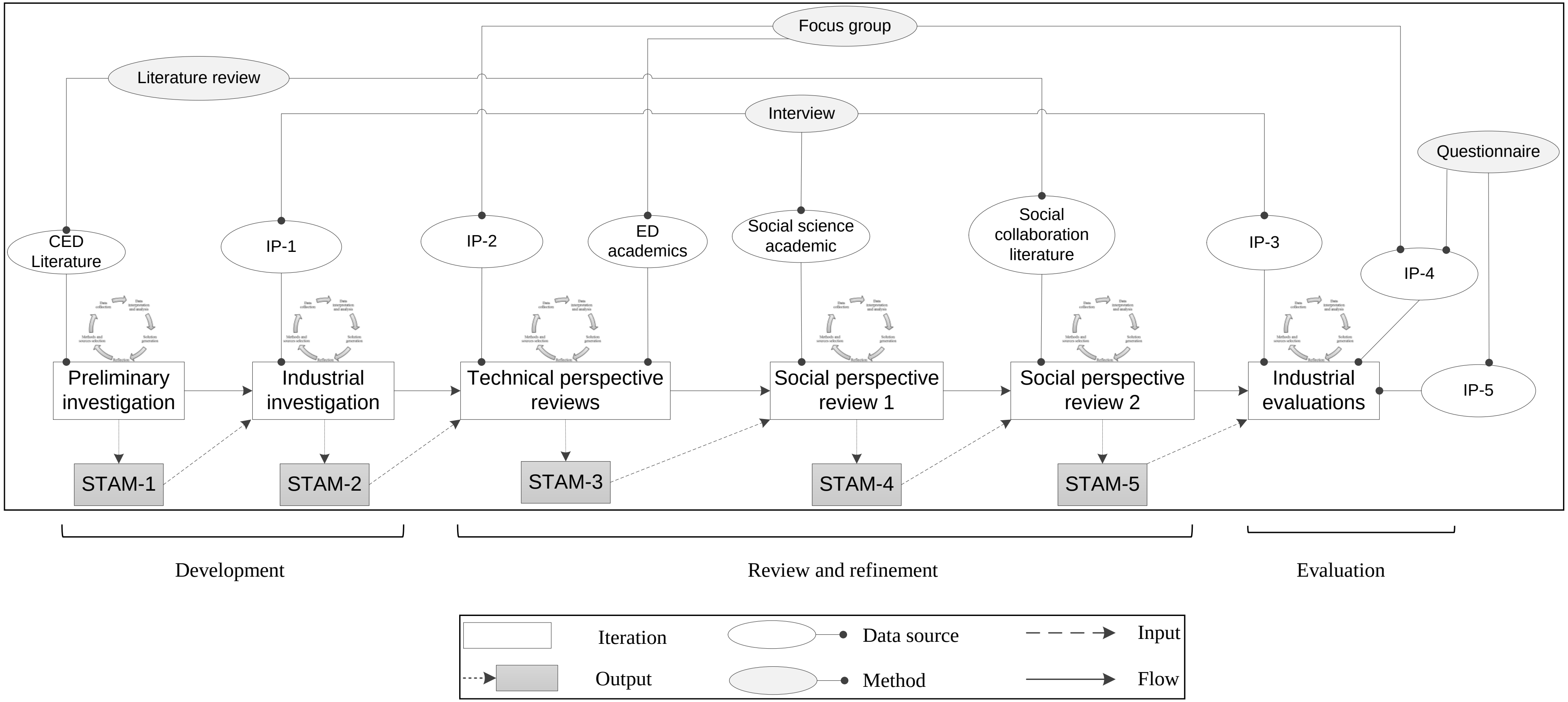


Figure 6 Solution generation and evaluation procedure

2.4 Summary

In this chapter, the methodology of the study presented in this thesis is outlined in three sections: the assumptions that the researcher brought into the study which underpinned the selection of research methods (i.e. research philosophy – Section 2.1), the tools used for data collection and interpretation (i.e. research methods – Section 2.2), and the overall procedure of the study (i.e. research design – Section 2.3).

Having identified the philosophical assumptions in the literature (Section 2.1.1), *interpretivism* was argued as the main philosophical assumption underpinning the study (Section 2.1.2). Based on this underpinning paradigm and the explorative nature of the study, four qualitative data collection methods were employed at different phases of the study: literature review, interview, focus group, and questionnaire (Section 2.2.1). The data collected was interpreted and conclusions were derived employing both inductive and deductive approaches (Section 2.2.2). The procedure of study can be divided into three phases: research focus definition (Section 2.3.1), solution generation (Section 2.3.2), and documentation (Section 2.3.4). Table 1 summarises the procedure of the study, which consists of the methods adopted, the sources of information, the outputs, and the related chapter within the thesis.

Table 1 Summary of research design

Sub-phase	Method	Data source	Output	Chapter
Phase 1. Research focus definition			**Research focus**	**3 and 4**
N/A	Literature review	CED literature	Definition of CED State of the art, Knowledge gap Research focus STAM-1	3 4
Phase 2. Solution generation			**STAM**	**5 to 7**
Development	Interview	Industrial practitioners 1	STAM-2	5
Review and refine	Focus group	Industrial practitioners 2	STAM-3	6
	Focus group	Engineering design academics		
	Interview	Social science academic	STAM-4	7
	Literature review	Social collaboration literature	STAM-5	
Phase 3. Evaluation			**Model's quality**	**8 to 9**
	Interview	Industrial practitioner 3	Strengths and weaknesses, Future work.	8 9
	Focus group	Industrial practitioners 4		
	Questionnaire	Industrial practitioners 4		
	Focus group	Industrial practitioners 5		

	Questionnaire	Industrial practitioners 5		
Phase 4. Documentation			**Thesis**	**N/A**

As may be seen from the above table (Table 1), this study used the triangulation of: data sources (i.e. literature, industrial practitioners from four different companies, engineering design academics, and a social scienceacademic), methods (i.e. literature review, interviews, focus groups, and questionnaires), and theories (i.e. social and technical).

Part 1. Research focus definition

3. Defining CED

As introduced in Chapter 1, the study presented in this thesis focusses on collaborative engineering design. Defining “collaborative engineering design” was considered essential for providing a foundation for- and to frame the context of the study. Whilst a number of studies on CED were discovered, a clear definition of CED was not identified. As engineering design may be perceived as a sub-set of product design (Horvath, 2004), to define CED, the definition of collaborative design in product design was initially explored. Within the different identified definitions, it was found that each definition emphasised on different aspects and associated collaborative design with different things. For example, the definition given by Kleinsmann (2006) emphasised on shared understanding, referring to collaborative design as a process, whilst the definition given by Chiu (2002) emphasised on the organisation of tasks and resources in addition to information sharing referring to collaborative design as an activity. Takai (2016) emphasised on the interaction of multi-discipline participants and referred to collaborative design as a methodology, not an activity. Similar to Takai (2016), Qin and Sun (2006) emphasised on the interaction of multiple participants. However, they referred to collaborative design as a complex system.

Due to the differences in the definitions of collaborative design as exemplified above, none was used as the basis to define CED. Instead, it was defined through the following approach: 1) defining the term “collaboration” in its literal sense, as this was perceived as the fundamental term that constituted towards CED, and 2) identifying the characteristics of engineering design to frame the definition of collaboration in engineering design context. In this chapter, these approaches were presented in Section 3.1 and Section 3.2, respectively. The definition of collaborative engineering design is inferred and presented in Section 3.3. A summary of work is presented in Section 3.4.

3.1 Collaboration

Generally speaking, the term “collaboration” may be interpreted as an act of working together (Bedwell *et al.*, 2012). However, this definition can also be referred to other forms of working together, namely “cooperation” and “coordination”. These terms are often used interchangeably (Hudson and Hardy, 1999; Kvan, 2000). Thus, defining collaboration as working together can potentially lead to miss-interpretation. Collaboration is fundamentally different with cooperation and coordination and as such, they need to be distinguished from one another (Gray, 1989). Based on this, defining the term “collaboration” in a detailed sense was done by differentiating it with the other forms of working together (i.e. cooperation and coordination). Several authors have distinguished these terms using various characteristics (see: Cheng and Kvan, 2000; Elmarzouqi et al., 2008; Gajda, 2004; Gulati et al., 2012; Kinnaman and Bleich, 2004; Lozano, 2008; Lu et al., 2007). Based on these works, the differences between cooperation, coordination, and collaboration are identified, outlined in Table 2, and explained subsequently.

Table 2 Differences between cooperation, coordination and collaboration

Aspects	Cooperation	Coordination	Collaboration
Interactions	Occasionally	Frequently	Almost always
Goals	Different	Same	Shared
Resources	Independent	Independent	Interdependent

Cooperation

Within cooperation, interactions between participants only occur when need be, often in an informal way (Kinnaman and Bleich, 2004; Kvan, 2000; Lozano, 2008; Mattessich and Monsey, 1992). Although each party sets their own individual goals, these goals mutually benefit one other and the interactions amongst the involved parties are aimed at supporting one another's goals (Gajda, 2004). In short, cooperation can be defined as, "…people actively working together for mutual benefit" (Kinnaman and Bleich, 2004, p.315).

Coordination

Lu et al (2007, p. 614) define coordination as "the process of managing unidirectional task dependencies between activities across multiple levels". When coordinating, participants work on their assigned task(s) separately, however there are frequent interactions to ensure that the tasks are aligned and synchronised towards the same goal(s) (Gajda, 2004; Bedwell *et al.*, 2012; Gulati, Wohlgezogen and Zhelyazkov, 2012).

Collaboration

Collaboration is a form of working together during which participants have shared goals and interdependent resources (Kinnaman and Bleich, 2004). It involves intensive participants interactions (Shen et al., 2010), both formally and/or informally (Johnson, 2005).

Above, the definition of collaboration was identified by differentiating its characteristics with the characteristics of cooperation and coordination. From analysing the various definitions, three characteristics of collaboration were derived: 1) collaboration involves intensive interaction, 2) collaboration participants share goals, and 3) collaboration resources are interdependent. However, the definitions of these characteristics are not articulated. The definition of the term "collaboration" was therefore considered too general due to possible misinterpretation of these characteristics.

Woodland and Hutton (2012, p.269) believe that characterising collaboration allows its "development, quantity, quality, and/or effects to be measured and observed." Several researchers were perceived to synthesise the literature and characterised collaboration as a foundation of their studies Thomson et al. (2007) and Woodland and Hutton (2012), for example, characterised collaboration to develop models for collaboration practice measurement within organisations. Considering this, to define the term "collaboration" in a more detailed sense, the literature was further explored to identify characteristics of collaboration. This resulted in five main characteristics. Three of them were similar with the characteristics of collaboration aforementioned, each was defined in a more detailed manner. The similar characteristics are highlighted in grey, along with the other two characteristics, presented in Table 3.

Table 3 Characteristics of Collaboration

Characteristics	Definition	Author
Human-centred activity	Human being is the main actor of collaboration. Collaboration's success and failure is mainly determined by the actor's actions.	Bedwell et al., 2012; Gajda, 2004; Lu et al., 2007; Ritter et al., 2007; Thomson et al., 2007
Involves multi-disciplinary participants	Collaboration actors usually come from multiple field of expertise, with different background (e.g. education, experience) that leads to multiple perspectives.	Axelsson and Axelsson, 2006; Detienne 2006; Ganser et al., 2007; Hara et al., 2003; Huxham and Vangen, 2004; Liang and Guodong, 2005; Stone, 2004; Woodland and Hutton, 2012
Consists of inter-related elements	Resources (e.g. actors, tools) used and activities conducted in collaboration are inter-connected and typically dependent to each other.	Bedwell et al., 2012; Durugbo et al., 2011; Klein et al., 2002; Ouertani, 2008; O'Donnel and Duffy 2005; Park and Cutkosky 1999; Woodland and Hutton, 2012
Requires communication	Dynamic interface between people, through direct (e.g. face-to-face) and indirect (e.g. network, technology)	Bedwell et al., 2012; Durugbo et al., 2012; Parung and Bititci, 2008;

	communication, is considered essential for the success of collaboration.	Terveen and McDonald, 2005
Share common goal(s)	Mutually defined and agreed objective as the basis of collaboration.	Erickson and Gratton, 2007; Gajda and Koliba, 2007; Hara et al., 2003; Kahn, 1996; Legardeur et al., 2007; Thomson et al., 2007

Inferring from the characteristics in Table 3, the term "collaboration" may be defined as *an act of working together between inter-related, multidisciplinary human beings, requiring communication to achieve shared common goal(s)*. To frame this definition within the context of engineering design, the characteristics of engineering design itself are identified in the following section.

3.2 Engineering design

Engineering design may be generally viewed as a branch of design that focuses on developing technological-related solutions (Hubka and Eder, 1987) to a design problem(s). A design problem may be affected by multiple factors (Maier *et al.*, 2011) such as customers' requirement(s), new technology development (McComb, Cagan and Kotovsky, 2015), new policies and regulations (Van Gorp and Van de Poel, 2001). Thus design problems tend to change with time (McComb et al., 2015), and are therefore, indefinite and inconsistent (Cross 2007). These are often regarded as the ill-defined characteristics of a design problem (Cross 2007; Gonnet et al 2007; Neumann et al 2008). A design problem is also characterised as being "wicked" (Arias et al 2000; Farrell and Hooker 2013; Larsson 2007; Smulders et al 2008) i.e. the problem cannot be understood prior to developing the solution (Larsson 2007). Consequently, design solutions evolve following the level of clarity of the problem and the level of the participants' understanding of the design problem (Kvan, 2000). This makes the design process iterative in nature (Cross 2006; Finger and Dixon 1989; Ostrosi et al 2012; Pahl et al. 2007). According to Pahl et al. (2007) and Dieter and Schmidt (2013), the engineering design process can be generally divided into two main stages: 1) conceptual design, where the design problem is identified (e.g. from customers requirement) and developed into ideas; and 2) embodiment design, where the ideas evolve into more detailed, tangible forms of design.

During the design process, it is required that the participants have a shared understanding towards the design (Arias et al., 2000; Reid and Reed, 2007; Smulders et al., 2008), the design process and the design participants (Kleinsmann and Valkenburg, 2008). This requirement is deemed important so that each designer has the knowledge to act "within the same overall frame" (Smulders et al. 2008, p.355). It has been argued that shared understanding can be established through an effective communication (Kleinsmann et al., 2007; Kleinsmann and Valkenburg, 2008), where the information conveyed and received is aligned. Visual communication through drawing and/or sketching is commonly utilised in addition to verbal communication (Chen et al., 2013; Cross, 2008; Gonzalez et al., 2008). Such communication may be supported by tools (e.g. computer supported collaborative design) in order to better express the design information (Inoue et al, 2013; Lu et al., 2006).

In addition to supporting communication surrounding design, tools are also used to support the resolving of design problems (Maher and Rutherford, 1997), for example, to calculate dimensions or predict behaviour of the technological-related solution being designed.

On the bases of the above points, the following characteristics of engineering design can be derived:

1. Engineering design focusses on designing technological-related solutions.
2. The design problem tends to be ill defined and can change overtime.
3. The engineering design process is iterative by nature.
4. Communication is required to achieve shared understanding.
5. The engineering design process is supported by various tools.

3.3 Collaborative engineering design

In Section 3.1, the term "collaboration" was defined as *the act of working together between inter-related, multidisciplinary human beings, requiring communication to achieve shared common goal(s)*. To define "collaboration" in the context of engineering design, the characteristics of "engineering design" were identified, presented in Section 3.2. Combining the definition of "collaboration" and the identified characteristics of engineering design, the definition of collaborative engineering design in this thesis was derived, which reads:

The act of working together between multidisciplinary human beings, all of which require communication for shared understanding and support from various tools to design a technologically-related solution to an ill-defined problem, throughout an iterative process.

From the definition above, six building blocks of CED can be derived. They are:

1. Multidisciplinary **human beings** that work together.
2. **Communication** (interaction) to share understanding.
3. **Tools** that support the design process.
4. Technology-related solution (**design solution**) as the main output of the design process.
5. Ill-defined **design problem** as the main input that limits what needs to be designed.
6. Iterative **design process** to generate design solution

Based on the aforementioned building blocks, the following elements of CED were derived (highlighted in **bold**): human beings, interaction, tools, design solution, design problem, and design process. The term “element” used here was defined as “an essential part of something [CED]” (The Oxford English Dictionary, 2013). Having identified these elements, it was found that they can be generally categorised into two groups: the social and technical group, based upon the following premises:

The social group

Generally speaking, social may be defined as “relating to society or its organisation”, whereas society can be generally defined as a “community of people” or “an organisation or club formed for a particular purpose of activity” (The Oxford English Dictionary, 2013). From this perspective, a design team, i.e. a group of people formed for designing a technological solution (Bucciarelli, 1988), may be categorised as a (small) society. Thus, “social” may be related to design team and its organisation. Based on this, from the element of CED identified above, human being and interaction can be categorised into the social group.

The technical group

With respect to the term “technical”, Oxford English Dictionary has broad definitions of the term. For example, “technical” can be associated with technique, knowledge, the use of machines or methods, laws and rules. Similarly, authors in the engineering design field seem to refer to the term “technical” differently. For example, Hubka and Eder (1988) referred to “technical” as operand, regulation, process control, and environmental condition; Hacker and Kleiner (1996) assigned the term to procedures and methods, while others attributed it to tools (for example: Cheng, 2003; Détienne, Boujut and Hohmann, 2004; Larsson, 2002; Lu and Cai, 2001). Despite these variations, it was identified that the definitions are mainly associated with the support for analytical engineering aspects of the design process. For example, tools facilitate information exchange between designers during the design process (Walthall *et al.*, 2011), required to design the technical systems. Methods govern the design process (Buur and Larsen, 2010). On this basis, “technical” may be related to the support for analytical engineering aspects of the design process. Referring on this, from the elements of CED identified, tools, design solution, design problem, and design process can be categorised into the technical group.

Having identified the above groups, it can be concluded that CED consists of social and technical elements, and thus, may be perceived as a socio-technical process. This conclusion underpinned the study presented in this thesis. To further define the focus of the study, recognising the current state of CED research from the socio-technical perspective was deemed important. For this reason, research on social, technical, and socio-technical CED needed to be reviewed.

3.4 Summary

This chapter has presented the definition of “collaborative engineering design” to frame the context of the study presented in this thesis. The definition inferred from defining the term “collaboration” and identifying the characterstics of “engineering design” derived from the literature. The definition reveals six elements of CED (i.e. human beings, interaction, tools, design solution, design problem, and design process) that can be grouped as social and technical, and thus, CED may be perceived as a socio-technical process. To define the research focus of the study, a literature review on these elements was conducted and the findings are presented in the following chapter.

4. CED research

In Chapter 3, CED was defined. It led to the conclusion that CED consists of six elements that can be designated as socio and technical. To define the focus of the study, a literature review on these elements was conducted. The literature was grouped into social and/or technical, and reviewed for its current state and knowledge gaps. The aim of this chapter is to present the findings from the review. The chapter starts with the approach of the literature review, presented in Section 4.1. In Section 4.2, Section 4.3, and Section 4.4 the findings from the social, technical, and socio-technical studies review are respectively provided. The review leads to the definition of the research focus presented in Section 4.5. The summary of the key points covered are given in Section 4.6.

4.1 Approach

The literature review was conducted without following any study protocol (i.e. formal methodology). This type of literature review may be regarded as *traditional literature review* (Jesson, Matheson and Lacey, 2011). Without a formal methodology that needed to be followed, the literature exploration could cover a wider research domain than a systematic review due to the flexibility it allows. This was considered beneficial when forming a broad basis for the research focus definition. However, there are many published academic papers in the literature. This can create a challenge for researchers that apply the traditional literature review. As Jesson, Matheson and Lacey (2011) mentioned, without a formal methodology, researchers can find a large number of academic papers that may not be relevant to their topic of study and can potentially divert focus. To mitigate this challenge, in this study, the following steps were applied:

Firstly, the initial literature search was focussed on design-related journals only, e.g. CoDesign, Design Studies, and Journal of Engineering Design, and the design society publications. These were searched using the term “collaborative engineering design”; “collaborative design”; “collaborat* design”, and “design collaboration”.

Secondly, Web of Science and Google Scholar were used to identify articles that cited the relevant papers derived from the aforementioned journal. This was done to expand the literature search while retaining the search within the relevant research field.

Thirdly, the researcher went through the title and abstract of each paper obtained from the first and second step to identify the context of the collaboration discussed. Papers that discussed collaboration in a general design context (e.g. industrial design, product design) were excluded, as they were not within the scope of the study (i.e. collaboration in engineering design context). The papers that focussed on collaboration within engineering design context were then grouped into themes and/or sub themes. The themes and/or sub-themes were identified by cross comparing the definition of collaborative engineering design (Chapter 3) with the topic that each paper focussed on. As such, each theme and/or sub-theme came organically as a result of the frequency of each theme and/or sub-theme, and were established once several papers had been read. It must be noted that some themes do not have sub-themes as there were no recurring sub-themes that could be identified within these themes.

Forthly, using the identified themes, the papers were categorised based on the premises that underpinned the social and technical group presented in Section 3.3. For example, it was identified that the main topic of the study by Shen *et al.*, (2007) was the personality of human beings in a design team. As the premise that defined the social group was "related to design team and its organisation" and human beings can be related to the design team in the sense that the members of a design team are human beings, the study of Shen *et al.,* (2007) was categorised as social.

4.2 Social CED research

Two social elements of CED were identified and presented in Chapter 3: human beings and interaction. Research on these elements were reviewed and the findings are reported in Section 4.2.1 and Section 4.2.2, respectively.

4.2.1 Human being

Designers are considered as essential elements of the design process. As Peeters et al. (2008, p.439) stated, "There would be no design processes without designers". In collaborative engineering design, designers can come from different disciplines (Hammond, Koubek and Harvey, 2001; Reilly, Lynn and Aronson, 2002; Alexiou and Zamenopoulos, 2008) such as mechanical, electronic, and systems engineering. They collaborate with each other as well as with non-designers such as marketing and finance personnel to perform the design process (Kleinsmann, 2006; Legardeur, Minelb and Savoieb, 2007). In such a way, both designers and non-designers can be considered as the main actors of collaborative engineering design.

Actors are human beings, and human beings are different in nature. These differences can originate from the properties that characterise a human being as a unique individual (Bucciarelli, 1988, 2002; Ostrosi, Haxhiaj and Fukuda, 2012). The differences in these individualistic properties can be identified as influencing factors of a CED process (Larsson, 2007; Hayes, Knight and Newnes, 2008; Maier *et al.*, 2008; Ostergaard and Summers, 2009; Barré, Buisine and Aoussat, 2017). Three properties emerged from the literature: personality, roles, and cognitive property. Studies related to these properties are presented in the following sections.

4.2.1.1 Personality

According to Devaraj et al. (2008), every human being possesses a personality that represents their unique traits. From the social psychology perspective, personality refers to a unique set of characteristics of an individual (Hofstade, 2001), and thus, can be included as a personal identity (Brown, 1985). Such characteristics may be difficult to alter using external influence, such as training (Kichuk and Wiesner, 1997). As “personality” is a property of a “human being”, their relationship can be depicted by Figure 7.

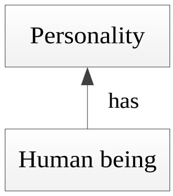


Figure 7 Relationship between personality and human being

In collaborative engineering design, human beings with different personalities work together in a design team. According to Shen et al. (2007) as well as McLening and Buck (2012), to form a productive (design) team, a mixture of personalities needs to be considered. As Kichuk & Wiesner (1997, p.215) remarked, to be successful, “…there are certain characteristics that the team must exhibit…”. This may be achieved through a mixture of personalities. Nonetheless, Kichuk and Wiesner (1997) also argued that high heterogeneity can lead to conflict and increase the stress level of the team members. Additionally, it can trigger conflicts that can potentially obstruct the design process (Goldschmidt and Planning 1995; Peeters et al. 2008).

The effects of personality on collaborative engineering design activity have been identified from the literature. McLening and Buck (2012), for example, revealed that personality affects the designers’ approaches (i.e. ways of working). Kleinsmann (2006) linked this approach to the problem-solving approach. Ostergaard *et al.* (2005) found that certain personality types may increase the productivity of a design team. Productivity can be seen as an indicator of performance (Reilly, Lynn and Aronson, 2002). From this perspective, it can be concluded that there is a relationship between the personality of team members and the performance of a design team. A current unknown is how the properties of a human being influence the performance of a design team.

Peeters *et al*. (2008) applied a personality framework, known in social psychology as the Five-factor Model (FFM) to identify the influence of personality on the performance of student design teams. The study revealed that the personality of a human being can influence their design behaviour, i.e. a set of behaviours that are considered essential for the success of accomplishing design tasks (Peeters *et al*., 2008), and thus, the composition of personalities in a design team is essential. Along a similar vein, Shen *et al.* (2007) believed that the composition of a personality needs to be considered when forming a design team. Shen et al. (2007) identified the effect of personality on the design outcomes, and revealed two personality traits linked to creativity and learning styles that can be beneficial for the design team. To help understand the personality traits of team members, Shen *et al.* (2007) proposed the use of personality method such as *Belbin Roles.*

Notwithstanding the contribution of the studies presented above, it was found that the personalities and behaviours discussed in the aforementioned studies were mainly linked to the design outcomes and design process. For example, Shen et al (2007) seemed more concerned with the effect of personality on the design outcomes linked to creativity and learning styles. However, Peeters et al (2008) appeared to focus on both the design process as well as the design outcomes. As CED involves interaction between human beings, understanding what influences their personality and behaviour towards one another was deemed important. The relationship between personality and behaviour towards other team members was however not evident from these studies.

Additionally, the empirical results from the studies related with the human beings were found to derive mostly from student design teams. However, the CED process practiced in industry and to apply information in industry captured from student design teams requires caution (Stempfle and Badke-Schaub, 2002). Results derived from CED practitioner design teams were only identified in the study of Baird *et al.* (2000).

4.2.1.2 Roles

In addition to personal identity (i.e. personality), human beings may also be characterised by their social identity. Social identity may be defined as the properties of an individual contributed by "…the social groups to which they [i.e. the human being] perceive themselves to belong" (Turner et al. 1979, p. 190). When individuals are interacting with each other in a social group (e.g. design team), they see themselves having the common features that define the group they belong to (Hogg and Tindale, 2005; Hayes, Knight and Newnes, 2008). In the context of collaboration, social identity is considered essential. According to Ellemers et al. (2004), social identity can lead group members to feel connected to the group and to associate themselves with the group outcomes and performance. Along a similar stream, Chatman & Flynn (2001) believe that social identify can break down "demographic heterogeneity" differences such as age and ethnicity, as all members of the social group feel connected, irrespective of demographic differences. A social identity emerged from the literature of CED was role.

During their interaction with others, human beings have a specific role (i.e. function) that define how they take part(s) in a team (Hellstrom 2005). In a team, including a design team, different roles can emerge when people are interacting with each other (Cross and Cross, 1995; Sonnenwald, 1996). Such roles tend to be implicitly defined and identifiable from the human beings' behaviour (Cross and Cross, 1995; Goldschmidt, 1995; Sonnenwald, 1996). From the social psychological perspective, these roles are linked to the individual's personality and behaviour (Belbin, 1997). Several studies suggest that employing a personality test method such as the Belbin approach may increase design team performance through equal role distribution (Wasiak and Newnes, 2008; Vanhatalo, Lehtonen and Halikka, 2011). These studies indicate that there is a relationship between personality, role, and team performance. However, as the studies were conducted with student design teams, whether such a relationship can be identified between industrial CED design team is not evident. As personality is unique to an individual, the roles that are linked to personality can vary broadly. In this thesis, such roles are regarded as "natural roles".

In an organisation, roles may be assigned to design actors based on their competency (Goldschmidt, 1995) and/or expertise (Cross and Cross, 1995; Badke-Schaub *et al.*, 2007). In this thesis, such roles are regarded as "assigned roles". Assigned roles can also be associated as well with functionality (Hellstrom, 2005; Feast, 2012) and hierarchical position (Feast, 2012) in an organisation. Such roles can influence a human being's behaviour and perception. For example, having a role would force individuals to share their understanding with the other team members (Valkenburg, 1998). Maier *et al*'s (2008) study reveals how the role of design actors (i.e. design engineers and simulation engineers) influences their perception towards the key success factor of communication in collaborative design.

Once a design team interacts externally, i.e. out with the team, two main roles can be identified: a supplier and a customer (Kleinsmann et al. 2007). When a design team plays the supplier role, they are required to closely interact with the customer to accommodate their needs and are responsible for ensuring the customer accepts the design (Kleinsmann, Valkenburg and Buijs, 2007). On the other hand, when they act as a customer, they are responsible to provide a set of initial requirements about the product to be designed by the supplier (Lin *et al.*, 2013). From this illustration, two conclusions can be derived. Firstly, an assigned role has a responsibility (i.e. tasks to fulfil) attached to it, and secondly, responsibility changes depending on the role. In this respect, role and responsibility are interrelated. As such, role and responsibility are often mentioned as a single term.

Similar with "personality", "role and responsibility" is a property of a "human being". The relationship between the human beings and role and responsibility is depicted by Figure 8.

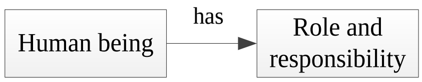


Figure 8 Relationship between human being and role and responsibility

Hellstrom (2005) suggested that people would feel worthier if they have responsibilities. Along the same vein, a study by Feast (2012) on multidisciplinary designers involved in collaborative design indicated that design actors tend to feel more committed and obligated to the collaboration if they are assigned with responsibilities. In this sense, a responsibility can be seen as an influencing factor to the human being's feeling. Valkenburg (1998) believed that roles can encourage people to share their understanding to the other team members. In other words, a role can influence a person's behaviour. As different human beings bear different roles, and hence different responsibilities, their interests and priorities might be different, and can potentially be conflicted (Bucciarelli, 2002).

The significance of the human beings' role to the CED process has been recognised, studies that focus on the role of human beings were perceived to be limited. Several studies include the discussion of human roles as part of their analysis. However, it was not the main concern of the study. For example, in a study by Cross and Cross (1995), the discussion of roles is included only as part of the analysis on how design is a teamwork and social process. The study by Hellstrom (2005) is perhaps the only study dedicated to analysing roles in collaborative design. Hellstrom (2005) identified how roles can be adopted, shifted and broken during collaborative design process. Nonetheless, these studies were conducted in the context of industrial and product design rather than engineering design per se.

4.2.1.3 Cognitive property

An assigned role may be given based on, for example, the expertise (Cross and Cross, 1995) and competency (Goldschmidt, 1995) of the human being. In human resource management, expertise and competency may be related to knowledge and skills (Herling, 2000). These can influence the way human beings think (i.e. cognitive process). The cognitive process of individual human beings is different (Dorst and Cross, 2001). These differences (i.e. cognitive conflicts) may provide multiple-perspectives that can be beneficial for resolving a design problem as well as issues such as misunderstandings in a design team (Badke-Schaub *et al.*, 2007). Thus, the cognitive process needs to be understood so that the differences can be managed. For this, studies have been conducted, providing insights into the cognitive process of design teams. Stempfle and Badke-Schaub (2002), for example, investigated the cognitive process of design teams when dealing with design problems. They proposed four basic elements of the cognitive process, namely *generation, exploration, comparison,* and *selection,* and linked them with the activity of problem solving to create a model of design activity. McComb *et al.* (2015) focussed on investigating the cognitive process when dealing with unexpected change during a design process and revealed a relationship between the ways design teams think towards the design problem with the performance of said team. Their study shows that high performing teams (i.e. the teams within the top five based on the predefined categories given by the researchers) tend to think simply while contrarily, low performing teams tend to think in a complicated manner. A limitation from the above studies is perceived to be that the primary focus is on the cognitive process of design teams and not on the cognitive process of individuals.

Linking the way design teams think with design performance was also identified in the study conducted by de Boer and Badke-Schaub (2008). They believed that aligning cognitive properties between human beings in a design team is important for team performance, particularly for those that design and engineer hi-tech products. Additionally, they also found that emotional alignment within a design team influences team performance, i.e. a design team with positive emotional alignment may have better performance. Although cognitive alignment and emotional alignment were deemed important for team performance, their relationship was unclear. Additionally, further discussion on the influence of emotion to the CED process was not identified.

4.2.2 Interaction

From a dictionary perspective, interaction may be perceived as a “reciprocal action” (The Oxford English Dictionary, 2013) between two individuals or more, as depicted by Figure 9.

According to Smulders et al. (2008), as collaborative design participants are multidisciplinary, they tend to have different perspectives and thus, "An actor in design cannot just send… information…without having a social interaction that aims to explicate [what is to be done with said information]," Smulders et al (2008, p.355). In the context of business collaboration, the term "social interaction" may be regarded as "communication" (Noorderhaven and Harzing, 2009), and as such, the concept of interaction between human beings in the context of collaborative engineering design is inseparable with the concept of communication. Based on this, in this thesis, the term "interaction" and "communication" are considered as synonyms and thus are used interchangeably.

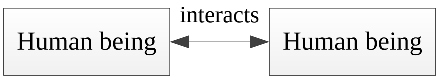


Figure 9 Interaction between human beings in collaborative design activity

It has been widely accepted that communication is an essential factor of CED (Cash, Dekoninck and Ahmed-Kristensen, 2017). As Maier *et al.* (2011) stated, "…effective communication facilitates an effective design process which contributes towards a good product…". The study conducted by Red *et al.* (2013) echoed this statement, their survey of 144 people involved in CED shows communication as the first determinant factor of effective team collaboration. Communication is however not merely about information and knowledge exchange (Rockwell *et al.*, 2009). Through communication, design team members allow themselves to establish shared understandings (Détienne, 2006; Kleinsmann, Valkenburg and Buijs, 2007; Hayes, Knight and Newnes, 2008; Kleinsmann and Valkenburg, 2008; Grogan and de Weck, 2016), clarify different perceptions (Kleinsmann, Valkenburg and Buijs, 2007), and negotiate differences (Adelson, 1999; Kilker, 1999; McDonnell, 2012).

One challenge in communication highlighted by different authors, for example, Valkenburg (1998); Kleinsmann & Valkenburg (2008); van Dijk & van der Lugt (2013), is the issue when shared understanding is lacking. Törlind & Garrido (2012, p.571) defined shared understanding as "a common ground of the boundaries, rules, and needs" of the product/system being designed. Along a similar vein, Valkenburg (1998, p.120) defined shared understanding as "mutual view amongst team members" on what to design, how to design it, and why. Shared understanding has been identified as an important factor in a design team. For example, Valkenburg (1998) believed that a lack of shared understanding can lead to aggravations and can interrupt the process of designing. Dong (2005, p.446) added that team effectiveness can be enhanced if the team members have a shared understanding on the "Team's objectives, processes, and situation". Further emphasising the importance of shared understanding, Törlind & Garrido (2012, p.571) remarked, "One of the first things that a team must come up with is a shared understanding of the problem". To construct shared understanding, collaborative design participants are required to communicate effectively (Kleinsmann, Valkenburg and Buijs, 2007; Kleinsmann and Valkenburg, 2008).

The study by van Dijk and van der Lugt (2013) revealed that a combination of social (i.e. with other team members) and physical (i.e. with design artefact) interactions can form the basis to achieve shared understanding in a design team. Additionally, visualisations such as model or sketches are commonly used to achieve shared understanding (Rahman, Cheng and Bayerl, 2013). Visual communication through drawing and sketching is often conducted in addition to verbal communication (Cross, 2008). It is supported by computer tools recognised as computer-aided design (CAD) to ease the communication process (Lu *et al.*, 2006; Inoue *et al.*, 2013). However, using visualisation does not necessarily influence the effectiveness of communication in the sense that, design solution can be achieved without the use of visualisation as indicated by the study of Reid and Reed (2007). They argued that when visualisation is absent, design team members increase the use other channels of communication such as speech and gesture. Correspondingly, when gestural communication was restricted, design team members increase the use of other channels of communication, as revealed during the study between distributed design teams (Eris, Martelaro and Badke-Schaub, 2014).

Larsson (2007) argued that the utilisation of visual communication may only facilitate effective information exchange, which is different with effective communication. To promote effective communication in design teams, Tavčar et al. (2005) suggested the development of communication skills within the team members. They perceived the lack of communication skills held by the team members as a greater obstruction to communication than the need for tools to improve communication. From a different stream, Larsson (2007, p.609) suggested applying the concept of "social capital", i.e. a concept that focusses on the "connection between individuals" instead of the individual's quality (e.g. skill) to improve communication effectiveness. Tavčar et al. (2005) and Larsson (2007) similarly acknowledged the importance of trust for effective communication.

In the studies presented above, shared understanding was primarily discussed within the technical context, i.e. understanding towards design information. According to Neumann, Badke-schaub and Lauche (2008) the effectiveness of a design team can be improved if team members also develop a shared understanding on team cohesion, i.e. "team climate and the preference of the members to be part of the team" (Neumann et al. 2008, p.1107). Team cohesion may be perceived as being social. In this sense, it can be concluded that shared understanding should be discussed within the social context. However, such discussion was only found in the domain of collaborative industrial design (e.g. Neumann, Badke-schaub and Lauche, 2008). The study in the domain of CED per se was not evident.

In addition to shared understanding, studies into communication were identified that focus on its influence over various elements of CED. For example, Vijaykumar and Chakrabarti (2007) studied the patterns of communication between designers, focussing on the types of questions asked by and the answers given by the designers to others during a design process. They identified four patterns of questions and answers between designers during a design process. These patterns were then used as the basis to identify the behaviour of designers during their interaction with others. Yang et al. (2012) studied the relationship between verbal communication coherence to the quality of collaboration and the quality of design outcome in a design team using a method called linguistic statistical approach (LSA). Their study showed that verbal communication coherence is more significant to the quality of collaboration than the quality of the design solution. Singh et al. (2013) investigated the influence of direct and indirect communication, on various team structures (i.e. flat, distributed, and hierarchical), to discover how task coordination and the formation of *transactive memory* (i.e. related to the shared understanding of groups' knowledge and competence) are affected. Both were considered as prerequisites of effective teamwork. Their study suggests that the differences between direct and indirect communication influences both the effectiveness of task coordination and the formation of *transactive memory*.

While the above studies focus on how communication influences various elements of CED, studies below focus on the other side of this relationship, i.e. how various elements of CED influence communication. The basic argument of the authors conducting such studies was that by identifying the influencing factors, factors that caused issues in communication (and collaboration) can then be understood, and eventually, be addressed (Eckert, Stacey and Earl, 2013).

Maier *et al*. (2008, p.37) identified nine inter-related core factors that influence communication from empirical studies, where mutual trust and collaboration emerged as prominent influencing factors. As a continuation of this study, Maier *et al*. (2011) compiled a number of recommendations to improve CED from the literature. Whereas Maier *et al.*, (2008, 2011) took a holistic approach towards identifying the factors that influence communication in collaborative design, others were perceived to take a fragmented approach, i.e. focusing on a particular influencing factor of communication. For example, Eckert *et al.* (2013) investigated the influence of formality to design communication at different stages of collaboration (e.g. meetings) within various design domains, including engineering design. They concluded that both, formal and informal communications is significant to collaborative design in the sense that they can facilitate effective communication and avoid potential misunderstanding.

Rahman et al. (2013) identified the influence of collaboration settings (i.e. synchronous and asynchronous) towards the quality of the collaborative process between distributed design teams. One of the collaborative process quality indicators was communication quality in terms of its frequency and fluency. They found that differences in collaborative settings influence the quality of communication differently depending on the phase of the collaborative process. For example, during synchronous settings, the communications between team members was perceived to be more “frequent” and “fluent” compared to asynchronous settings, particularly during problem definition phase. Larsson's (2007) empirical study on companies practicing distributed collaborative engineering design showed that knowing “who knows” and “who to trust” can be beneficial in the communication between design team members. This was echoed by Hayes et al. (2008).

In a general collaboration context, lack of trust has been identified as one of the main challenges of communication (Lam and Chin, 2005; Weiss and Hughes, 2005; Wijngaards, Boonstra and Brazier, 2005; Larsson, 2007; Distanont *et al.*, 2012) as it can potentially lead to reluctance to communicate (Cloonan, Matheus and Sellini, 2008).

Larsson (2007) remarked that when human beings communicate, they already have a preconceived assessment towards their interlocutors. Such assessment can be determined by, for example, trust based on the personal relationship between the interlocutors (Jarvenpaa and Leidner, 1999) and past collaborations (Panteli and Sockalingam, 2005). As such, trust affects how human beings value their interlocutors (Wijngaards, Boonstra and Brazier, 2005; Evans, 2012). The term “trust” used here is thus referred to as belief in someone else’s values (e.g. reliability). According to Susman et al. (2003), trust can facilitate openness in communication. Along the same line, Loehr (1991) believed that a greater degree of trust increases the likelihood for people to share information and knowledge that they own. From these perspectives, it can be concluded that the level of trust can be linked with the amount of information and knowledge that the human beings share. In addition to this, the level of trust in communication can be linked with conflict (Panteli and Sockalingam, 2005). Lam & Chin (2005) identified lack of trust as one of the main sources of conflict, i.e. disagreement between people. According to Tavčar et al. (2005), a greater degree of trust can reduce the occurrence of conflict and facilitate conflict resolution. On the other hand, Panteli & Sockalingam's (2005) study showed that conflict can lead to mistrust, and thus can reduce the level of trust between human beings. From these different perspectives, it can be concluded that conflict and trust hold influence over each other.

Within a collaborative product design context, Noori and Lee (2004) also identified trust as an influencing factors of communication through their case study on six collaborative product design projects. Similarly, Cloonan et al. (2008) identified trust as an influencing factor of communication from their interviews with design engineers in the aerospace industry. In this sense, the influence of trust on communication in collaborative work, including CED, can be perceived as significant. Nonetheless, study pertinent to trust within the CED context was not evident.

Most of the studies aforementioned were focussed on the interaction between team members within a design team. Lee and Jin (2014) took a different stream by focussing their study on the interaction between different design teams as well as the interaction between team members in a design team. Their study was aimed at developing a discussion technique in different phases of design activity, grounded upon the concept of “collective intelligence”, with particular emphasis on “the collective ability of people who can share and create knowledge” (Lee and Jin 2014, p.450). This study was particularly aimed at facilitating future engineering design educational course. The study that facilitates the interaction between design teams within an industrial setting was however not identifiable.

With respect to the number of studies, it was found that studies that covered interactions between human beings in a design team were far more in number compared to studies that covered human beings identified above (i.e. the properties that characterise human beings and how these properties influence the CED process). Although the importance of communication to CED has been generally accepted (Maier *et al.*, 2008), without human beings, a design process cannot be conducted (Peeters *et al.*, 2008). Furthermore, collaborative design can be perceived as a teamwork activity (Bucciarelli, 1988; Rong *et al.*,

2008) and thus, "identifying what makes teamwork effective" is considered important to obtain a better understanding on the social design process (Neumann et al. 2008, p.1105). As a human being is the fundamental constitutor of a team (Rong *et al.*, 2008) their involvement warrants further investigation.

4.3 Technical CED research

In Chapter 3, four technical elements of collaborative engineering design were identified. They were "tools", "design solution", "design problem" and "design process". "Design problem" can be seen as a boundary of a collaborative design activity, as it sets a limitation on what needs to be designed. Thus, design problem can be regarded as a "boundary" in a CED process. "Design solution" was refined into a more specific term in collaborative engineering design context, i.e. "technical system", following the terminology used by Hubka and Eder (1987). This term can still encapsulate the main point of the definition, that is, the result of the design process.

Given the aforementioned categorisation and term refinement, four technical elements were resulted: "tools", "boundary", "technical system", and "design process". Research on these elements were reviewed. Two prominent themes emerged from the review: tools and process management. The findings from reviewing these themes are presented in this section, in Section 4.3.1 and Section 4.3.2, respectively.

4.3.1 Tools

The term "tools" can be generally defined as a "device used to carry out a particular function" (The Oxford English Dictionary, 2013). The function of tools in the design process was identified to support two activities: the communication (including visual communication) between design participants (i.e. communication tools), and the creation of visualisation such as models (i.e. technical tools). In this sense, tools may be seen as a supporter of the design process. This relationship between tools and the design process can be depicted by Figure 10.

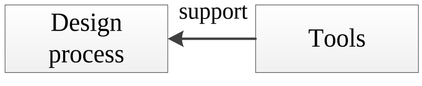


Figure 10 Relationship between tools and design process

Studies into communication and technical tools identified from the literature review are presented in the following sub-sections, respectively.

4.3.1.1 Communication tools

Communication can be viewed as an important element in CED (Section 4.2.2). The tools used to support communication are regarded in this thesis as communication tools. As CED often involves participants found at different geographically locations, the use of communication tools to facilitate their communication becomes essential. Hammond *et al.,* (2005, p.146) remarked that communication tools "…allow geographically dispersed teams to exchange, advance, and use information".

To support the development and/or improvement of communication tools, studies have also been done to identify the team members' preferences on communication tools in different collaboration type. The study of Détienne, Boujut and Hohmann (2004) on distributed design team identified that email was most preferred for asynchronous collaboration. The same preference was identified in industrial practice as shown in the study of Lee and Panteli (2011), Gutierrez Lopez *et al.* (2015), and Gopsill, McAlpine and Hicks (2014). The study of Lee and Panteli (2011) revealed that design practitioners prefer simple means of communication such as email. Both studies highlight the drawbacks of using email, with the primary issue being the impracticality issues due to the difficulty to explicate technical design issues in text (Gutierrez Lopez *et al.*, 2015) which in turn may trigger conflict (Lee and Panteli, 2011) arising from misinterpretation. Elicited from a number of studies, Gopsill, McAlpine and Hicks (2014, p.1785) also concluded that email "does not provide suitable support for EDC [Engineering Design Communication]". Based upon this, they developed a social media tool that includes, among other features, visualisation of technical design issues. Along a similar vein, Walthall *et al.* (2011) proposed the use of *Wiki*, a social-media tool that allows multiple users to read, add, and edit the same information using a web-based platform. The main difference between *Wiki* and email is that *Wiki* displays only the latest version of information to avoid team members accessing invalid information, which commonly occurs when communicating through email.

Despite the effort to address the drawbacks of email, misinterpretation may still occur as the communication is mainly done through text. A different alternative for communication was identified by Lee and Panteli (2011) and Gutierrez Lopez *et al.* (2015) who recommended combining the use of email with face-to-face meetings or tele conferencing. With respect to face-to-face meetings, Thomson, Stone and Ion (2007) remarked that it can be useful to discuss any discrepancies or confirm hesitations directly, and thus, conflicts resulting from misunderstanding and delays can be mitigated.

The types of communication tools that can be used to support distributed team varied broadly. Red *et al*., (2013) categorised them based on the two general types of collaboration: *synchronous*, when the collaboration is conducted at the same time, and *asynchronous*, when the collaboration is conducted at different times. The categorisation is depicted by Figure 11. However, studies into communication tools aforementioned only address a small number of the communication tools shown in Figure 11, which are *face-to-face, email,* and *wiki*. Studies that address other communication tools within the context of CED were not evident.

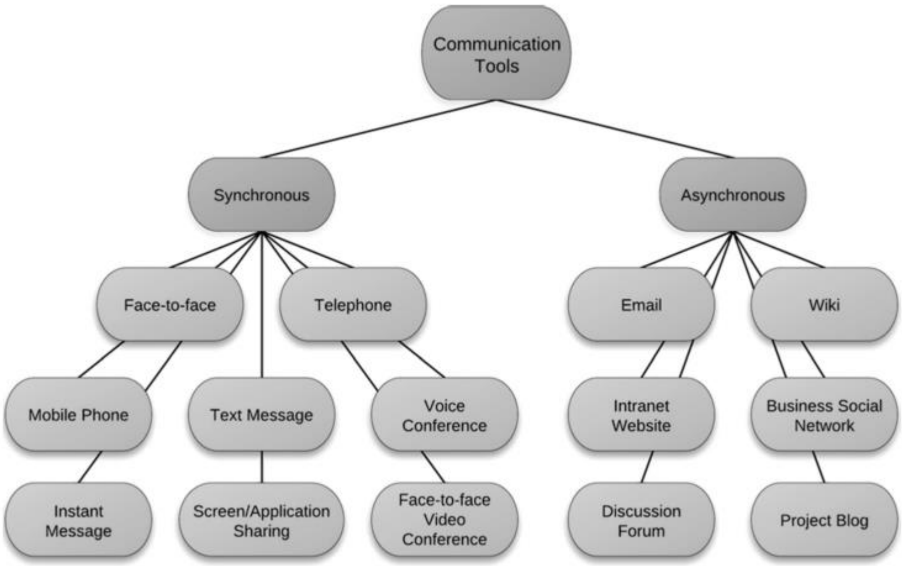


Figure 11 Communication tools categorisation for collaborative product development (Red *et al.*, 2013, p.13)

4.3.1.2 Technical tools

In CED, design information such as dimensions, form, and structure needs to be communicated to all team members (Belkadi et al, 2012). However, one of the characteristics of CED is the multi-disciplinary design team members (see Chapter 3). Due to this characteristic, multiple interpretations towards the design information commonly occur. Liu and Boyle (2009) argue that one of the challenges in communicating design information is representing the information in the simplest manner possible (Liu and Boyle, 2009). Sutherland (1963) believed that to communicate design information, visualisation was considered the most practical option (compared to "typed statement"). Along a similar vein, Cross (2008) remarked that visualising design information through drawings and sketching is considered effective for communicating design information in a common language. The tools used to support the creation of visualisation may be regarded as technical tools. Computer Aided Design (CAD) software is an example of such a tool (Li *et al.*, 2005).Visually representing the design problem can help team members to perceive the information at the same level (Goldschmidt, 2007). Sutherland (1963) and Cross (2008) echoed that visual representation such as drawings and sketches may be effective for sharing design information in a common language.

Computers have long been used to facilitate design practice (Ray 1985; Davis and Subrahmanian 2001). Sketchpad developed by Sutherland in 1963 was recognised as the pioneer of a computer system that supports the creation of visual representations and is generally acknowledged as the predecessor of Computer Aided Design (CAD), commercial applications that are commonly used by engineering designers to create visual representations (Li *et al.*, 2005; Zheng, Shen and Sun, 2009). Regardless of its popularity, a number of weaknesses of CAD in its application to CED were acknowledged, motivating studies to address them. For example, Chen *et al.* (2005) created Distributed Computer Aided Design (DCAD), motivated by the lack of project management feature such as task coordination in CAD. Zheng, Shen and Sun (2009, 2011) introduced CoAutoCAD, to address the single-user limitation of CAD, allowing multi-users to use the application concurrently. Fu, Bian and Xu (2013) integrated IP-based video conferencing systems with CAD to address the lack of multi-communication features between distributed design participants. Motivated by the lack of collaborative features as well as arguing that CAD is mainly used in the detailed design stage, Vasantha *et al.*, (2015) tested the use of an interactive whiteboard software called Smart Board that allows participants to manipulate any documents displayed on the screen simultaneously. Although the study shows a negative relationship between the software and CAD, it confirms the need for collaborative features in CAD to support a CED process.

The lack of collaborative features was identified as one of the prominent weaknesses of CAD within the context of collaborative design (Piegl, 2005; Li and Shen, 2008; Shen, Ong and Nee, 2010; Red *et al.*, 2013). Computer supported collaborative design (CSCD) was perceived to address this weakness (Shen, Hao and Li, 2008; Shen, Barthès and Luo, 2015) with its three basic aspects (Geisler and Rogers, 2000; Huifen, Youliang and Jian, 2003; Li *et al.*, 2005): visualisation (e.g. modelling), communication (e.g. instant messaging), and a multi-user interface (e.g. tool integration). Shen, Barthès and Luo (2015) regarded these three aspects as “coordination, communication, and cooperation”, respectively. As new technology continuously emerged, studies were identified intending to improve CSCD by adapting it to new technology. For example, Shen, Ong and Nee (2010) developed an interface application using Virtual Reality (VR) technology allowing distributed participants to collaboratively modify the 3D design representation in real-time.

A number of technical tools to address certain shortcomings in the CED process were developed, independent from CAD and CSCD. For example, Collaborative Axiomatic Design Support (CADS) was proposed by Favela, Wong and Chakravarthy (1993) to address the lack of awareness on the *design rationale* (i.e. reasoning behind the design), which deemed essential for achieving shared understanding and for mitigating conflict. A framework for Multidisciplinary Design Optimization (FMDO) was generated by Shi *et al.* (2006) accommodating the lack of integration between different computer (technical) tools used by design team member. The Operational Collaboration Model (OCM) was developed by Vuletic *et al.* (2013) to address the lack of concurrent communication. Aimed at addressing the multiple -perspectives that can potentially lead to misunderstanding, a collaborative design tool was developed by Pei, Campbell and Evans (2010) to link different design representations used and developed by inter-disciplinary team members (i.e. engineering and industrial designers). Other tools were developed to facilitate project management such as the Virtual Integration Platform (VIP) developed by Whitfield, Duffy and Coates (2007) that facilitates resource management (i.e. allocation and scheduling) and task distribution.

The consideration of the social elements of CED that provide the basis for the evaluation of collaborative tools was found within the literature. Nonetheless, the considerations were deemed limited in comparison to the consideration of technical elements. For example, Gendron *et al.* (2012) developed seven classifications (nature, dimension, point of view, status, context, structure, and type) to define indicators for a collaborative platform, which allows users to reflect and improve their collaboration. However, the majority relate to the technical elements of CED, only two of these classifications were concerned with the social element of CED (i.e. *dimension* of design activities, and *point of view* of the design team members). From a different perspective, Törlind and Garrido (2012) identified five senses of interactions that can be used as the basis to evaluate collaborative tools and improve them for use in a design meeting of creative collaborative work (e.g. CED): *sense of presence, sense of space, sense of sharing, sense of time,* and *sense of naturalness*. Again, the majority relate to the technical elements of the CED process. Only one social element was included, i.e.

sense of presence, that is the "feeling of being together that comes from the interactions between people" (Törlind and Garrido, 2012, p.572).

4.3.2 Process management

As aforementioned, within the context of this thesis, the term "boundary" was associated with acts/objects that limit the design activity. A design problem is typically expressed in a general manner and as such can be ill-defined (Cross, 2008b), or as Hubka & Eder (1988) recognised it, "dirty", meaning that the design problem is "rarely expressed in the form of an explicit and coherent statement" (Andrews 1998, p.195). As such, design problems tend to be inconsistent (Cross, 2008b), and can leave unanswered questions, and thus, can limit the process of designing. For this reason, the ill-defined nature of the design problem was considered as a boundary of collaborative engineering design activity.

The ill-defined nature of the design problem has been recognised as one of the main challenges in collaborative design activity. For example, Lu et al. (2007) mentioned that a solution depends on the problem definition. If the design problem is ill defined, it can potentially create discrepancy between the participants on how to define the problem. Concerning the design problem-solution relationship, the design problem can also be regarded as being "wicked" (Rittel and Webber, 1984; Arias *et al.*, 2000). To understand a "wicked" problem, according to Rittel and Webber (1984), one has to work on the solution. Working on the solution of a design problem may be defined as designing a product or system (Bucciarelli, 2002; Lombard and Yesilbas, 2006). This can be regarded as the goal of collaborative design activity, commonly shared between the design participants (Durugbo *et al.*, 2011).

Legardeur et al. (2007) remarked that collaborative work begins when a common goal is defined. In collaborative design, the participants work together towards the design team's common goal, rather than the individual's interest-based goal (Lu *et al.*, 2007). For this reason, having an explicit and shared common goal is considered essential. It has been identified as one of the success factors of any collaborative activity (San Martín-Rodríguez *et al.*, 2005; Feast, 2012).

Being directed towards a common goal was identified as one of the characteristics of collaborative engineering design (see Chapter 3). Such characteristic was highlighted as a distinguishing factor between collaboration and the other forms of working together such as cooperation and coordination (Mattessich and Monsey, 1992; Kvan, 2000; Chiu, 2002; Lombard and Yesilbas, 2006; Lu *et al.*, 2007; Maier *et al.*, 2009).

According to Chiu (2002) the process of designing needs to be repeated until the (common) goal is achieved. In this view, a goal can be seen as a limit of the design process and thus, can be considered as a boundary of collaborative design activity. As Lu et al. (2007) remarked "common goal" (together with two other factors, namely shared values and team strategy) define the boundary of collaborative design activity.

With respect to the relationship between boundary and other elements of collaborative engineering design activity, both identified boundaries (i.e. ill-defined design problem and common goal) were viewed to limit the design process. This relationship can be depicted by Figure 12.

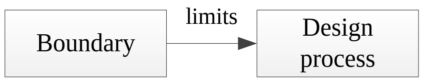


Figure 12 Relationship between boundary and design process

In a general sense, a design process may be defined as the process to transform a design problem into a solution (Luckman, 1967; Hyman, 1998; Hurst, 1999), or in other words, a problem-solving process. In a detailed sense, Hubka & Eder (2002) described the engineering design process as the process of transforming information, which can arise from various sources such as customer's requirements, into a technical system. They regarded a technical system as "a designed artefact with a substantial technical content [i.e. related to product/system functions]" (Hubka and Eder 2002, p.49). From this perspective, a technical system (design) can be seen as the result of a design process or, in other words, a design process produces a technical system. In Section 3.3, a technical system was identified as an element of collaborative design activity. Thus, the relationship between the design process and the technical system needs to be represented, as shown in Figure 13.

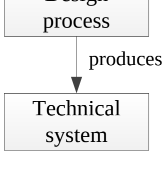


Figure 13 Relationship between design process and technical system

Technical systems can be presented in different forms, such as sketches, models, and prototypes (Perry and Sanderson, 1998). To create these, design software such as computer-aided design (CAD) is often used (Red *et al.*, 2013). From this perspective, design software can be viewed as an instrument that supports the creation of the technical system, and thus, supports the design process.

Design processes are often being regarded as complex processes (e.g. Frankenberger & Badke-Schaub 1998; Bierhals et al. 2007; Gonnet et al. 2007; Hayes et al. 2008; Ouertani 2008; Stempfle & Badke-Schaub 2002; Maier et al. 2011). they deal with ill-defined design problems (Bierhals *et al.*, 2007) and consist of interrelated elements (Ouertani, 2008). Whitfield et *al*. (2002, p.243) remarked, “There are many factors that need to be simultaneously considered to effectively manage the complexity”. Studies have been done to manage this complexity using various approaches, each focussing on a different element of CED the process. Design process modelling, i.e. constructing a structured design process representation, is one of the common approaches to manage the complexity of the engineering design process. Examples of this are: Evan’s design spiral introduced in 1959; Pahl and Beitz’s systematic method developed in 1984, and Pugh’s total design method developed in 1991). According to (Hurst, 1999, p.8), “A systematic approach permits a clear and logical record of the development of a design.”

A process model decomposes the design process into phases (Vajna, 2005) and/or activities. However, the developed design process models only focus on the artefact creation. Furthermore, they were not developed within the context of the CED process, and thus, exclude the social collaborative elements such as coordination activities between each phase. To address these issues, Park and Cutkosky (1999, p.84) created a framework for process modelling within the CED context with focus on addressing the need to include collaborative elements (e.g. conflict management strategy, coordination activities). Another approach, i.e. creating a methodology for collaboration management, was done by Girard and Robin (2006), who argued that to manage complexity and improve design process performance, in particular within a collaborative setting, focus should also be given to the relationship between the design team members. As such, they identified the type of collaboration amongst design team members, the prerequisites of each collaboration type, and the situation in which the collaboration can be applied to form the basis of said methodology.

One of the identified factors that cause complexity in a CED process is the multi-disciplinary nature of the team members. This can affect the CED process in several ways. Pei, Campbell and Evans (2010, 2011), for example, argued that one of the effects is the multiple-perspectives seen towards the design representation (artefact). To manage this, they produced a hierarchical taxonomy of visual design representation from both the industrial and engineering design perspectives. From a different perspective, Inoue *et al.,* (2013) argued that the multi-disciplinary nature leads to multiple-preferences towards the design solutions. To manage this, they proposed the use of Preference Set-based Design (PSD) and tested the use within a CED context.

Among other reasons, communication is conducted to share knowledge and design information, to achieve a shared understanding. Knowledge and information can thus be identified as essential elements in the CED process (Lang, Dickinson and Buchal, 2002; Conway and Ion, 2013). However, in a collaborative environment, it can be difficult to ensure that all relevant knowledge is shared consistently with all design team members (Zhang *et al.*, 2013). A few studies were identified in the domain of knowledge and information transfer within the CED context. For example, Shooter *et al.*, (2000) developed a model, representing how design information (i.e. design specification) flows, starting from customer needs and finishing with requirement evaluation, to form the basis to develop standardisation for design information exchange. Aimed at improving the documentation of knowledge and information, Conway and Ion (2013) created a system called KEN (Knowledge Enhanced Notes), a web-based system that allows design participants to capture and record design knowledge and information to be used at later stages. Zhang *et al.* (2013) proposed a knowledge flow network model for knowledge distribution planning, to ensure that information is shared properly. However, not all information needs to be shared. Its values needs to be assessed (Pavković and Štorga, 2013). Pavković and Štorga (2013) believed that the value of a piece of information can be assessed by tracing how the information is developed and therefore they proposed an information-traceability methodology.

The studies that discussed knowledge and information were primarily related to the design information. However, Belkadi *et al.* (2013) remarked that not only design related, but also activities-related knowledge and information needs to be shared. They believed that sharing such information may support awareness, i.e. an essential factor to improve the effectiveness of a design process. Aiming to support awareness, they developed a generic situation model that can be used as the basis to represent a design activity. This was identified as the only study supporting awareness in a CED process from the technical perspective.

Failure to achieve shared understanding can result in design conflict (i.e. disintegratd design). Such conflict can negatively impact the design process and design outcomes

(Favela, Wong and Chakravarthy, 1993). For example, disintegrated design can potentially lead to rework (Klein *et al.*, 2002). A number of propositions to reduce design conflict were identified in conflict management. Lombard and Yesilbas (2006) proposed a methodology for managing conflict solving, consisting of three steps: 1) *detecting conflict*, 2) *deciding action*, and 3) *applying the solution* to the design. Focussing on the step 2, Ouertani (2008) argued that when selecting an action, the impact of the action needs to be considered. They believed that the impact can be identified from the dependency relationships between "the conflict sourced data and the data previously produced" (Ouertani, 2008, p.883). Based on this argument, they proposed a method to identify dependency relationships between pieces of design data (e.g. specification) as a way to manage conflict (Ouertani, 2008; Ouertani and Graza, 2008). Also focused on step 2, Ostrosi, Haxhiaj and Fukuda (2012) proposed a formal approach to filter consensus on conflict solution based on the idea that achieving consensus for conflict solution between design team members can support conflict management. Taking into consideration the (design) attitudes of design team members and arguing that design conflict is justified when there is a gap between the satisfaction levels of the design team members towards the design, Canbaz, Yannou and Yvars, (2014) proposed CoCSP (Cooperative Constraint Satisfaction Problem) technique for conflict management.

From the three steps of conflict management developed by Lombard and Yesilbas (2006), studies that focus on conflict detection and solution application were not apparent. With respect to conflict detection, Klein *et al.*, (2002, p. 30) remarked that CSCD should support conflict management and proposed that CSCD can be used to identify "early warning sign[s] of non [-]convergent dynamics" by, for example, monitoring a number of changes made in the design. Further study in this regard was however not identifiable.

Wang *et al.*, (2002) postulated that conceptual design may be the most important phase of the design process. Kim and Xirouchakis (2010) and Inoue *et al.* (2013) echoed that the decisions taken in the conceptual design phase influence crucial factors such as the cost and the quality of the product being designed. However, it is also considered the most challenging phase, as it can lead to uncertainties due to the ill-defined nature of the design problem (Wang *et al.*, 2002). This causes challenges in the decision-making process. This process is perceived important as the decisions taken during the conceptual design phase can determine the direction of the design (Toh and Miller, 2015). Studies were identified to address this challenge. For example, Kim and Xirouchakis (2010) developed decision support systems that facilitate the selection of design concepts. While the supporting system developed by Kim and Xirouchakis (2010) primarily focussed on design information, Rockwell *et al.* (2009) develop tools that focussed on the design decision process. Taking a different approach, Safavi *et al.*, (2015) proposed a method, namely CMDO (Collaborative Multidisciplinary Design Optimization), which integrates multidisciplinary experts (including experts from detailed design) into the conceptual design phase.

4.4 Socio technical CED research

Based on the definition of CED presented in Chapter 3, it was concluded that CED can be perceived as a socio-technical process. To define the focus of the study presented in this thesis, recognising the research that based on this perspective was conducted and the findings are presented in this section.

Design was initially perceived as a technical process. However, acknowledging that design is not an individual action (Kvan, 2000; Hammond, Koubek and Harvey, 2001; Détienne, 2006), the notion of design as a social process in addition to a technical process became commonly acknowledged. For example, Dilnot (1982) argued that the exclusion of social element in the definition of design, may have contributed to the difficulties in understanding the phenomena of design. Bucciarelli (1988; 2002) emphasised the importance of perceiving engineering design from a social perspective, in addition to technical, as it mainly involves teamwork between different human beings. They made a comprehensive definition of engineering design process from a social perspective. The definition highlights the significance of the interaction between human beings that hold different characterising properties (e.g. skills and interests) to the design process and quality of design solution.

Researchers also pointed out the importance of perceiving CED process from the socio-technical perspective. Perry and Sanderson (1998), for example, highlighted that studying social interaction may aid the identification of technological limitations developed to support CED. Rong *et al.* (2008) , believed that including social element into the study of CED can provide a wider perspective towards the CED process, while McGowan *et al.* (2013, p.1150) echoed that socio-technical awareness "…may ultimately foster greater efficiencies" in the design process and design outcomes.

Studies based on the notion of CED as a socio-technical process, focused on different aspects were identifiable in the literature and they are presented in the following paragraphs.

A CED process may be generally perceived as a complex process (Lu *et al.*, 2006; Lu and Suh, 2009; McLening and Buck, 2012; Grogan and de Weck, 2016). Perceiving the complexity of CED from the socio-technical perspective, Grogan and de Weck (2016) conducted an experiment to investigate the influence of both social and technical complexity towards the design performance (i.e. measured by task completion time). In their study, social complexity referred to team size while technical complexity referred to problem size. Their study indicated that while team size and problem size both influence the design performance, the influences of social and technical complexity to the design performance are independent from one another.

According to Lu et al. (2000) and Lu and Cai (2001), a common issue identified in a CED process as a result of its complexity is design conflict. Their socio-technical process architecture model of engineering design shows that design conflict is mainly influenced by the social interaction and technical decisions of the stakeholders (i.e. participants of CED process) due to "task interdependencies and perspective differences" (Lu et al. 2000, p.70). Additionally, they argued that from a socio-technical perspective, design conflict should be viewed as an enabler of the CED process in the sense that it "…drives social construction process and design innovations" rather than a barrier (Lu et al. 2000, p.70). As such, they believed that conflict should be managed instead of avoided. The same beliefs and socio-technical process architecture were used as the basis to create collaborative engineering design computer support prototypes. The prototypes evolved from STDPM (Socio-technical Design Process Management) (Lu et al. 2000) to STARS (Social Technical Analysis Research System) (Lu and Cai, 2000; Cai, 2002; Lu *et al.*, 2006) and STCP (Socio-Technical Co-construction Process), the latter with more focus on negotiation approaches. These studies covered the following socio-technical elements of VED: human beings and their perspectives, the social interaction between human beings, and the technical decision making process (i.e. design process (Lu and Jing, 2009; Jing and Lu, 2011).

Covering different socio-technical elements, aiming to improve the interaction between engineering design students located in different geographical locations, Esparragoza et al. (2015) investigated how these students interact from the social (i.e. the communication between the team members) and technical (i.e. the communication tools used) perspectives. Their study revealed that the quality of information (e.g. value and volume of information shared) and the behaviour of the team members (e.g. contribution to the design project and active participation in design meetings) were considered the most important elements during social communication. With respect to the communication tools used, email was identified to be the most preferred tool.

Focussing on distributed design teams and the interaction between them, based on the socio-technical systems theory that advocates the joint optimisation of both social (i.e. related with the human beings) and technical (i.e. related with the technology) sub-systems of an organisation, Hammond et al. (2001) investigated the relationship between the interaction of team members and the tools used through a literature review. They concluded that interaction is fundamentally influenced by the tool(s) used. Based on this finding, Hammond et al. (2005) investigated the influence of communication tools towards the "mental workload" of the team members and their interaction behaviour during the decision making process through experimentation with students. The findings suggest that the use of communication tools influence the "mental workload" (i.e. increased), frequency (i.e. decreased) and duration of communication (i.e. increased). Although this study discussed collaborative design from the socio-technical perspective, the socio-technical elements were discussed separately. Inter-relationship between the elements discussed cannot be identified.

Another issue of the CED process due to its complexity is uncertainty, which makes planning the design process challenging (Hassannezhad and Montagna, 2016). To understand the phenomena of uncertainty in a design process, Hassannezhad and Montagna (2016) investigated the impact of uncertainty to the design process with respect to the cost and behaviour from the socio-technical perspective. They identified three socio-technical uncertainties that exist in the CED process: 1) the specification of product or process, 2) the customer needs, and 3) the behaviour of human beings and their interaction with one another. The study shows that there are inter-dependencies (direct and indirect) between these socio-technical uncertainties. Nonetheless, the articulation of the inter-dependencies was not identified.

4.5 Research focus

This chapter presents a literature review on CED research to identify the current state of the knowledge. The review was grouped into social and technical research based upon the premises discussed in Section 3.3. The findings from the review were presented in Section 4.2 for social CED research and Section 4.3 for technical CED research. Additionally, as CED was perceived a socio-technical process, studies based on the notion of CED as a socio-technical process (regarded as socio-technical studies) were also reviewed and the findings were presented in Section 4.4. This section outlines the summary and main conclusions from these literature reviews to arrive on a research focus and boundary. In Section 4.5.1, the main literature themes reviewed are summarised and presented. In Section 4.5.2, the summary of key elements derived from the literature findings are provided. In Section 4.5.3, the challenges facing CED research identified from the literature review are presented. These were used as the basis to define the focus and boundary of the study, given in Section 4.5.4 and Section 4.5.5, respectively.

4.5.1 Main literature themes reviewed

A total of 68 papers were reviewed. From these, 23 were considered as social, 35 as technical, and 10 as socio-technical. Table 4 summarises the general research areas reviewed. The first column identifies the focus as either social and/or technical, the second the main theme (topic), the third is the sub-theme, and the last is the relevant articles focussing on the identified theme and/or sub-theme. The elements of the table were chosen based on the third step of the literature review approach described in Section 4.1.

Table 4 Summary of the literature on CED reviewed

Social/Technical	Theme	Sub-theme	Authors
Social	Human beings	Personality	Baird *et al.*, 2000; Peeters *et al.*, 2007, 2008; Shen *et al.*, 2007
		Roles	Wasiak and Newnes, 2008; Vanhatalo, Lehtonen and Halikka, 2011
		Cognitive property	Stempfle and Badke-Schaub, 2002; de Boer and Badke-Schaub, 2008; McComb, Cagan and Kotovsky, 2015
	Interaction		Ostergaard *et al.*, 2005; Vijaykumar and Chakrabarti, 2007; Larsson, 2007; Reid and Reed, 2007; Hayes, Knight and Newnes, 2008; Kleinsmann and Valkenburg, 2008; Maier *et al.*, 2008; Yang, Dong and Helander, 2012; Eckert, Stacey and Earl, 2013; van Dijk and van der Lugt, 2013; Rahman, Cheng and Bayerl, 2013; Singh, Dong and Gero, 2013; Eris, Martelaro and Badke-Schaub, 2014
Technical	Tools	Communication tools	Détienne, Boujut and Hohmann, 2004; Lee and Panteli, 2011; Walthall *et al.*, 2011; Red *et al.*, 2013; Gopsill, McAlpine and Hicks, 2014; Gutierrez Lopez *et al.*, 2015
		Technical tools	Favela, Wong and Chakravarthy, 1993; Chen *et al.*, 2005; Shi *et al.*, 2006; Whitfield, Duffy and Coates, 2007; Zheng, Shen and Sun, 2011, 2009; Pei, Campbell and Evans, 2010; Shen, Ong and Nee, 2010; Fu, Bian and Xu, 2013; Vuletic *et al.*, 2013; Vasantha *et al.*, 2015
	Process management		Park and Cutkosky, 1999; Shooter *et al.*, 2000; Klein *et al.*, 2002;

			Girard and Robin, 2006; Lombard and Yesilbas, 2006; Ouertani, 2008; Ouertani and Graza, 2008; Rockwell *et al.*, 2009; Pei, Campbell and Evans, 2010, 2011; Kim and Xirouchakis, 2010; Ostrosi, Haxhiaj and Fukuda, 2012; Conway and Ion, 2013; Pavković and Štorga, 2013; Zhang *et al.*, 2013; Inoue *et al.*, 2013; Canbaz, Yannou and Yvars, 2014; Safavi *et al.*, 2015
Socio-technical	Conflict management		Lu *et al.*, 2000, 2006; Lu and Cai, 2001; Cai, 2002; Hammond *et al.*, 2005; Lu and Jing, 2009; Jing and Lu, 2011
	Interaction		Hammond, Koubek and Harvey, 2001; Esparragoza *et al.*, 2015
	Complexity management		Hassannezhad and Montagna, 2016

4.5.2 Key elements of literature findings

From the review of the papers listed in Table 4, socio-technical elements and their inter-relationships were identified and can be explained as follows.

Firstly, from the review on the social research, “human beings” were defined as the main actors, designers and non-designers who conduct CED process. Interaction was defined as communication between two or more human beings to share understandings. The review on the human beings’ literature revealed four properties that characterise them and influence a CED process: personality (i.e. a unique set of characteristics of an individual that can be difficult to alter by external influences), roles (i.e. human beings’ function in a CED process, which can naturally exist or be assigned) and responsibility (i.e. tasks required of human beings based on roles), and cognitive property (i.e. related to the way human beings think). The relationship between the social elements is depicted by combining Figure 7, Figure 8, and Figure 9, as can be seen in Figure 14.

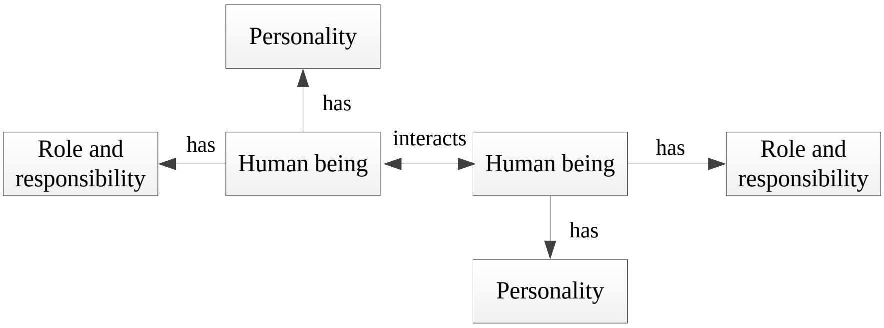


Figure 14 Relationship between social elements of CED

Secondly, from the review on the technical research, tools were viewed as devices to carry out particular functions, i.e. to support a design process. From the review on process management literature, the term “boundary” was used to replace the term “design problem” representing the act/objects that limit the design activity, and the term “technical systems” was used to replace “design solution”, i.e. the result of a design process. It was also found that design process may be perceived as the process to transform a design problem into a solution (i.e. technical system). The relationship between the technical elements is depicted by combining Figure 10, Figure 12, and Figure 13, as can be seen in Figure 15.

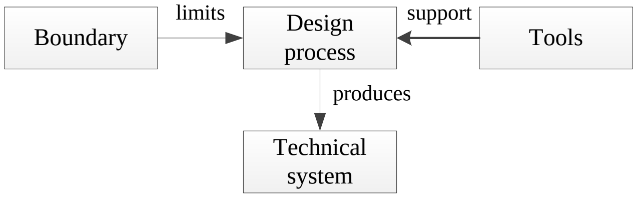


Figure 15 Relationship between technical elements of CED

4.5.3 Research challenges

The following points summarised the challenges facing the research of CED identified from the literature review:

Firstly, from the review on the socio-technical literature, the notion of CED as a socio-technical process was acknowledged and the importance of focussing the studies on both social and technical elements was discussed. However, studies tended to focus on one or two socio-technical elements only, and therefore, gave limited knowledge on the socio-technical elements of CED. For example, Lu et al’s (2000) study covered human beings, interaction, and design solution, while Esparragoza et al. (2015) covered interaction and the tools used.

This lack of knowledge can also be seen in Table 4 where there are no specific articles that cross multiple sub-themes. Additionally, while the relationships between certain socio-technical elements and their influences towards a CED process were identified (e.g. Hassannezhad and Montagna, 2016), no consensus on the socio-technical constitution and their inter-relationships could be identified from the literature.

The review of the technical and socio-technical literature revealed the inter-relationships between social and technical elements. For example, the study by Pei, Campbell and Evans (2010) indicates the relationship between the multiple-perspective of human beings (a social element) and tools (a technical element). However, as can be seen from the example, studies tend to focus on parts of the elements only – the second challenge facing CED research. The influences of certain socio-technical elements towards CED were discussed in previous work. However, the findings of these discussions showed that no work had been done on viewing the socio-technical elements from a holistic point of view. Consequently, the literature provided limited knowledge on the inter-relationship between the socio-technical elements of CED. As CED is a socio-technical process, recognising the social and technical elements and their inter-relationships holistically was perceived important.

Finally, the review showed that the number of socio-technical studies was relatively low, compared to the number of both social and technical studies. This can be seen from the number of articles addressing the theme (see Section 4.5.1).

Given the above points, it was concluded that there is a need for a holistic investigation into socio-technical CED that identifies a fundamental constitution of socio-technical elements and their inter-relationships.

4.5.4 Focus of study

To address the aforementioned need, the study presented in this thesis focusses on the development of a socio-technical architectural model (STAM) of CED. The following paragraphs elaborate this focus further.

According to Sim (2000, p.17), models are often used to "…understand and explain natural phenomena…" as this provides "…an understandable character of the observation [i.e. phenomena of CED process]…" As the study aims to understand the phenomenon of collaborative engineering design from the socio-technical perspective, presenting the socio-technical elements of CED and their interrelationships as a model was deemed appropriate.

Architecture may be generally referred to the structure of something (Lankhorst, 2005; Jensen, Cline and Owen, 2011), and a structure may be viewed as an organisation of elements and their inter-relationships (The Oxford English Dictionary, 2013). Thus, architecture may be defined as an organisation of elements and their inter-relationships. In a more detailed sense, ISO 42010, a standard for systems and software engineering (ISO/ IEC/ IEEE 42010 2014) defined architecture as "the fundamental organisation of a system, embodied in its components, their relationships to each other… and the principle governing its design and evolution." In other words, architecture can be defined as a structure of something consisting of components (elements) and inter-relationships based upon defined principles. Based on these points, a socio-technical architectural model is may therefore be described as a model that consists of socio-technical elements and inter-relationships which are themselves based upon a principle, which in this case, is CED as a socio-technical process. As Figure 14 and Figure 15 depict socio-technical elements and their inter-relationships, they can be regarded as the first version of STAM (STAM-1).

In developing the model, the position taken in the research was that presented by Duffy and O'Donnel (1999). They believed that a reality can be envisaged with "…a fundamental understanding, in the form of theories or models…" of that said reality (Duffy & O'Donnel, 1999, p.2). The fundamental understanding of the reality is regarded as a *descriptive phenomena model*. In this sense, to improve the CED process, having a phenomena model of the CED process itself was considered important. For this reason, the development of STAM was focussed on the descriptive phenomena model that is "…based on the observations and analyses of the reality…that reflects design practice" (Duffy & O'Donnell, 1999, p.5) (see Figure 16). The main purpose of developing STAM was to form the basis to postulate an "envisaged reality" by, for example, identifying strengths and weaknesses of current collaborative design practice. Through the focus of STAM, the study would contribute towards the knowledge of CED by providing insights into the phenomena of CED from the holistic socio-technical perspectives. Furthermore, such a model could potentially address the lack of awareness of the social elements in industrial practice (Appendix 1: Industrial challenges).

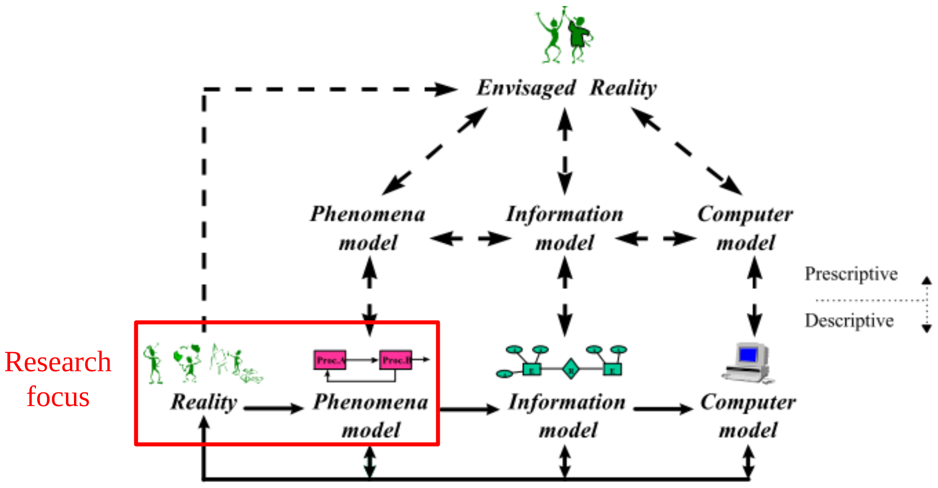


Figure 16 Research focus (source: Research framework by Duffy & O'Donnel, 1999, p. 5)

4.5.5 Boundary of study

To develop STAM, a boundary must be defind. The following points were determined as the boundary of study:

Firstly, the aim of developing the model is to gain knowledge on the phenomena of CED. As such, the model may be perceived a descriptive phenomena model. Such a model, according to Duffy and O'Donnell (1999), is based on "observation and analysis" of a CED practice. Considering that the initial motivation of the study was the current CED practice in a company (Chapter 1), basing the model within the organisational context of CED practice was deemed appropriate. To focus the applicability of the model, the "organisation" was bounded to one that can be categorised as an ETO company that specialises in the design and manufacture of complex technical systems (see Section 1.1).

Secondly, to constrain the boundaries of the model itself, all social and technical elements within the model should be within the context of CED defined in this thesis (i.e. social being related to design team and its organisation, and technical being related to the support for analytical engineering aspects of the design process). With this boundary in mind, the model should therefore not include aspects such as business strategy and management, finance, and marketing. The model should also include the inter-relationships between the socio-technical elements and the properties that characterise the socio-technical elements as they were found to influence CED process (see Chapter 4).

Thirdly, to provide knowledge on the influence of socio-technical elements towards CED in a holistic manner (which was found to be currently lacking (Section 4.5.3)) the elements that should be included in the model were those that could be considered as key influencing factors of a CED process. These factors will be further discussed in Section 5.2.2.

4.6 Summary

This chapter has presented a review on the social, technical, and socio-technical elements of CED. The aim of the review is to identify the current state of knowledge and issues facing CED research (knowledge gaps). A total of 68 papers were identified. From these studies, 23 were considered as social, 35 as technical, and 10 as socio-technical. The review revealed that the literature on CED is lacking a holistic investigation of socio-technical CED. In particular, there is a lack of a fundamental constitution of socio-technical elements and their inter-relationships. This lacking became the basis of the research focus, i.e. to develop a model that consists of socio-technical elements of CED and their inter-relationships (STAM). The model development was aimed to provide knowledge on the phenomena of CED from a socio-technical perspective. The model development was limited to a CED practice in an ETO company specialises in the design and manufacture of complex technical systems.

Part 2. Model development

5. Industrial investigation

To identify socio-technical elements of CED and their inter-relationships within the boundary of the study explained in Section 4.5.5, an industrial investigation was conducted in Company 1. As explained in Section 1.1, Company 1 is an ETO company, specialising in the design and manufacture of compex technical systems. The company's CED practice was deemed appropriate to provide the basis for developing a STAM of CED due to the following reasons. Firstly, the main motivation of the study was the CED practice in Company 1 (see Chapter 1). Secondly, when the investigation was conducted, the company was just finishing one design project and had just begun a new design project. This meant that both retrospective and current views on the CED practice could be derived from the participants. Having both views could mitigate potential bias and information inaccuracy, and thus, increase the data reliability (Miller, Cardinal and Glick, 1997).

This chapter aims to report how the investigation was conducted and how the findings from the investigation were used as the basis to refine STAM-1 to STAM-2. The organisation of this chapter is as follows; In Section 5.1, the process of data collection is presented. In Section 5.2, the process of data interpretation and analysis is presented. In Section 5.3, findings obtained from the investigation and how the findings were applied to develop the model is reported. In Section 5.4, the second version of the socio-technical architectural model of collaborative design is presented. The summary of refinement to STAM-1 is outlined in section 5.5. This chapter is concluded with a summary of work and a discussion, highlighting lessons learned during the industrial investigations. They are presented in section 5.6.

5.1 Data collection

The data was collected through interviews (Section 2.2.1). The interview type used during the industrial investigation may be categorised as an exploratory semi-structured interview. In an exploratory semi-structured interview, "The interviewer introduces an issue, an area to be charted or a problem complex to be uncovered, follows up on the subject's answers, and seeks new information about and new angles on the topic, instead of testing hypotheses" (Kvale 2007, p.38). The study aimed to identify the elements of CED from a socio-technical viewpoint. As discussed in Chapter 4, socio-technical can be regarded as a new perspective (i.e. "angle") to understand the CED phenomenon. In this sense, the aim of the study aligns with the aim of exploratory semi-structured interview, and thus, exploratory semi-structured interview was adopted.

Several limitations of exploratory semi-structured interview were identified. To address these limitations, actions were applied. They are outlined in Table 5.

Table 5 Interview limitations and action plan

Limitations	Actions
The interviewee's answers may be incomplete or unclear (Best 2014)	Probed and prompted (Best 2014), through: Repeating question; Rephrasing question; Asked follow-up questions (Creswell 2007), such as, "what do you mean by…".
Can be subjective and biased (Valenzuela and Shrivastava 2009)	Interviewed other people with different roles for multi-perspectives.
Mainly based on interpretation (Kvale 2007) of both interviewer and interviewee	Clarified interviewees response during the interview (Kvale 1996) Sent the interpretations to the interviewees after the interview Verified the interpretations with different groups of participants (e.g. academics), used different approach (i.e. workshop).
Social factors such as trust and relationship can influence the response of the interviewees (Fontana and Frey 2000; Best 2014)	Built rapport (Silverman 2011), through: Ice-breaking conversation, i.e. start the interview with small talk that is outside the research topic; Maintained eye-contact

The interview was conducted in three stages with different aim and involving different participants. The structure of the interview and the type of questions asked are explained in Appendix 2: Interview structure.A set of open-ended questions were prepared as guidance, allowing new questions to rise from the interviewees' response (Kvale and Brinkmann, 2009). An audio recorder was used to capture the interviews, with consent from the interviewees.

At the early stage of the data collection, to acquire participants (interviewees), recommendations were asked to the industrial supervisor (i.e. the company's employee who is responsible to supervise the industrial investigation). The desired profile of the interviewees was people who participate in the company's CED process and have different roles to obtain multiple perspectives. From the industrial supervisor, four interviewees were nominated. These interviewees were then asked to nominate their peers. The remainder of the interviewees were obtained using the same peer-nomination approach.

The interviews were terminated when the saturation point was reached. As Kvale (2007) remarked, when the interview is conducted to explore a phenomenon of something, the saturation point can be used as the end-point. Saturation point may be defined as the point where new knowledge is considered seldom, or no longer obtained (Kvale 2007). Marshall et al. (2013) defined it as the point where the information obtained from the interview becomes redundant. During the industrial investigation, saturation point was considered reached after the 25th interview. However, according to Marshall et al. (2013, p.14), "…to justify data saturation, it would require a researcher to conduct several interviews past that point (to indicate that the data set is indeed becoming redundant)". Owing to this, the interviews were continued. After conducting three additional interviews with relatively little new information obtained, the interviews were terminated.

In total, twenty-eight interviewees with various roles and responsibilities were interviewed. This number fulfilled the general recommendations for qualitative interview data collection identifiable from the literature. For example, in their study of identifying sample size in qualitative research, (Marshall, Bryan; Cardon, Peter; Poddar, Amit; Fontenot, (2013) suggested a general rule of between 20-30 interviews for grounded theory qualitative studies and 15 to 30 interviews for a single case study. Around a similar range, Adler and Adler (as cited by Baker and Edwards, 2012) recommended 12 to 60 with 30 being an average, while Kvale (2007) suggested five to 25 interviews depending on the availability of time and resources.

The list of the interviewees, their roles and years of experience are listed in Appendix 3: Profile of IP-1. To manage their anonymity, each interviewee was assigned with a specific code of identification. The codes were used to identify the interviewees throughout the thesis. The code for each participant is also listed in Appendix 3: Profile of IP-1.

5.2 Data analysis

Prior to data analysis, the data obtained from the semi-structured interviews was transcribed to log the conversations in a detailed manner. The transcription process is explained in Section 5.2.1. The transcriptions were analysed by *coding* and *condensing* the interview transcriptions, described in Section 5.2.2.

5.2.1 Transcribing

Transcribing may be described as a process to transform recorded oral conversation into written text (Kvale and Brinkmann 2009; Bernard and Ryan 2010). In the study presented in this thesis, the recorded conversations were replicated word-for-word. This is called "verbatim transcription" (Poland, 1995). Verbatim transcription was conducted to ensure that no information mentioned during the interview was overlooked in the analysis process.

The process of transcribing was carried out by the interviewer (i.e. the researcher) for data familiarisation purposes. Familiarity with data can be considered as an "important first step in data analysis" (Bailey 2008, p. 129). The interviewer is a non-native English speaker, and as such, there was a possibility of error transcriptions, meaning the transcription may not be accurate. To minimise error in transcriptions, two approaches were taken. Firstly, the interviewer sent the verbatim transcriptions to the interviewees for their review. Secondly, the recorded interviews were given to a professional English transcriber for re- transcribing under confidentiality agreement. The transcriptions from the interviewer and the native English speaker were then compared. Due to the length of the transcriptions, and to retain confidentiality, they were not attached in this thesis. They may be made available upon request.

5.2.2 Analysis

To identify the socio-technical elements of CED and their inter-relationships from the interview transcriptions, they were coded and condensed (Kvale, 2007). In a qualitative study, *coding* and *condensing* are essential as they enable researchers to "…retreive the most meaningful material, to assemble chunks of data that go together… into readily analyzable units" (Miles, Hubeman and Saldana, 2014, p.73).

Coding (or categorisation) entails assigning specific codes into the interview transcription. A code may be defined as a keyword that represents the idea or concept of a sentence(s) and/or word(s) (Saldana, 2009; Gibbs and Taylor, 2010). To create codes, two methods were identified in the literature (Miles, Hubeman and Saldana, 2014): 1) deductive coding, where initial codes were developed beforehand based on, for example, theoretical understandings and conceptual framework, and 2) inductive coding, where codes emerge from the data. In the study reported in this thesis, both methods were employed.

Deductive coding was employed to identify the existence of the initial codes in a CED practice. The initial codes and their definitions were grounded on the socio-technical elements identified from the literature review (Chapter 4). The initial codes and the definition of each code is outlined in Table 6. These codes were assigned to any part of the interview transcriptions that were considered align with the code definitions, including synonyms. If a word or sentence replicates the term in the initial codes, it was coded as it is. For example, from the excerpt presented in Table 7, "personality" ([1]) was coded under the same term, as personality was identified in the initial codes. However, if a word or sentence is a synonym of an initial code, it was coded with the term used in the initial code. For example, the word “clash” ([4]) was coded as “conflict” because the terms are synonymous based on their lexical definition (see The Oxford English Dictionary, 2013).

Table 6 Initial coding scheme

	Initial codes	Definition
SOCIAL	Human beings	The main actors of CED (Section 4.2.1).
	Personality	A unique set of characteristics of an individual (Section 4.2.1.1).
	Roles	Functions of human beings (Section 4.2.1.2).
	Natural roles	Roles that relate with the human being’s personality and behaviour (Section 4.2.1.2).
	Assigned roles	Roles that relate with the human being's assigned function and/or hierarchical position in an organisation (Section 4.2.1.2).
	Responsibility	Task required fulfilling that attached to the assigned role (Section 4.2.1.2).
	Interaction	Communication between two or more human beings (Section 4.2.2).
	Conflict	Disagreement, disintegrated (Section 4.2.2, Section 4.3.2).
	Trust	Belief in someone else’s value (Section 4.2.2).
TECHNICAL	Boundary	Acts/objects that limit collaborative design activity (Section 4.3).
	Tools	Devices that are used to support the design process (Section 4.3.1).
	Communication tools	The tools that are used to support communication between collaborative design participants (Section 4.3.1.1).
	Technical tools	The tools that are used support creating visualisations of design (Section 4.3.1.2).
	Design process	The process to transform a design problem into a solution (Section 4.3.2).
	Technical system	Result of a design process (Section 4.3.2).

Throughout the coding process, the initial codes listed above were “inductively adjusted” (Deken *et al.*, 2009, p.3) as new codes emerged from the interview transcriptions. This, may be regarded as inductive coding (Miles, Hubeman and Saldana, 2014). The emergence of new codes was identified based on the following criteria:

1. *An elaboration of the initial codes*. For example, from the excerpt presented in Table 7, "engineers" ([2]) was viewed as an elaboration of "human beings", and thus, was identified as a new code.
2. *Result of the inductive reasoning of the researcher and within the boundary of study* (see Section 4.5.5). For example, from the excerpt presented in Table 7, the following sentence was coded as "behaviour": "…you'll get some engineers that are quite academic and then you'll get this team who's probably more practical…" ([3]) for three main reasons. Firstly, from this sentence, being "academic" and "practical" was perceived as the way engineers act. The way human beings (engineers) act may be generally regarded as behaviour (The Oxford English Dictionary, 2013). Secondly, as behaviour relates to human beings (i.e. their action), it is therefore fulfill the premise of social CED (see Section 3.3). In this sense, "behaviour" was within the second boundary of study (see Section 4.5.5). Finally, the behaviour of human beings was mentioned in the literature as an influencing factor of design outcomes (i.e. technical systems). Technical system is an element of CED (Section 4.2.1.1). As such, behaviour can be seen as an influencing factor of the CED process (the third boundary of study – Section 4.5.5).

Table 7 An example of identifying new codes from an excerpt

Excerpt	Code
I think it more or less just a personality[1] thing, you know, you'll get some engineers[2] that are quite academic and then you'll get this team who's probably more practical[3] and sometimes there is a clash[4] there.	[1] – Personality [2] – Engineers [3] – Behaviour [4] – Conflict

3. *Key influencing factors of CED*. The identification of key influencing factors can be derived from two sources. Firstly, from the statement of the interviewees. For example, INT-6 stated, "…it all hinges on supplier information, when we get that in. If we don't have any supplier information, we can't do the design". From this statement, it can be concluded that suppliers (who provide information) have a significant influence on the CED process. Thus, "supplier" was identified as a new code. Secondly, from the inductive analysis of the researcher. For example, according to INT-6 and INT-26, the customers have an ability to alter the design of the technical system, as they deem appropriate. When the design of the technical system is altered, the design process needs to be restarted. Which means, customers (who have the power of altering the design of the technical system) can significantly

affect the CED process. Based on this, the researcher identified “customer” as a key influencing factor of CED, and thus, a new code.

A further example of coding can be seen in Appendix 4: Coding and condensing example.

By applying *coding* criteria as exemplified above, a number of new codes emerged from the interview transcriptions. They were narrowed down by clustering based on common properties. For example, communication, negotiation and clarification can be clustered as *interaction* as they can be similarly related to reciprocal action between human beings, while perception, interpretation, and understanding can be clustered as *cognitive* as they can be related to human being’s intelligence and the way of thinking. Using the new-clustered codes, the interview transcriptions were re-coded. At the end, 116 codes (i.e. socio-technical elements) were derived.

The identified codes were grouped into a smaller number of categories to develop key socio-technical themes from the interview data. This was done to compare the themes with the key socio-technical elements derived from the definition of CED (Chapter 3). For this, codes were assembled based on their context commonality. For example, “personality” and “behaviour” were discussed as properties that characterised human beings, while engineers as an elaboration of human beings. Thus, these codes were grouped in “human beings” theme. Conflict, however, was discussed in two contexts, disagreement/ incompatibilities between human beings (social conflict), and disagreement/ incompatibilities between the design of technical systems (technical conflict). Hence, “conflict” cannot be grouped under human beings or technical systems only. As such, codes discussed in more than one context (such as “conflict”) were assigned as a new theme. From the categorisation, nine themes were resulted: human beings, interaction, conflict, organisation, boundary, design information, tools, technical system, and design process.

The list of the final codes, their definitions, and themes can be seen in Appendix 5: Codes.

Condensing involves compressing long statements to elicit the main meaning(s) of a statement (Kvale, 1996). In the study presented here, condensing was conducted to identify the relationship between the elements of CED. For this reason, condensing was only applied to the sentences that contained codes (i.e. social and/or technical elements). By eliciting the meaning of a statement that contains social and/or technical elements of CED, the relationships between the elements can be identified. For example, the excerpt shown in Table 8 indicates that the differences in engineers’ behaviour (i.e. being academic and being practical) relates with their personality. Thus, the excerpt can be condensed into “engineers’ behaviour is related to their personality”. From this condensation, three relationships can be derived: 1) enginers have behaviour, 2) engineers have personality, and 3) personality and behaviour are related.

Table 8 An example of condensing a statement

Excerpt	Code	Condensation
I think it more or less just a personality[1] thing, you know, you'll get some engineers[2] that are quite academic and then you'll get this team who's probably more practical[3] and sometimes there is a clash[4] there.	[1] - Personality [2] - Engineers [3] - Behaviour [4] – Conflict	Engineers' behaviour is related to their personality

Further example of condensing can be seen in Appendix 4: Coding and condensing example

Similar with *coding*, the process of *condensing* was done until relevant sentences (i.e. sentences containing socio-technical elements and their relationships) had been identified and condensed. From this process, thirty-three relationship types, which connect different codes, were obtained. The relationships are listed in Appendix 6: Relationships between codes. The model was built based on the identified codes and their relationships, which will be explained in Section 5.3.

It should be noted that the analysis process was conducted by the researcher only due to confidentiality issue. This was considered as a limitation of the study. To verify the researcher's interpretation, the data analysis process and the model was presented to a group of CED participants in Company 1. Four group members were previously involved as interviewees, while five were not. The group was asked to briefly review the model. No disagreement on the elements and inter-relationships were mentioned. Thus, it can be concluded that the interpretation of the researcher was verified.

5.3 Development of STAM-2

In Section 5.1 to Section 5.2, the process of data collection and data analysis during an industrial investigation in Company 1 was presented. In this section, how the results from the analysis process was used to develop the second version of the architectural model is described. The descriptions are divided into two main sections. Those in Section 5.3.1, that describe the basic concept of the model (e.g. the structure), and those in Section 5.3.2, that describe the content of the model (e.g. the socio-technical elements).

5.3.1 Concept of the model

Having obtained the codes, it became clear that not all the identified elements could be clustered into one level of category. For example, stakeholders (one code that was identified) can be perceived as a sub-division of human being (another code that was identified), while personality (a further code that was identified) as a property of human beings. Thus, stakeholders, personality, and human beings cannot be grouped in the same category. For this reason, the identified codes were further categorised and three categories were resulted: **main elements, sub-elements,** and **properties** that characterise the said elements. In the example above, the human being would be the main element, the stakeholder would be a sub-element of human beings, and the personality would be the property of human beings and stakeholders (as the sub-element of human beings). The categorisations of the identified elements are listed in Appendix 7: Categorisation of results from meaning coding.

In comparison with *coding*, a simpler categorisation of outcomes was derived from *condensing*. Only one category was identified from the outcome of *condensing*, i.e. relationship.

To develop the model that consists of main elements, sub-elements, properties, and relationship between the elements, the utilisation of boxes, lines, and arrows, as seen in the first version of the model (Chapter 4) was considered inappropriate. For this reason, the utilisation of a formal modelling language was investigated, presented in Appendix 8: Information modelling language review.

From the investigation on formal modelling language, EER was selected as a formal modelling language to develop the socio-technical model of CED. According to EER, a model may be constructed of entities, sub-entities, attributes, and relationships (Appendix 8: Information modelling language review). These were aligned with the categorisation of socio-technical elements, resulted from analysing the industrial investigation transcriptions (i.e elements, sub-elements, properties that characterise them and relationships).

5.3.2 Content of the model

In this section, the identified socio-technical elements and their inter-relationships (i.e content of the model), and how they were used as the basis to develop STAM is presented. The presentations are divided into nine sections (i.e. from Section 5.3.2.1 to Section 5.3.2.9), following the nine themes as identified and outlined in Section 5.2.2.

5.3.2.1 Human being

In Chapter 4, a human being was identified as the main actor that conducts the collaborative design process. The industrial investigation revealed that human beings own various attributes, i.e. properties that characterise them as individuals and influence their action towards others. Seven attributes were elicited from the transcriptions of the interviews. They can be explained as follow:

a. Cognitive

When designing a complex system, people have their own point of view (INT-3; INT-5) and they interpret information differently (INT-19). Different interpretations (i.e. cognitive) and points of view can be influenced by experience. As INT-26 stated, “A lot of people are…deliver the next ship based on their experience from the last.” This may influence their actions towards the design. For example, because of the different points of view and interpretations, designers may locate the same piece of equipment in a different place (INT-5).

b. Affective

Affective, within this context, refers to emotion and feeling. The interviews implied that being affective could correspond to various factors in collaborative design activity (e.g. tasks and company’s new policy). However, the correspondence between affective towards other people’s behaviour was mentioned more frequently. An example of the correspondence between affective and behaviour was mentioned by INT-12 during the interview, “…if you keep telling people that they are late, they start to get a bit demotivated…” In other words, demotivation (i.e. affective) can be resulted if a negative behaviour is shown.

Affective also leads to a specific behaviour. This can be concluded from several interviewees’ statements. As an example, INT-4 stated that they would call or communicate face to face if they need to solve an issue because they are “annoyed” with the way people communicate through email and the lack of accountability that comes from using email (people claiming to not have received messages, for example). In this sense, INT-4’s communication behaviour is led by their feeling towards other people’s behaviour.

c. Assigned role

Identified in the industrial investigation, an assigned role was referred to the role appointed by the company, related to the hierarchical position and organisational structure (as stated by INT-26). A role is often characterised by the responsibility that is attached to it. For example, principle engineers are characterised by their responsibility to ensure the integration and consistency across the ship design (INT-2). To assign roles, the company looks at a variety of parameters such as level of experience (as discussed by INT-1 and INT-13), and cognitive-related aspects (e.g. knowledge and skill) (as discussed by INT-4 and INT-12).

d. Personality

INT-27 believes that it is more challenging to adapt with different personalities than different skills. Furthermore, INT-12 remarked that skill can be developed through training. However, personality is unalterable, and thus needs to be understood. The topic of personality often emerged during the discussion regarding social challenges in collaborative design practice. Personality differences were mentioned as one of the causes of clashes. INT-9, INT-10, INT-11 and INT-19 similarly pointed out that personality differences can lead to different solutions for completing tasks. INT-2 and INT-18 stated that personality also influences human being's communication style (e.g. a face-to-face communication versus email). Personality was also mentioned as an influencing factor to the way a human being deals with their problem (INT-20). The way human beings complete their tasks, the way they communicate, and how they are dealing with problems can be related with human being's design behaviour. Concluding from this, personality can be viewed as an influencing factor to a human being's behaviour that eventually influences their success to accomplish a design task.

e. Socio demographic

Socio-demographic may be defined as the profile of a human being related to their demographic and sociological characteristics. Based on this definition, the attributes of human beings derived from the interview that can be categorised as socio-demographic were age, tenure, experience, and gender.

From the interview results, it was seen that the socio-demographic profile of a human being influences collaborative design practice through its effect on behaviour. For example, the experienced population tends to resist more to changes such as the utilisation of new information system and changes in process, when compared to the less experienced population (INT-3; INT-22). The experienced population also tends to have less social interaction with their colleagues than the less-experienced population (INT-9). The less-experienced population tends to be more enthusiastic than the experienced population (INT-3; INT-23; INT-27), and finally, experienced employees tend to be more technical than those with less experience (INT-3). In this case, the differences between experienced and less-experienced population can be related to, although not always, age. The evidence of the way gender influences the "human being" group was not mentioned explicitly in the interview. However, INT-24 and INT-15 pointed out their concern regarding the small number of female engineers involved in the project. As such, gender was seen as an influence on the collaborative design activity.

f. Priority

In the context of the study documented in this thesis, priority was regarded as things perceived by human beings to be more important than others. Priority is determined by their role and responsibility in the company. For example, INT-3 and INT-5 similarly mentioned that "function people" (i.e. people sitting at management level) often focussed on corporate-related issues such as what is good for the company, and what is needed in the future. On the other hand, "project people" focussed on the success of their project. Different priorities can be identified among project people in different teams, as mentioned by INT-27 and INT-28. Since human beings have different properties, their behaviour in collaborative design differs in accordance to their priorities, and thus conflict can occur (as mentioned by INT-10; INT-19; INT-25; INT-26).

g. Conative

Having analysed the aforementioned attributes of a human being it can be concluded that all of them influence the conative attributes of human being.

Applying the graphical notations of EER (Appendix 8: Information modelling language review), the human being and its attributes can be depicted by Figure 17.

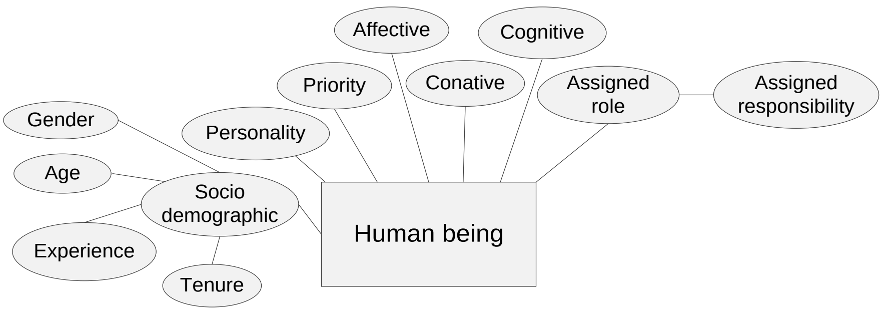


Figure 17 Human being and its attributes

In Chapter 4, the term "human beings" was generally defined as the main actor of CED, and thus, were used to represent it. However, during the interview, the term stakeholders was revealed as a more specific term that can be used to represent the main actors of collaborative design. For example, INT-3 mentioned that due to the complexity of the technical system, it involves a mix of skilled stakeholders to design it.

The industrial investigation indicated that stakeholders not only have interest and are affected by “what the team does” they are also involved in it (i.e. conducting CED practice). As INT-22 stated, “[in collaborative design practice] we have a number of different stakeholders that involved through [out] the design process…” Based on this, within the context of collaborative design, stakeholders may be referred to all human beings who are involved in collaborative design practice and who are affected by it. From this perspective, stakeholders can be viewed as a division of the human beings. This can be represented by a superclass/subclass relationship (see Appendix 8: Information modelling language review), as depicted by Figure 18.

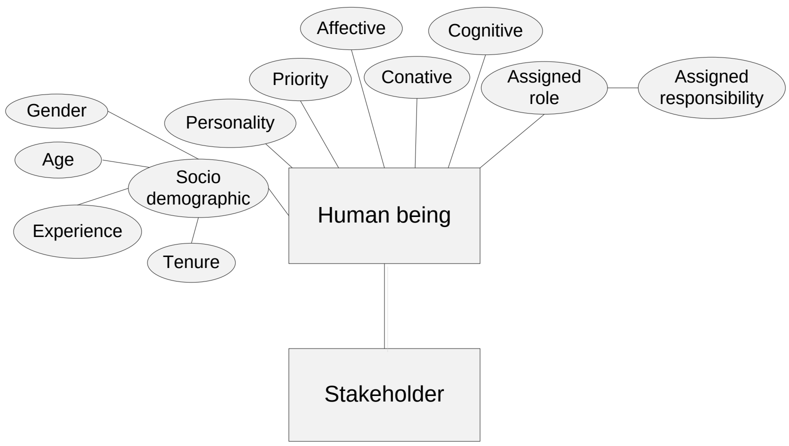


Figure 18 Relationship between stakeholders and human being

As stakeholders were seen as a subclass of human beings, they inherit the attributes of human beings. However, the stakeholder also has attributes that differentiate it with other human beings. Firstly, stakeholders are employed by different organisations. Secondly, stakeholders are located in different locations. For example, as indicated by INT-26, “…we [engineers] interact with different sites, the specialist and I interact with [a street’s name], which is the [customer name] centre, about a mile and a half down the road.” The location relates with the location of the organisations that employed them. Thirdly, each stakeholder has different interests towards the design and its process, and thus their involvement and influence may vary. For example, customers and users are involved in the design process by providing design information and reviewing the design of the technical system (INT-1; INT-11; INT-13; INT-18; INT-19; INT-23), while suppliers by providing information regarding a part of the technical system (e.g. equipment) being designed (INT-18).

With respect to the influence of customers and users on collaborative design practice, according to INT-6 and INT-26, the customers have an ability to alter the design of the technical system, as they deem appropriate (INT-6). Although not as strong as the influence of the customers, suppliers have a significant role in the design practice. As INT-6 stated, "…it all hinges on supplier information, when we get that in. If we don't have any supplier information, we can't do the design".

In summary, stakeholders are employed by different organisations, based at different locations, and have influence, interest and involvement towards the design of the technical system and its process. These can be identified as characteristics of stakeholders and can be utilised to differentiate stakeholders from other subclasses of human beings. From this perspective, <u>employer</u>, <u>location</u>, <u>influence</u>, <u>interest</u>, and <u>involvement</u> can be categorised as the attributes of <u>stakeholders</u>.

Stakeholders share a common goal in collaborative design practice. As INT-26 stated, "we're working towards the same goal" which is to design a technical system. To achieve the goal, stakeholders share any risks associated with the design and its process. For example, as mentioned by INT-19, if there is any delay with the schedule because of rework, stakeholders share the consequences (e.g. increase in cost, delay in delivering the product).

Two types of stakeholders can be derived from the industrial investigation: <u>internal</u> (i.e. employed by Company 1) and <u>external</u> (i.e. employed by other companies) stakeholders. The difference was identified as sub-classes of stakeholders. A stakeholder can be an employee of merely one company, even though they work closely with another company. In this sense, a stakeholder can only be an internal or external stakeholder. Thus, the relationship between <u>stakeholders</u> and its sub-elements can be considered disjointed. This is depicted by Figure 19.

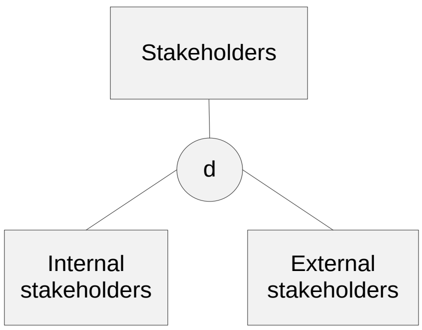


Figure 19 Relationship between stakeholders and its subclasses

During collaborative design, internal and external stakeholders interact with each other for a number of purposes, to exchange design information (INT-2) and to review the design of the technical system (INT-4; INT-22) for examples. Such interactions may be conducted in two scenarios: formally (e.g. a formal monthly meeting to review the design) or informally (e.g. brief passing discussion). These different interaction scenarios define the type of interaction in collaborative design practice (i.e. formal and informal). INT-5 believed that the formal interaction is more structured and rigid than the informal ones. The industrial investigation indicated that because of this, collaborative design practitioners favour informal conversations more than formal ones (INT-5; INT-20).

Regardless of its type, the interaction in collaborative design requires communication (as indicated by INT-15; INT-18; INT-20) and trust (as indicated by INT-1; INT-6; INT-14).

The types (i.e. formal and informal) and requirements (i.e. communication and trust) of interaction can be utilised to characterise interaction in collaborative design practice. Thus, in the model developed here, these types and requirements can be considered as the attributes of interaction.

INT-18, an engineer in Company 1, mentioned that, as internal stakeholders their main responsibility is to ensure that the design quality is in accordance to the customer's requirement and that the collaborative design process is conducted as planned. For this, they are required to coordinate closely with customers and suppliers. As such, internal stakeholders may be viewed as the host of CED. This means, they act as the main coordinator throughout the practice. The internal stakeholder's role as a host in collaborative design practice differentiates them with external stakeholders. Thus, host can be identified as an attribute of internal stakeholders.

In Company 1, internal stakeholders are divided into different teams. It was mentioned that the teams' division was based on the stage of design process (e.g. stage 1, stage 2), as well as the specific area of the technical system (e.g. electrical, platform, or combat system). Internal stakeholders can be characterised by the team they belong. Each team has individual objectives, even though they work under the same organisational structure and have a common goal (i.e. to design a complex engineer-to-order technical system). For example, INT-2 explained that the functional design team has the objective to design equipment based on the customer's requirements, while the spatial design team has an objective to design a space that fits all the required equipment. These objectives can be used to distinguish between one team and another. Individual objectives are often utilised as a parameter to measure the team and individual performance in Company 1. Team division, objective, and performance were identified in internal stakeholders only. Their existence in external stakeholders was not indicated in the interview.

The industrial investigation suggested that internal stakeholders can be divided into two types, based on their skill and mind-set:

1. Engineers mainly focus on the technical side of the design and its process (e.g. mechanical engineer, electrical engineer, piping engineer, system engineer). INT-6 regarded an engineer as being technical-minded. Their skill is predominantly engineering-related, which can be categorised as "hard skills". Being technical-minded and having hard skills were highlighted as the main differences between engineers and non-engineers, and as such were identified as attributes of engineers.
2. Non-engineers mainly focus on the commercial/social side (e.g. marketing and supply chain). INT-2 regarded a non-engineer as being commercial-minded. Contrarily to engineers, the non-engineers skill is dominated by, what can be categorised as, soft-skills (e.g. management, communication). Being commercial-minded and having soft skills were highlighted as the main differences between non-engineers and engineers. Thus, these differences were identified as attributes of non-engineers.

To design a technical system, engineers and non-engineers interact with each other. For example, because "There's also areas like risk and cost estimating…that we [engineers] interact with, in relation to our scope of work" (INT-25), engineers need to interact with, for instance, legal and finance personnel. An evidence that an internal stakeholder can be both an engineer and a non-engineer, for example, an engineering designer is also a finance officer, cannot be identified from the industrial investigation. Thus, it can be concluded that in this investigation, an internal stakeholder only had one role, i.e. an engineer or a non-engineer. Based on this, the relationship between internal stakeholder and its subclasses (i.e. engineer and non-engineer) can be considered disjointed (depicted by Figure 20).

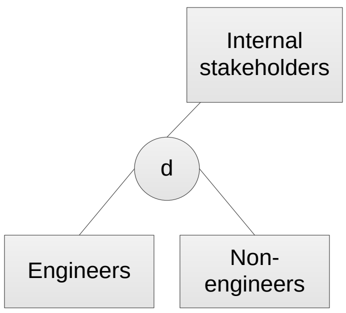


Figure 20 Internal stakeholders and its subclasses

In contrast with the internal stakeholders, the external stakeholders are not the main coordinator of the collaborative design practice. From the industrial investigation, customers, users and suppliers were identified as the divisions of external stakeholders of collaborative design practice (depicted by Figure 21). Customers, users, and suppliers are three different entities. Although user is mainly represented by customers during the interaction with Company 1, user and customer were seen as two separate entities. The indication that a stakeholder can have two different roles (e.g. a supplier and a customer) was not evident from the industrial investigation. As such, the relationship between external stakeholder and its subclasses was deemed disjointed. The relationship between external stakeholders and its subclasses are depicted by the following figure (Figure 21).

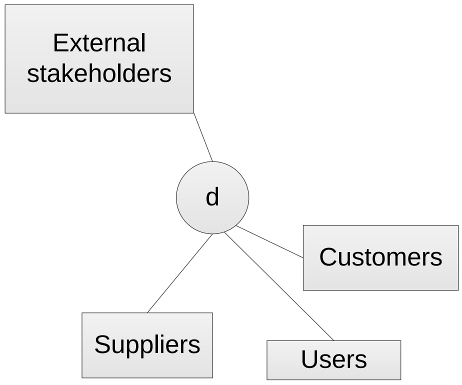


Figure 21 External stakeholders and its subclasses

As discussed above, external stakeholders are involved in the design practice and they can influence the design of the technical system. The level of involvement and influence are determined by the host of collaborative design practice (i.e. internal stakeholders). To differentiate the role with the internal stakeholder, the external stakeholder is viewed as the guest of collaborative design practice. This was identified as an attribute of external stakeholders.

In the specific case of Company 1, customers sit at the company's site, closely engaged in the collaborative design practice. According to a customer (INT-2), this is done to ensure that the design of the technical system complies with their requirements throughout the design process. This level of engagement, according to INT-9, helps to reduce "design change and reworking." It is also perceived as a manifestation of the customers' commitment towards the design and the process of designing (as indicated by INT-26) and as such, it differentiates them (the customers) with other subclasses of external stakeholders.

Customers are committed to the collaborative design activity due to their interest in providing the systems that can fulfil the needs of their users (as implied by INT-2). Thus, the customers' satisfaction can be influenced by the users' satisfaction. This interest and satisfaction can be seen as the customers' characteristics as they could not be identified in the characteristics of users and suppliers.

To ensure that the technical system being designed fulfils the needs of the users, customers, and users interact closely. In Company 1, users are represented by customers in terms of communication with the company. Hence, from the Company 1 viewpoint, one of the aims of designing a technical system is to fulfil the needs of the customers (INT12; INT-19; INT-23; INT-26).

According to a supply chain officer in Company 1 (i.e. INT-16), during the design process, suppliers are asked to provide information (i.e. specification, delivery time and price) about the equipment requested by Company 1, to fulfil the requirements given by the customer. The suppliers are selected to supply the equipment when the design enters the manufacturing stage. The selection is based on suppliers' performance, rated mainly by product quality (e.g. compliance with specifications, reliability), delivery time and price. Such performance indicators become the characteristics of suppliers that can be used to differentiate: 1) one supplier to another, 2) suppliers and other subclasses of external stakeholders (i.e. customers and users). As such, performance and its subclasses (i.e. product quality, delivery time, and price) can be viewed as attributes of suppliers.

Based on the exaplanation above, an architectural model of human beings in CED activity was constructed, depicted by Figure 22.

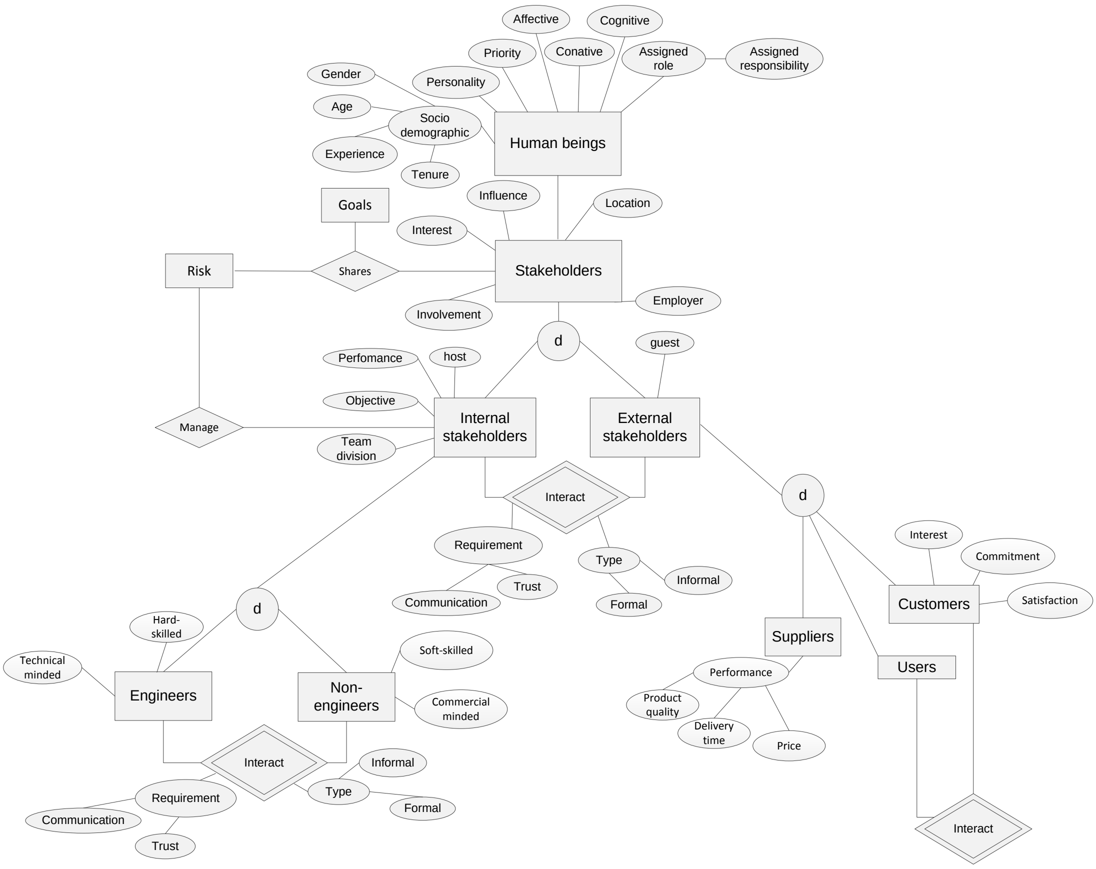


Figure 22 Architectural model of human beings

5.3.2.2 Interaction

Indicated in the industrial investigation, interaction is a way to build a relationship, with the term "relationship" defined as "the state of being connected" (The Oxford English Dictionary, 2013). As an example of this, INT-18 expressed how their supply chain officer encountered a supplier at a company event, socially interacted with them and from there established a good working relationship. In this sense, without interaction, a relationship between a supply chain officer and a supplier may not have been established. As such, it can be concluded that a <u>relationship</u> exists if there is an <u>interaction</u>, whether it is between <u>internal</u> and <u>external stakeholders,</u> <u>engineers</u> and <u>non-engineers</u>, and/or <u>customers</u> and <u>users</u>. The type of relationship between <u>relationship</u> and <u>interaction</u> can be categorised as an identifying relationship in EER, represented by a double diamond graphical notation (depicted by Figure 23).

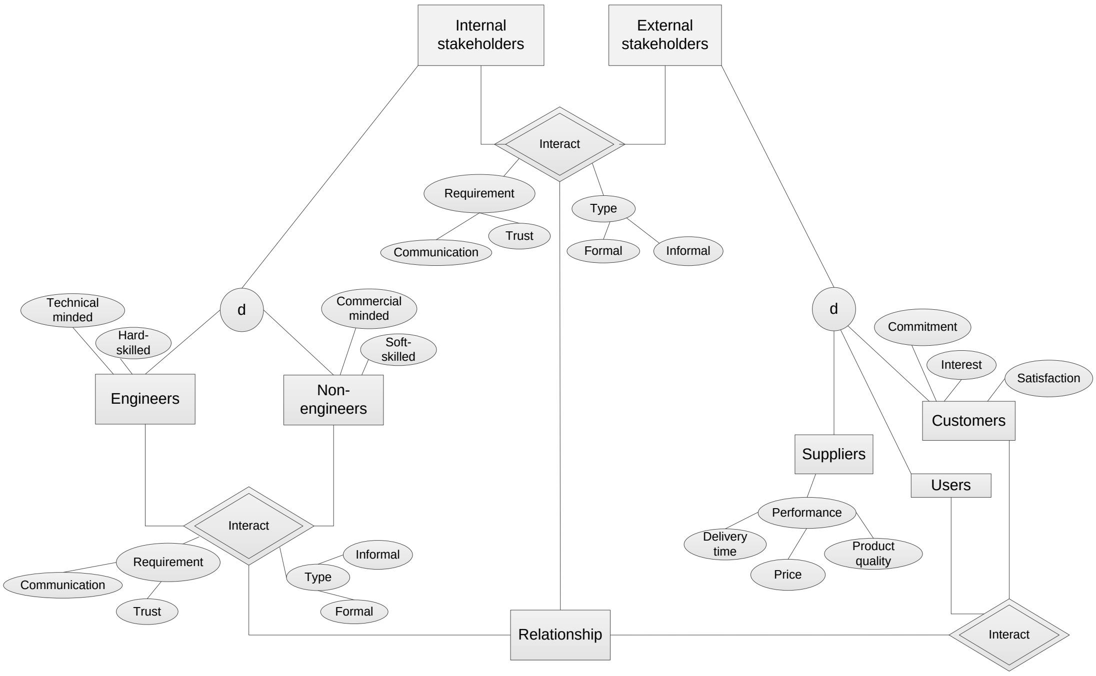


Figure 23 Relationship is generated from the interactions between stakeholders

Two types of relationships were identified from the industrial investigation:

1. Professional relationship, established through a work-related interaction. For example, customers and engineers of Company 1 establish a professional relationship following frequent discussions on the design of the technical system. In this sense, a professional relationship can be characterised as a work-related relationship.
2. Personal relationship, established through non-work-related interaction. As an example, relationships between design team members are established after having a social gathering (INT-13; INT-16). In this sense, a personal relationship can be characterised as a non-work-related relationship.

Depending on the individual, some would prefer to have professional relationship with their peers only. INT-23, for example, stated, "I'd like to keep my personal life from my working life." However, others indicated their determination to establish personal relationships to support their professional relationship. As an example, INT-18 mentioned, "I've been out with the supply chain team…and I've done it deliberately as a relationship building, because I think sometimes that engineering-supply chain relationship needs work." Regardless of this, a stakeholder can establish both types of relationship, personal and professional, regarded as an overlapping relationship. The representation of relationship and its subclasses, and the attributes of each can be seen in Figure 24.

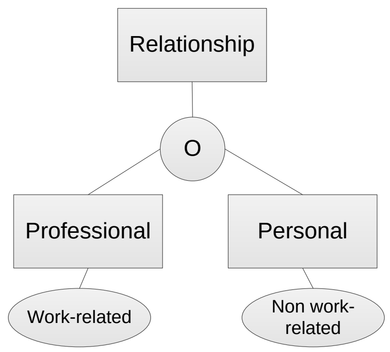


Figure 24 Subclasses of relationship

The interview results implied that personal relationship could potentially enhance the level of trust between participants. INT-2 believed that teams that know each other better and have established a good connection would feel more comfortable to work together and trust each other more compared to those teams without personal relationships. From this perspective, a personal relationship can be viewed as an influence on the level of trust.

Based on the explanation above, an architectural model of interaction was generated, depicted by Figure 25.

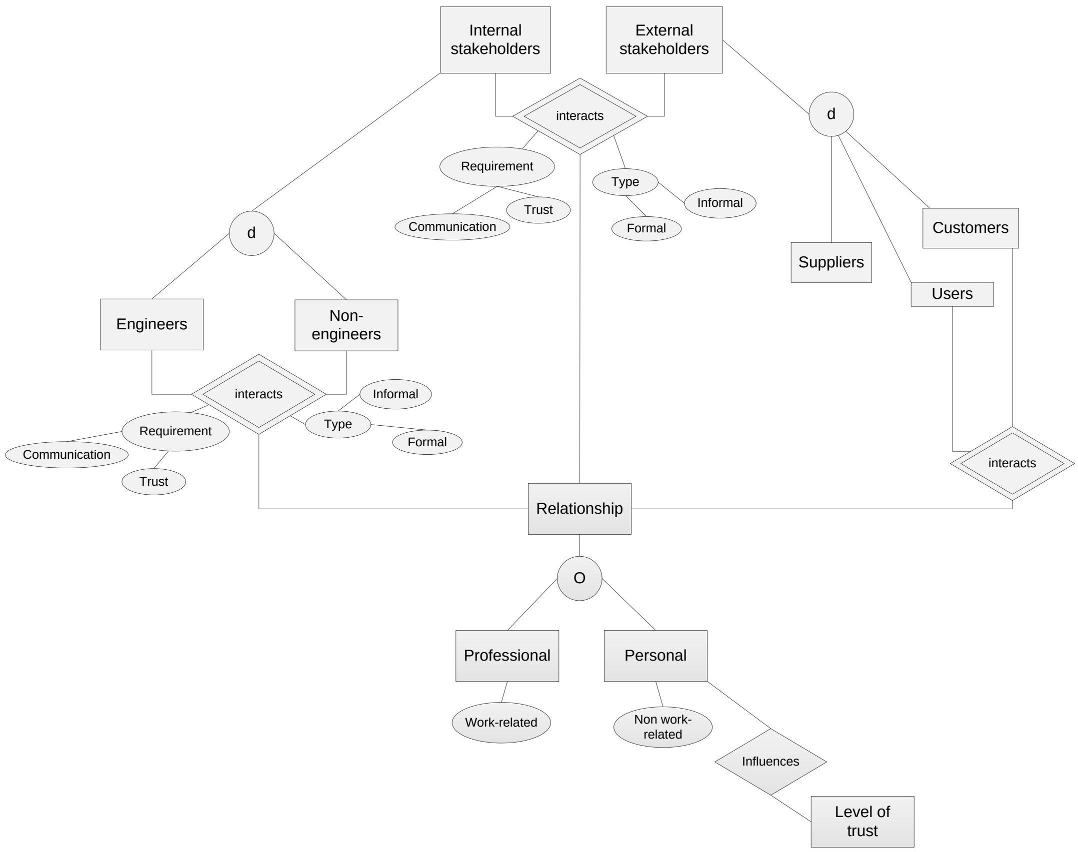


Figure 25 Architectural model of interaction

5.3.2.3 Conflict

The industrial investigation revealed two categories of conflict:

1. Social conflict
   This type of conflict can be characterised as an incompatibility of personalities between participants (i.e. personality clash). For example, a participant with introvert personality may be incompatible with a participant with extrovert personality. From this perspective, personality clash can be considered as an attribute of social conflict.
2. Technical conflict
   This type of conflict can be characterised as disintegrations in the design of the technical system. For example, the dimension of the equipment does not fit the dimension of the structure of the technical system, and thus, they are disintegrated. In this view, disintegrated design can be considered as an attribute of technical conflict.

In the Company 1's design practice, social and technical conflicts are often interrelated. For example, a personality clash can trigger a lack of communication, which eventually causes disintegrated design to occur (as explained by INT-26). This also works in reverse, i.e. disintegrated design can trigger social conflict between design participants (as explained by INT-2). From this perspective, social and technical conflict can overlap, depicted by Figure 26.

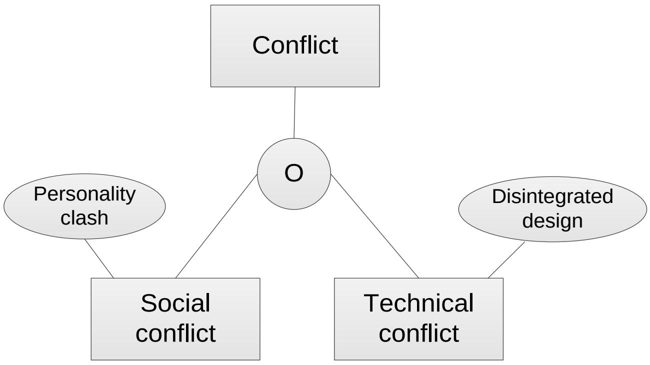


Figure 26 Subclasses of conflict

Several interviewees pointed out the effect of social conflict to the design process. INT-26, as an example, stated, "Stakeholders who have personality clashes often refrain from communicating with each other." This hampers the relationship between the conflicted design participants. Likewise, technical conflict can hamper relationships. As INT-2 remarked, "…when you start to get a spatial team to try and place equipment or try and place a pipe into the ship CAD model, and it doesn't fit, we have to go back and ask, the guys that are responsible for the functional design, what do you want us to do with this? And that's where a bit of your social breakdown happens." In this sense, technical conflict, i.e. a pipe not fitting into the structure of the system, triggers conflict between the design participants (i.e. between spatial designers and functional designers), and cause a problem in their relationship. Thus, despite the type, conflict can be viewed as an obstruction to a relationship.

As conflict was perceived as an obstruction of a relationship between design participants, it can potentially influence the design practice (indicated by INT-18; INT-20). Company 1 often releases new policies to overcome it. For example, INT-10 mentioned, Company 1 introduced new team divisions, based on the major areas of the technical system, intending to address disintegrated design that often occurred. In this sense, conflict can be seen as a motivation of a new policy.

Based on the discussion above, an architectural model of conflict can be derived, illustrated by Figure 27.

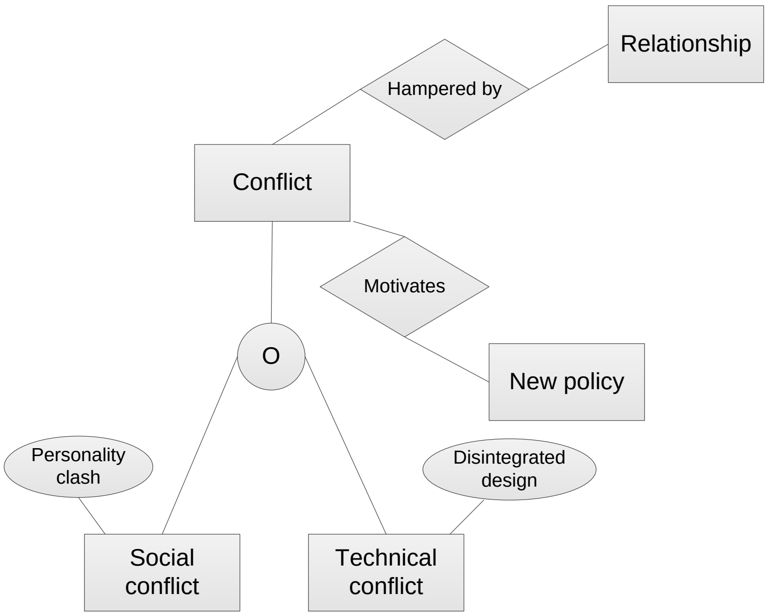


Figure 27 Architectural model of conflict

5.3.2.4 Organisation

As mentioned in Section 5.3.2.1, stakeholders are employed by different organisations. The evidence that a stakeholder is independent (i.e. does not belong to any organisation) was not identified in the industrial investigation. From this perspective, it can be concluded that all stakeholders involved, belong to an organisation. It needs to be noted that in this context, organisation was broadly defined as a group of people with purpose, not limited to a specific type of organisation.

From the industrial investigation, seven attributes of organisation were derived. They can be explained as follows:

a. Business type

Within the study documented in this thesis, business type refers to the industry in which the organisation specialises. Company 1, for example, specialises in the design and manufacture of complex engineer-to-order technical systems. The industrial investigation indicated that the way a company conducts their collaborative design practice hinges on the company's business type. For example, aviation and ship industries have different design processes (as implied by INT-1). Based on this, two conclusions can be made: 1) business type can describe a specific characteristic of an organisation (e.g. specialised in complex engineer-to-order technical systems), and 2) business type influences collaborative design practice in an organisation.

b. Structure

In the context of the study presented in this thesis, structure refers to organisational structure. In a business context, organisational structure relates to the arrangement (e.g. hierarchical) of functions (e.g. authority, roles and responsibility), and typically directs towards the organisation's goal (Sellitto, 2011). Similar with strategy, structure relates to an organisation's goal, and it can differ from one organisation to another. In this view, structure can be used to characterise an organisation.

Organisational structure was often associated with role and responsibility in the industrial investigation. According to INT-22, roles and responsibilities in Company 1 were assigned based on the employee's hierarchical position in the organisation structure. In this sense, the structure of an organisation can be viewed as a determinant factor of roles and responsibilities. Roles and responsibilities were perceived as influencing factors of collaborative design practice as they influence human being's action and priorities (as discussed in Section 5.3.2.1). As such, organisational structure can be considered an influencing factor of collaborative design practice.

c. Politics

The industrial investigation suggested that Company 1 can be characterised as being heavily influenced by the company and the government politics. INT-26 stated, "…We are caught on politics… there are a lot of political factors, which affect how well we do our business".

The influence of politics in collaborative design practice was discussed during the interviews. INT-1, for example, explained that the company's and the government's political situation drives customer's requirements on the design of the technical system. From this perspective, politics can be considered as an influencing factor of the customer's requirement, underpinning the design of the technical system.

d. History

The industrial investigation indicated that a company can be characterised by their history. Here, history refers to past events that occurred in the company such as the way collaborative design practice was organised in the past. Company 1, for example, was formed from a number of different companies in the past. This is considered as a characteristic that can be used to describe them (as discussed by INT-11).

The industrial investigation suggested that an organisation learns from history. Many historical learning points were identified through a change of strategy. For example, learning from the amount of reworks identified in the past, a strategy to closely involve customers from the earliest stage of the design practice was applied (as discussed by INT-1; INT-11). As such, history plays a major role to define the company's current collaborative design practice (as remarked by INT-26). For this reason, history was presented not only as an attribute, but also as an entity.

e. Location

In this thesis, location refers to physical placement of an organisation. In Company 1's collaborative design practice, stakeholders are distributed in different locations. The design teams, for example, are dispersed in three different cities. In one city, the company has different locations, where each consists of segregated buildings. Having stakeholders located differently was perceived as an obstruction to communication. INT-14 remarked that although technology has helped to support communication between different locations, direct face-to-face interaction is lacking. This, according to INT-15 can be a barrier to "social cohesion". INT-2, INT-7 and INT-16 believed that establishing a personal relationship is relatively easier when two people are co-located.

Location was also viewed to influence a relationship. As discussed by INT-18, "you need to actually, physically make the effort to go down there, they need to make an effort to come here… but if everybody is in the one location…it makes for a better working relationship."

Finally, location was considered as an influence to the culture of a company. For example, INT-26 mentioned that in Company 1, different sites have different working hours, i.e. "One site starts much earlier and tends to finish earlier while another site starts slightly later, finishes later". In this sense, location can lead to culture differences.

f. Culture

The type of culture indicated by the interviewees related to the customs or habits embedded in an organisation. As such, it can be used to characterise an organisation. As discussed in Section 5.3.2.1, culture influences the behaviour of design participants during the collaborative design practice. This can potentially influence the design of the technical system and the process of designing it.

g. Strategy

In the context of this thesis, strategy refers to a plan of an organisation to achieve their goals (The Oxford English Dictionary, 2014). Goals are different between one organisation and another. As such, strategy is considered unique to the organisations, and thus, can be used to characterise it (i.e. attribute). For example, in Company 1, INT-26 discussed one of the current company's strategies to save cost is to consolidate their ship building into a single dock. When this strategy is realised, Company 1 can be characterised as having a single dock.

The influence of strategy towards collaborative design practice can be seen from the following example. INT-26 discussed that one of the Company 1's strategy was focussed on cost saving. To support this, many aspects of the company, including the practice of collaborative design, were changed (e.g. increasing the involvement of external stakeholders). According to INT-20, the company's strategy changes frequently. Consequently, its collaborative design practice needs to be adapted. From this perspective, similar with history, strategy plays a major role to define the company's collaborative design practice.

In addition to the above, a relationship between strategy and history was identified, as discussed in point d, which mentioned, "Many historical learning points were identified through a change of strategy". In this sense, history can be seen as a modifier of strategy.

Organisation and its identified attributes are depicted by Figure 28.

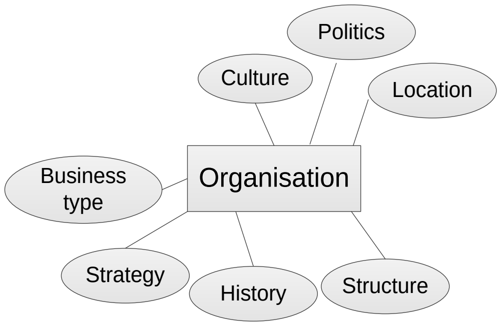


Figure 28 Organisation and its attributes

Indicated by INT-6, INT-16, and INT-19, the design of the technical system must comply with pertinent legislations created by governing bodies such as the government. Legislation, in this context, refers to laws that regulate the design of the technical system. An example of legislation in the design of the technical system is maximum noise level (as discussed by INT-19).

In its most literal sense, a governing body may be defined as a body that governs. From the dictionary perspective, body is a synonym of organisation. As such, governing body can be regarded as a type of organisation. Based on this, it can be concluded that legislation is created by an organisation.

The industrial investigation identified that collaborative design practice is governed by rules that are created by the organisation. The term rules as used in the model refer to the regulations that must be followed by collaborative design participants. For example, the design of the technical system has to be approved by technical authorities (as discussed by INT-26).

Finally, the industrial investigation revealed that an organisation also creates policy relating to collaborative design practice. Policy here refers to the "principle of actions adopted by an organisation" (The Oxford English Dictionary, 2013). It often relates to the implementation of rules. For example, to ensure that the design is approved by technical authorities, a design review process has to be conducted (as discussed by INT-1; INT-4; INT-16).

From the industrial investigation, two divisions (subclasses) of policy were identified:

1. Standardisation

   This subclass of policy refers to a framework to which all parties in the company are required to follow for standardisation purposes. For example, a policy related to design maturity standardises the definition of level of maturity in the design of the technical system, as applied in Company 1 (INT-1, INT-26, INT-27, and INT-28).

2. Guideline

   This subclass of policy refers to a suggestion-based policy for when conducting a specific task. These suggestion-based rules (e.g. how to design) can be customised depending on the need of the design team (as mentioned by INT-16). For example, a policy relating to design rules (i.e. how to design) can be customised depending on the need of the design team (as remarked by INT-1).

The interview results implied that a policy can be both, a standardisation and a guideline. For example, in Company 1, the policy called design maturity can be categorised as a standardisation, as it mainly consists of mandatory parts with required application throughout the design process. On the other hand, it can also be categorised as a guideline as it has parts that can be tailored depending on the stage of the design process (identified from INT-4). From this perspective, the relationship between policy and its subclasses can be considered to overlap, depicted by Figure 29.

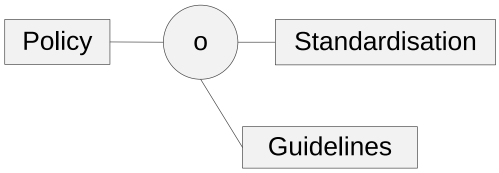


Figure 29 Policy and its subclasses

Based on the explanation above, an architectural model of organisation was generated. The model is shown by Figure 30.

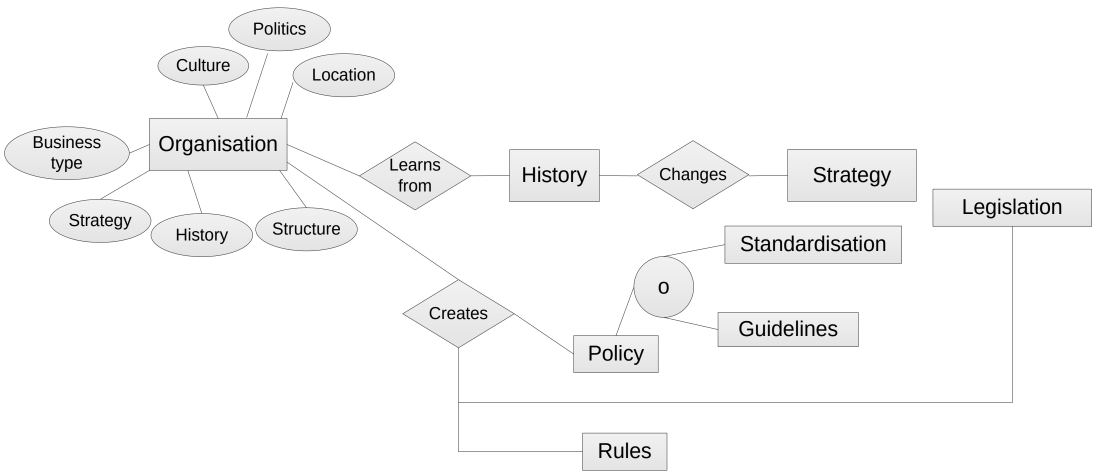


Figure 30 Architectural model of organisation

5.3.2.5 Boundary

As presented in Section 4.3.2, the term "boundary" referred to acts/objects that limit collaborative design activity. The first boundary identified from the industrial investigation was location, which in Section 5.3.2.4 was presented as an attribute of organisation. According to INT-10 (and similarly implied by INT-1, INT-2, INT-6, INT-7, and INT-8), the distributed location of Company 1 (stated in Section 5.3.2.4) makes it challenging to interact on a daily basis. A relationship exists when there is an interaction between stakeholders (see Section 5.3.2.2). As such, to build a relationship between stakeholders located on different sites can be difficult (as mentioned by INT-18). From this perspective, location can be seen as a boundary of relationship.

As said in Section 5.3.2.4, location refers to the physical placement of an organisation and can be characterised by the distance between these physical points. For example, in Company 1, some places are separated within walking distance, a few meters away, while others are separated kilometres away (i.e. in different cities or even countries).

As discussed in Section 5.3.2.4, location was perceived as an influencing factor of culture. Specifically, location can lead to cultural differences.

Two types of culture were derived from the industrial investigation. They can be explained as follows:

1. Organisational culture
   This refers to customs that are embedded in an organisation such as working hours (INT-26), and the utilisation of email as the main means of communication to exchange information (INT-2).
2. Social culture
   This refers to customs that are embedded in the society such as language and behaviour (INT-3).

The type of culture aforementioned can be considered as a division (i.e. categorisation) of culture. In this perspective, organisational and social can be viewed as subclasses of culture. Additionally, the type of culture can be considered as an attribute that describes the culture difference. In other words, organisational culture and social culture can be used to explain the culture difference in collaborative design practice. If type was considered an attribute of organisation, its division (i.e. organisational or social) can be considered as sub-attributes. However, the relationship between the aforementioned types of culture to the other elements of collaborative design practice was not evident from the industrial investigation. On this basis, type was presented as an attribute of a culture difference, instead of a subclass.

The industrial investigation revealed culture difference as a cause of conflict, i.e. an influencing factor of the design process (see Section 5.3.2.3). For example, different arrangements of working time between different sites can cause conflict between design team members (as mentioned by INT-26).

The second boundary identified from the industrial investigation was rules (i.e. regulations that must be followed by collaborative design participants (see Section 5.3.2.4). Rules bound collaborative design practice through its influence to relationship between the design participants. For example, as discussed by INT-16, in Company 1, engineers are not allowed to contact the suppliers directly. They argued that such a rule limits the relationships between engineers and suppliers. This can potentially hamper the design process as it can take a longer time to solve an issue.

Similarly, policy was also perceived as a boundary of collaborative design practice through its influence to relationship between the design participants. One of the company policies that perceived to bound relationship relates to team division. INT-5 (supported by the statement of INT-6; INT-7; INT-8; INT-9; INT-19) argued that the policy to divide design team based on the stage of the design process creates a “stiffed-pipe” effect. In which, design participants only concern themselves with their part of the design, and thus, only establish relationships with their team, and ignore what others do.

Combining all elements, attributes, and relationships explained above, an architectural model of boundary was constructed. The model is depicted by Figure 31.

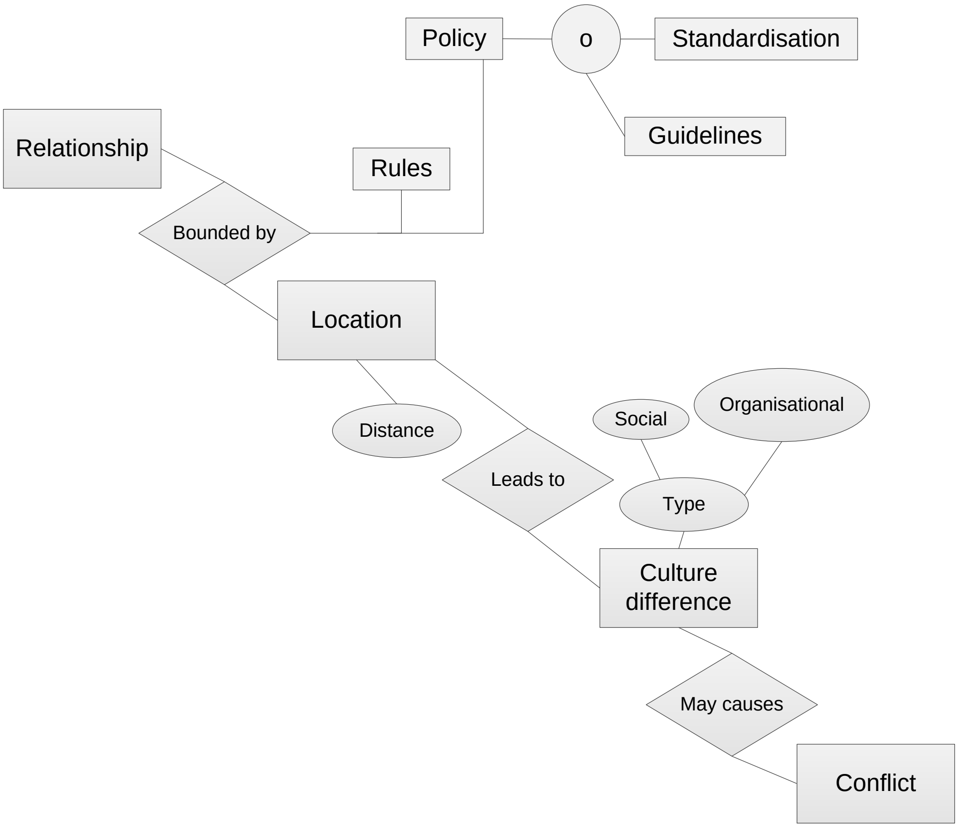


Figure 31 Boundaries of relationship

The last boundary identified from the industrial investigation was legislation. Legislation bounds design collaborative practice through its influence on the technical system. INT-19 discussed how the design of the combat system (i.e. a part of the technical system being designed) is driven by a particular legislation named *Defence Standards*. From this perspective, the design of the technical system is restricted by legislation. The relationship between the technical system and legislation is represented by Figure 32.

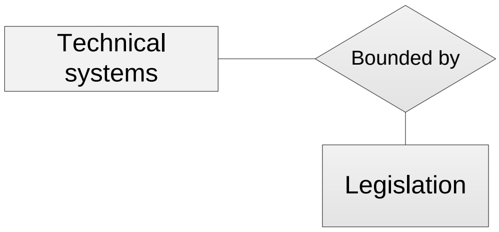


Figure 32 Boundary of the technical system

Unlike the previous themes where one model was generated for each theme, within the theme boundary, two segregated architectural models were generated. One model consists of the boundaries of relationship (Figure 31), and the other consists of the boundary of the technical system (Figure 32).

5.3.2.6 Design information

Throughout the collaborative design practice, stakeholders exchange design information. The term design information as used here refers to the information utilised as the basis to design the technical system. As an example, at the earlier stage of the design process, customers hand over a requirement document reflecting what the ship (end-product/ system) "should be able to do" (e.g. launch a specific type of weapon, hunt a submarine) (as mentioned by INT-1, and similarly, INT-18).

From the industrial investigation, design information can be divided into three divisions. These divisions can be regarded as subclasses of design information. They can be explained as follows:

1. Design requirements and constraints
   At the earliest stage of the design process, customers and users create a requirement document. It consists of general information on what needs to be included and/or excluded in the design of the technical system. For example, as explained by INT-8 "[the end product/ system needs to be] able to hunt submarines… and avoiding being hunted by submarines".
2. Design specification
   Design requirements and constraints are translated into detailed technical specifications, regarded as the "design specification" in this thesis. For example, the requirement "to be able to hunt submarines" can be translated into, for example, minimum required speed, and the requirement "to avoid being hunted by submarines" can be translated into, for example, a maximum permissible level of noise (as described by INT-1). In this case, minimum speed and maximum level of noise are viewed as design specifications.
3. Design problem
   Design specifications are provided to Company 1, and used by the company as the basis to identify design problems. That is, the problems those relate to the design of the technical system, and therefore, need to be considered when designing the said technical system (as mentioned by INT-19). For example, intersection points (i.e. the point where users and system cross) between the users with the system (INT-19), and the size and position of compartments (INT-4).

Design information can be divided into more than one category. As an example, in the case of Company 1's design (as implied by INT-1 and INT-19), a low level of noise can be considered as a design specification (required for avoiding submarine detection), as well as a design problem (it creates difficulties when integrating interrelated parts of the technical system). From this perspective, the relationship between design information and its division can be considered to overlap. The relationship between design information and its subclasses is depicted by Figure 33.

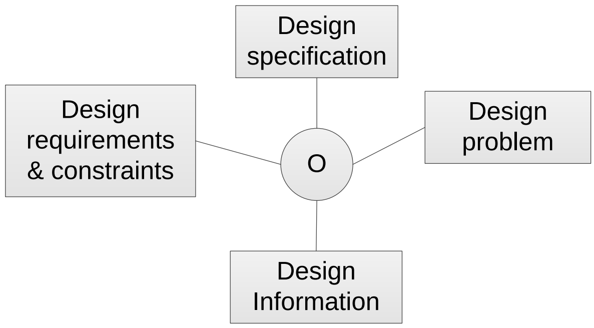


Figure 33 Design information and its subclasses

Five attributes of design information were elicited from the industrial investigation, as outlined below:

a. Nature

The industrial investigation indicated, when users alter their requirements, the design specification needs to be changed, and consequently, design problems identified from the design requirement also change (as indicated by INT-18; INT-19; INT-20). INT-5 stated, "If customers change their requirements, it will significantly influence the design process as they have to do more rework and start all over again." In this context, the interrelated nature of design information is used to characterise design information. In the model, the term interrelated was represented as a sub-attribute to show a specific type of nature that influences the design process.

b. Amount

In the context of the study documented in this thesis, the term amount refers to the quantity of design information being exchanged between the stakeholders. The attribute of amount was derived from the concern of several interviewees (e.g. INT-4) regarding the technical challenges in collaborative design activity. According to INT-4, one technical-related challenge was the excessive amount of design information due to frequent changes and thus, identifying the latest version of information can be arduous. The second challenge mentioned was the insufficient amount of design information provided by stakeholders. INT-6 observed that stakeholders, particularly customers and suppliers, often provided insufficient design information. This, according to INT-6, can potentially lead to rework.

c. Consistency

One of the main concerns of design information was its consistency. Consistent information can be described as having no contradictions, meaning the same information is held by all that require it. As INT-5 revealed, “getting across to everybody at the single point of truth, ensuring that everybody has the same information is a big challenge.” INT-20 revealed, inconsistent information “creates a lot of rework and impacts on planned costs”. From this perspective, design information must be consistent in order for it to hold maximum value for the company; inconsistent information is of little value as it creates big challenges.

d. Importance

Importance as an attribute of design information was elicited from the statements of INT-12 and INT-25. According to them, stakeholders tend to focus on the information that is important to them, and tend to ignore information that according to them is unimportant. From this perspective, it can be seen that information has different levels of importance dependent on the stakeholder involved.

e. Form

In the study presented here, the term form refers to the particular way in which design information exists (The Oxford English Dictionary, 2013). The industrial investigation indicated that for each stage of the design process, a form of design information was produced. For example, 2D drawings are created in Stage 1, and 3D models are created in Stage 2. Further to this, within each stage of the design process, different forms of design information are created, depending on the purpose. As an example, to present information that will be utilised for a non-detailed calculation, spreadsheets are produced (as discussed by INT-27). From this perspective, the form of design information can be used to describe pieces of design information, and thus, can differentiate one piece of design information and another.

The relationship between design information and its attributes identified above is depicted by Figure 34.

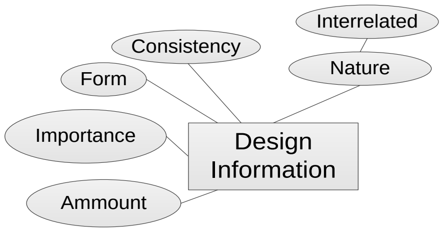


Figure 34 Attributes of design information

In Company 1, design information is stored in information systems, (as discussed by INT-4; INT-7; INT-16 and INT-26) to provide "a formal platform" for information sharing (as mentioned by INT-5) and facilitate information exchange. Within the context of the study documented in this thesis, the term information system refers to the system to organise, store, and, communicate information.

The information system that was frequently mentioned during the industrial investigation was a computer-based system called *Windchill* (mentioned by INT-4, INT-7, INT-10, INT-14, INT-16, INT-22, INT-26). The use of a non-computer based information system (e.g. paper-based), was not identified from the industrial investigation. Due to this, the information system used in the company's collaborative design practice has a characteristic of being operated by computer.

The industrial investigation suggested that during collaborative design practice, designers represent design information as a model. For example, designers represent the design specification to a 2D drawing (as indicated by INT-18).

Two types of model were identifiable from the industrial investigation, i.e. 2D and 3D. The 2D models are typically generated at the early stages of the design process (e.g. during concept generation), while the 3D models at the later stages (e.g. during the detailed design process) (as interpreted from the statement of, for example INT-5, INT-10, and INT-18). From this perspective, type can be used to describe a model according to the stage where the model was generated and can be considered as an attribute of model, with 2D and 3D as its divisions (i.e. sub-attributes).

Based on the explanation above, an architectural model of design information was constructed, as shown by Figure 35.

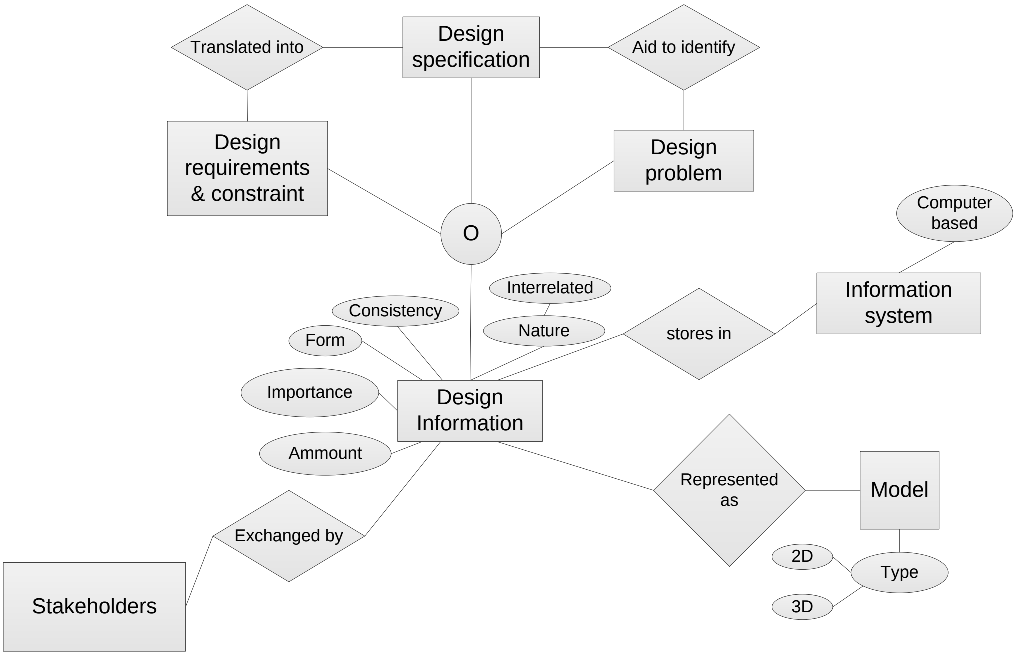


Figure 35 Architectural model of design information

5.3.2.7 Tools

The industrial investigation indicated that stakeholders use tools specific to their design task (as indicated by INT-6). The term tools used in this context refers to instruments or applications that execute a particular function(s) (The Oxford English Dictionary, 2013). For example, the electrical design team used a tool called CMPIC to manage electrical cabling (as discussed by INT-2), while the platform design team use finite element analysis software to assess reliability of the system (as discussed by INT-20).

Two types of tools were identifiable from the industrial investigation. They were perceived as the division (i.e. sub-classes) of tools:

1. Communication tool
   The type of tool(s) used to exchange information between stakeholders is regarded as a communication tools. This includes email and video conference device (as derived from the statements of INT-3, INT-8, INT-10, INT-22, INT-23, INT-27).
2. Technical tool
   The type of tool(s) used to design the technical system are regarded as technical tools such as, as aforementioned, CMPIC for electrical cabling management and finite element analysis for system reliability assessment.

The industrial investigation suggested that a tool can be a member of both the communication and technical sub-classes. As an example, Computer-Aided Design software has a primary function of creating 3D solid geometric models. However, it can be also used to exchange information using its sharing screen feature (as mentioned by INT-25). This indicates an overlapping relationship between tools and its subclasses, as depicted by the following figure (Figure 36).

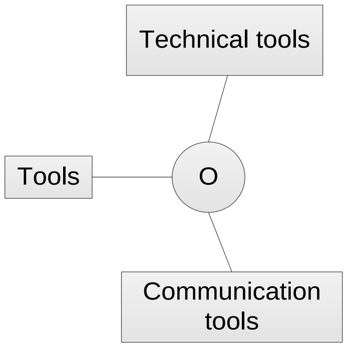


Figure 36 Tools and its subclasses

As mentioned above, technical tools refer to the tools utilises to design technical systems. In Table 9, examples of technical tools derived from the interview are outlined.

Table 9 Examples of technical tools and its functions identifiable from the industrial investigation

Tools	Description of function	Function	
		Calculation	Visualisation
CMPIC	To manage cabling system and routing	√	√
Finite element analysis	To analyse the behaviour of the technical system	√	√
Foran	To create 3D model		√
MathCAD	Math package to produce engineering calculation e.g. calculating structure	√	
PECD	Assess the extent of damage from, for example, blasts, to the technical systems	√	√

From Table 9, it can be seen that technical tools can be described based on their function. Thus, function can be viewed as an attribute of technical tools. Two divisions of function were identifiable, i.e. calculation, and visualisation and representation. As indicated by INT-6, "…the generic tool sets across all [i.e. design teams] would be the drawing [i.e. visualisation and representation] and calculating systems". On this basis, calculation and visualisation can be viewed as sub-attributes of function. Additionally, technical tools can also be characterised as being computer-based (i.e. operated through a computer). No evidence of non-computer based technical tools in Company 1 was identified. As such, computer-based was seen as a distinct character of technical tools.

The industrial investigation implied that the technical tools having calculation functions generate numbers, while those having visualisation and representation functions generate models (i.e. 2D and/or 3D). From this perspective, concerning their relationship with the model, technical tools can be seen as an instrument to create a model. In other words, a model is created using technical tools.

In addition, INT-6; INT-8; INT-11; INT-20 similarly implied that the main function of tools is to process design information (i.e. through calculation and visualisation). From this perspective, technical tools can be seen as instruments to process design information.

As aforementioned, communication tools refer to the tools utilised for exchanging information between stakeholders. In Company 1, design teams are dispersed in a number of locations (mentioned in Section 5.3.2.4). Communication tools are used to facilitate information exchange (i.e. communication) between the design teams. As INT-11 stated, "…because we are scattered all over the place, that [i.e. communication] will be a three-way video conference [i.e. a communication tool]." From this perspective, communication tools can be seen as a facility for communication between different locations (of participants).

The literature review revealed two types of communication tools (as outlined in Section 4.3.1). They were: 1) synchronous, referring to communication tools that facilitate real-time communication, such as telephone and video conference, and 2) asynchronous, referring to communication tools that facilitate deferred communication such as email. The industrial investigation indicated the existence of similar types of communication tools, as can be seen in Table 10.

Table 10 Examples of communication tools and its types identifiable from the industrial investigation

Tools	Type	
	Synchronous	Asynchronous
Telephone	√	
Email		√
Lync video conferencing and instant messenger	√	√
SharePoint		√
3D virtual suites	√	

From above, it can be seen that communication tools can be described based on their type, consisting of synchronous and asynchronous. As such, type can be considered as an attribute of communication tools, whilst synchronous and asynchronous as the divisions of type (i.e. sub-attributes).

Representing the elements of tools and their inter-relationships aas discussed above, an architectural model of tools was generated, illustrated by Figure 37.

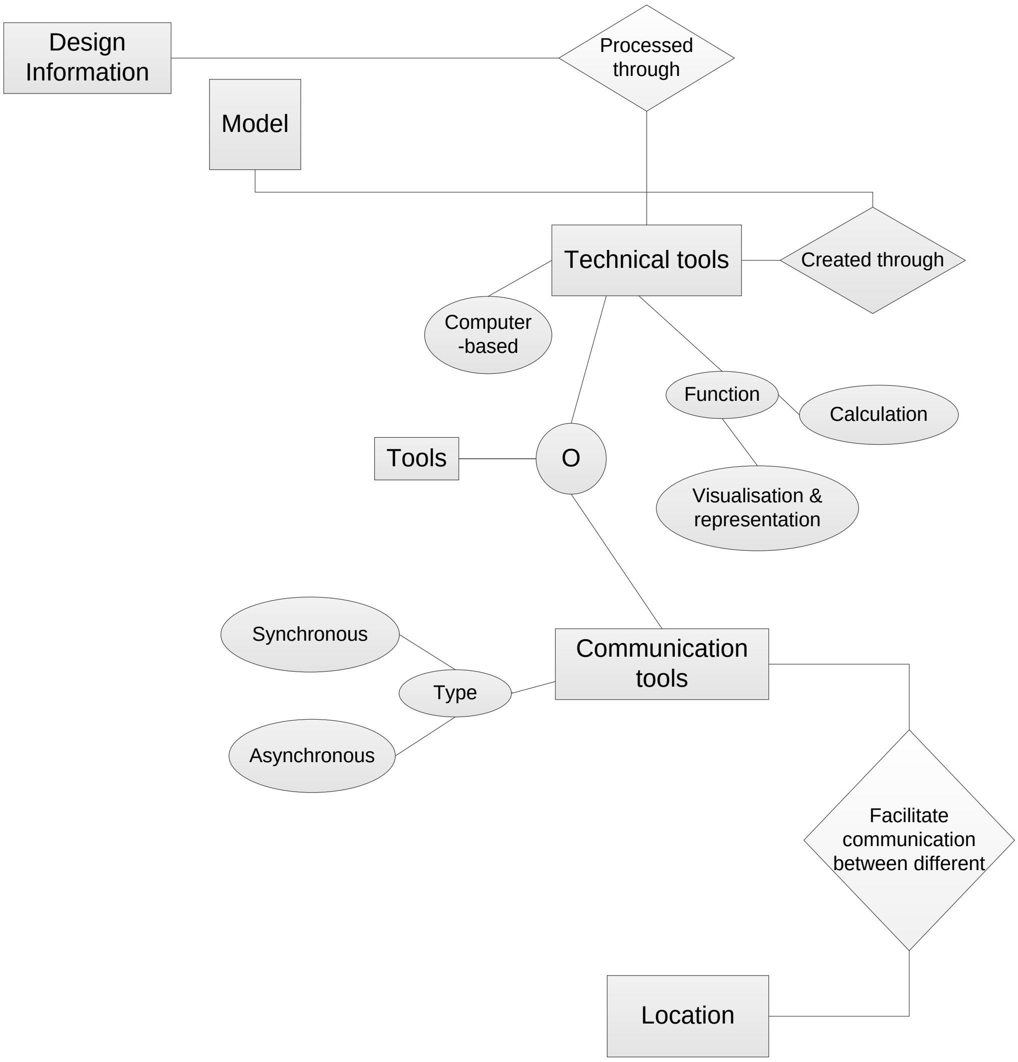


Figure 37 Architectural model of tools

5.3.2.8 Technical system

In CED, stakeholders collaborate for a common goal, which is to design a technical system (as mentioned in Section 5.3.2.1). From this perspective, stakeholders can be viewed as the designers of technical system. The term technical system used here refers to the artefact, the result of the engineering design process (See Chapter 4.3.2).

INT-5 stated, "The design activity in the company is conducted at a high level of dependencies in the artefact [i.e. technical system]. Almost everything has an interaction by abstruse logic [i.e. everything affects everything else]". From this perspective, a technical system can be described as being interrelated.

The technical system was also noted as being integrated. This means that multiple parts of the technical system work together as a unit to perform a required function. For example, electricity, GPS systems and control systems have to work together to track the current position of the ship (as discussed by INT-1; INT-19).

In addition to the above, INT-7 stated, "…With our product…you've got multiple…conflicting and integrated elements". From this perspective, a technical system may be described as being complex.

To ensure that the interrelated elements of the technical system are integrated; the performance of the technical system is assessed using a number of variables (INT-19). Such variables are typically determined based on the design information provided at the earliest stage of the design process (as discussed by INT-4; INT-6; INT-8; INT-12; INT-18; INT-26). The performance of the technical system is measured by the customers' acceptance or rejection of the design (INT-1). In this respect, the technical system may be described by its performance.

The industrial investigation revealed that throughout the design process, the technical system is divided into a number of zones (as mentioned by INT-2; INT-3; INT-19; INT-12; INT-22). The term zone utilised here refers to a physical area. Each area of the technical system is utilised as the basis to assign tasks for each design team (as explained by INT-4). Zones can be used to describe an area of the technical system by defining its location and the part of the technical system located in the zone. For example, Zone 1 of the technical system, located at the front-end of the ship (i.e. the technical system), consists mainly of weaponry systems (as mentioned by INT-19).

Being interrelated, integrated, and complex, as well as having performance and zones were identified as the characteristic of technical systems. Thus interrelated, integrated, complex, performance and zones were identified as the attributes of technical systems. Figure 38 illustrates technical system and its aforementioned attributes.

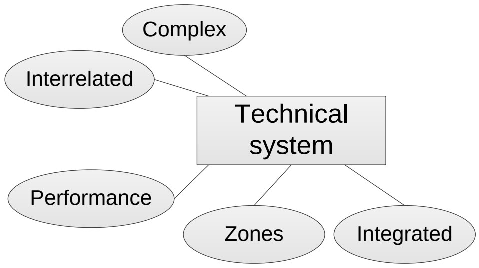


Figure 38 Technical system and its attributes

The industrial investigation revealed that technical conflict often occurred during the design practice. As INT-26 remarked, "We often end up with three distinct parts of the systems, that don't integrate in anyway". In Section 5.3.2.3, technical conflict was characterised as disintegrated design. This was indicated as a cause of rework, which can potentially alter the design of the technical system. INT-5 stated, "When it [i.e. technical conflict] happened, they [i.e. stakeholders] will have to see the design all over again, and revise it". On this basis, technical conflict can be viewed as an influencing factor of the technical system.

As pointed out above, customers used the performance of the technical system as the basis to accept/ reject the design. To ensure that the technical system would be accepted, its design is aimed towards complying with its design requirements and constraints. As INT-26 commented, "What we are seeking is delivering requirements to the customer and then influencing the product to meet that." In this regard, concerning the relationship between the technical system and design requirements and constraints, it can be perceived that in collaborative design practice, the technical system should comply with the design requirements and constraints.

Representing the elements of technical systems and their relationships as discussed above, an architectural model of a technical system was constructed. The model is represented by Figure 39.

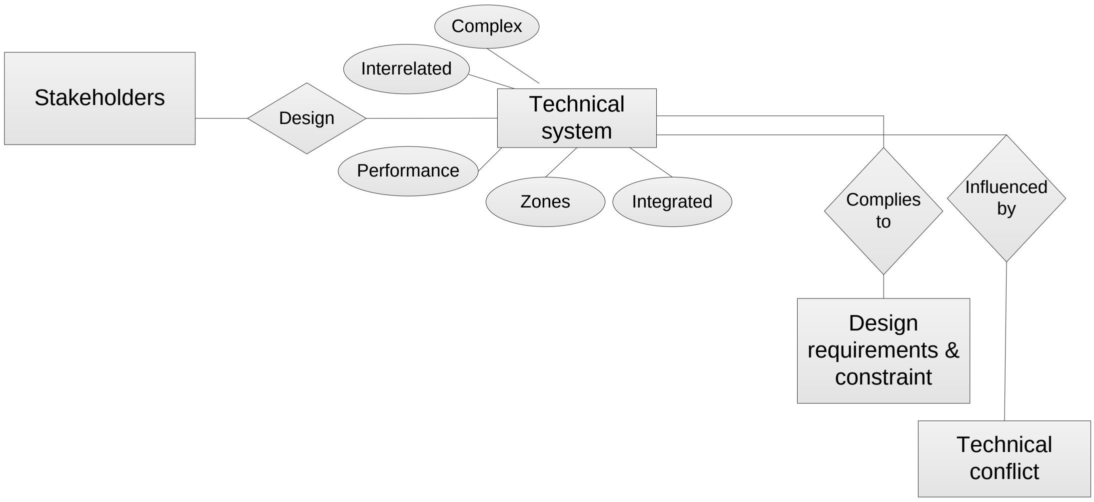


Figure 39 Architectural model of technical system

5.3.2.9 Design process

The last theme identified from the industrial investigation was design process. This refers to the course of designing a technical system. Seven attributes of design process were elicited from the interview transcriptions.

a. Duration

The industrial investigation implied that the whole process of design, from accepting customer requirements until the customer acceptance of the design, can take between five to ten years (as mentioned by INT-13; INT-21; INT-27). According to INT-27, this long design process owes to the high complexity of the technical system. From this perspective, it seemed reasonable to conclude that a less complex system can have a shorter design process. Thus, <u>duration</u> can be considered as a descriptor of <u>design process.</u>

b. Performance, parameter, and measurement

INT-20 indicated, prior to the design process (i.e. after design requirements and constraints are received), the company estimates the time (i.e. schedule) and cost throughout the design process. Based on these time and cost estimations, targets such as tasks and deadlines, are established (INT-27). The performance of the design process in Company 1 is measured against these (as implied by INT-20). For example, INT-20 indicated, the design process can be considered to be performing well if the real schedule is ahead of the estimated schedule. In this sense, the design process in Company 1 can be described using 1) performance (e.g. good), 2) how to measure the performance (e.g. comparing the estimated and real time schedule of the design process), and 3) parameters to measure the performance of said design process (e.g. time schedule).

c. Requirement

The design process requires consistency in the information being exchanged (as discussed in Section 5.3.2.6).

Due to the interrelated and integrated nature of the technical system (as discussed in Section 5.3.2.8) the design process requires each design team to be aware of the tasks of other teams, as well as to know how their task affects other team tasks (as implied by INT-4; INT-6; INT-12; INT-18; INT-22). Conflict, both social and technical often occurs from lack of awareness (INT-12; INT-25). As INT-25 pointed out, "There will be an issue which somebody was aware of, but they thought it might have impacted on their area [only], but they weren't aware of the impact across everybody else's, and because of this, tension happened".

INT-17, human resource (HR) personnel in Company 1 revealed that there are more than 500 people involved in the design process. Each of them is assigned with task(s), which signifies their involvement in the design process (as indicated by INT-6). The assigned task(s) typically correspond to a zone of the technical system (as mentioned in Section 5.3.2.8). Individuals assigned to the same zone are grouped into a design team. To ensure that the design is well integrated, design teams are required to communicate with each other throughout the design process (as mentioned by INT-15).

The requirements of the design process were a result of the complexity nature of the technical system, i.e. interrelated and integrated. From this view, such requirements can be considered unique to CED process for a complex technical system. Thus, they can be used to characterise the design process and can be considered as attributes of the design process. Additionally, consistency, awareness, and communication can be considered as sub-attributes of requirements, as they signify the requirements of the design process.

d. Stage

The design process in Company 1 can be divided into three stages (as mentioned by INT-2; INT-6; INT-8; INT-10; INT-22). Each stage is focussed on different tasks. For example, Stage 1 focusses on developing the concept of the design and provides the layout of the technical system, while Stage 2 focusses on detailing the concept design and physical integration of the system, and Stage 3 focusses on preparation for production.

e. Zone

In addition to the aforementioned stage divisions, the design process is also divided into different zones, following the zones of the technical system. This, according to INT-2, is done to "break up the scope of work so that it's at manageable levels". In general, the design processes throughout the zones are similar. However, in a more detailed sense, there are distinct processes that can only be identified in a specific zone. For example, INT-12 mentioned a particular simulation process as a part of the design process in their zone, evidence this same of simulation process in other zones of the design process was not seen. Furthermore, INT-12 remarked, in each zone, the division of stages of the design process can be different. As an example, Zone x has no Stage 2, Zone y has no Stage 1 (as discussed by INT-12).

The design process and its identified attributes mentioned above can be depicted by Figure 40.

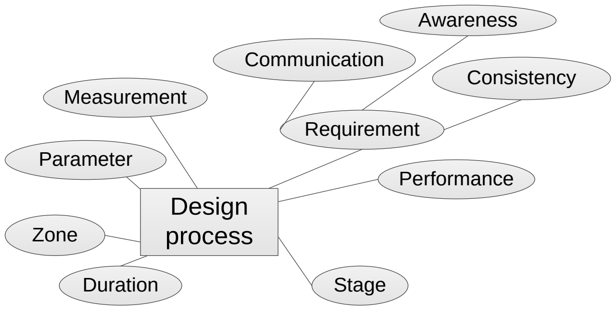


Figure 40 Design process and its attributes

One of the attributes identified and briefly analyse above was stage. The stage attribute divided the design process into three stages: Stage 1, i.e. concept design process, Stage 2, i.e. detailed design process, and Stage 3, i.e. post-design process. Each stage consists of different activities and each activity has a different connection with the other identified elements of CED. The three stages can be perceived as subclasses of the design process. Additionally, the industrial investigation indicated that the design process in Company 1 overlaps, meaning the design process can consist of more than one stage at the same time. For example, Stage 2 can start although Stage 1 is still in progress in several zones (INT-12; INT-18; INT-27). The relationship between the design process and its subclasses is illustrated by Figure 41.

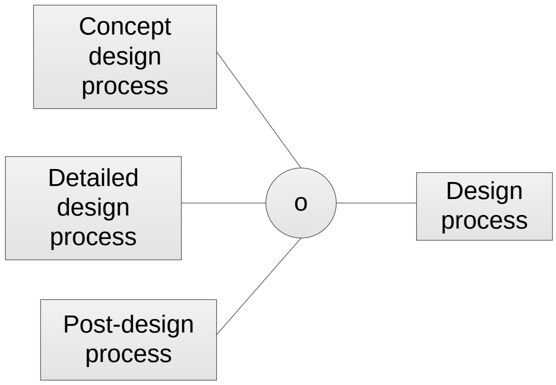


Figure 41 Subclasses of design process

The sequences of the design process in Company 1 can be explained as follows:

a. Stage 1 (Concept design process)

According to INT-5 and INT-14, the basic conceptual design of the technical system was made based on the design information provided at the earliest stage of the design process. INT-5 regarded the basic conceptual design as a general arrangement of the technical system. The layout of the technical system can consist of, for example, the basic structure and dimensions of the technical systems components (as mentioned by INT-5). They are presented as 2D models. The process where the layout and 2D models are produced was recognised as the concept design process or Stage 1 design process.

b. Stage 2 (Detailed design process)

In Stage 2, the design is further specified in the detailed design process. The designers focus on the physical integration of the design (as implied by INT-19; INT-22). This physical integration is presented as 3D models (INT-5).

c. Stage 3 (Post-design process)

Stage 3, the last stage in Company 1 is the post-design process. At this stage, the design begins its final approval prior to production. The design teams prepare the design drawings to be provided to the production teams (INT-8; INT-19; INT-22).

To ensure that the design of the technical system is well integrated, stakeholders meet regularly throughout the design process (i.e. concept design and detail design) to review the design, as mentioned by INT-4, INT-6, and INT-13. This process is regarded as the design review process.

As mentioned, conceptual design and detailed design are presented as 2D and 3D models, respectively. In the design review process, the same model hierarchy is used.

During the design review process, decisions regarding the design (e.g. refinement, approval) are made (INT-19), the design problems are discussed, and feedback is given to resolve the problems. From this perspective, two points can be summarised. Firstly, the design review process consists of decision-making processes, and secondly, the design problem can be resolved during the design review process.

Two influencing factors of the design process were identified from the industrial investigation. The first influencing factor was conflict, e.g. personality clashes and disintegrated design. The influence of this can be perceived both positively and negatively. For example, INT-3 highlighted that conflict hampered the design process while INT-26 discussed that conflict motivates a new and improved design.

The second influencing factor of the design process identified from the industrial investigation was new policy. According to INT-1, when the company started to adopt the new policy of having the customers involved from the earliest stage of the design process, it changed the organisation of the design process. For example, initially, customers were not involved in the design review process, and their inputs were only asked at the later stages. With the new policy, a new review process, which involves the customers from the outset of the project, was applied.

As discussed in Section 5.3.2.1, internal stakeholders were viewed as the hosts of the collaborative design practice. With respect to this, internal stakeholders act as the main coordinator, including coordinating the design process to ensure that it is conducted as planned. From this perspective, internal stakeholders can be seen as the manager of (i.e. in charge of managing) the design process.

Having identified the elements of design process and their inter-relationships, an architectural model of design process was created, illustrated by Figure 42.

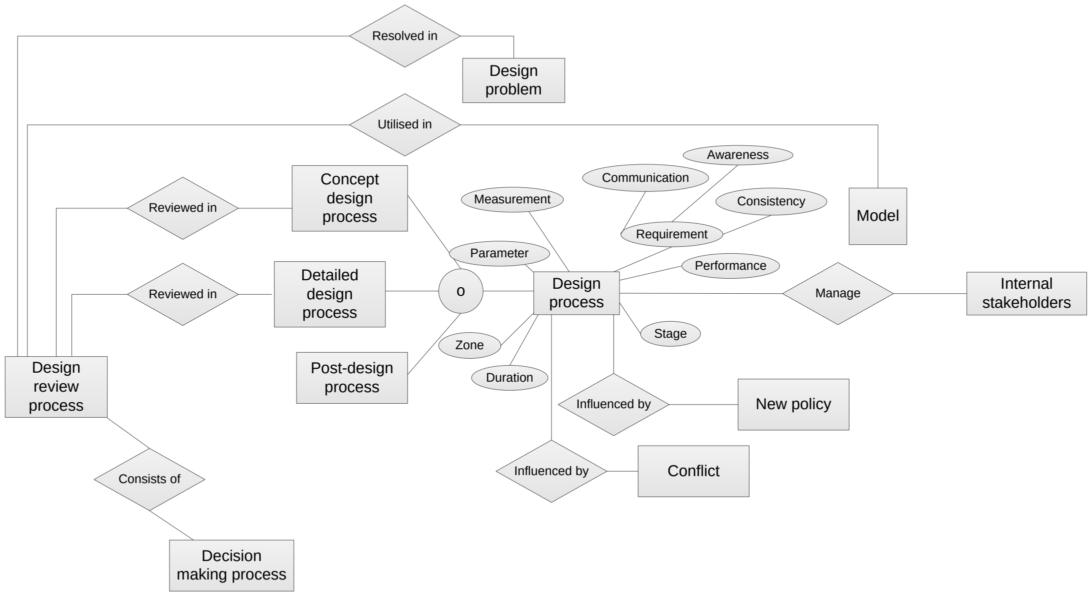


Figure 42 Architectural model of design process

5.4 STAM-2

In Section 5.3, findings from the industrial investigation were presented, and their usefulness to develop a socio-technical architectural model of CED was discussed. These findings were divided based on the nine identified themes, i.e. human being, relationship, conflict, organisation, boundary, tools, design information, technical conflict, and design process. From each theme, a fragmented socio-technical architectural model consisting of elements, sub-elements, attributes, and relationships was generated. The fragmented models have been combined to create a holistic socio-technical architectural model of the CED, presented in this section. To aid visualisation, colours were assigned to each theme (see Nomenclature), and to highlight the connection between the themes, the appropriate line(s) have been widened in each figure.

In Section 5.3.2.2, it was shown that the interaction(s) between stakeholders generate relationships. Three interactions between stakeholders were identified (see Section 5.3.2.1), i.e. interaction between internal stakeholders and external stakeholders, interaction between engineers and non-engineers, and interaction between users and customers. These interactions combine the architectural model of human being and relationship as seen in Figure 43.

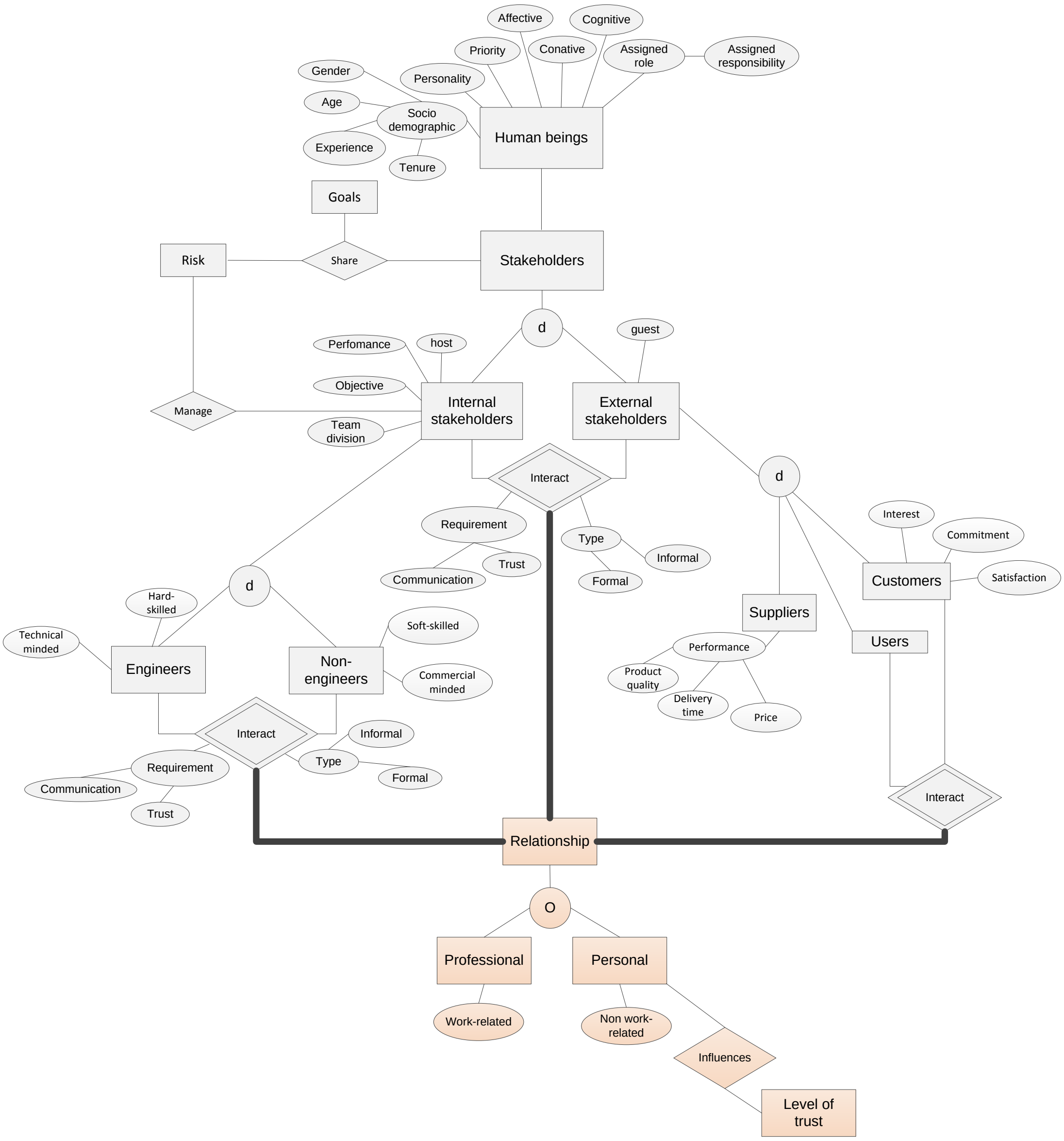


Figure 43 Combining the architectural model of human being and architectural model of relationship to develop STAM of CED

In Section 5.3.2.3, the connection between relationship and conflict was discussed, the result of which being that relationship is hampered by conflict. Through this connection, the architectural model of conflict was combined with the architectural model of human being and relationship. This is depicted by Figure 44.

Aforementioned in Section 5.3.2.1, and again in section 5.3.2.4, stakeholders belong to the organisation that employs them. Using this, the architectural model of organisation was combined with the architectural model of human being, relationship, and conflict, as illustrated by Figure 45.

In the architectural model of relationship boundaries (depicted by Figure 31), the bounded by relationship connects relationship with three different entities: location, rules, and policy. Location was not present in the architectural model of the previous themes (i.e. Figure 45). However, rules and policy were present (under the organisation section). As such, the architectural model of relationship boundaries was combined with the model from Figure 45 and those entities (rules and policy) that were already present were taken into account. The combination is depicted by Figure 46.

In the architectural model of technical system boundaries (depicted by Figure 32), the bounded by relationship connects technical system with the only entity, i.e. legislation. Since legislation was already in place in Figure 46, it did not need added. Instead, only the remainder of the architectural model of the technical system boundaries needed affixed, as shown in Figure 47.

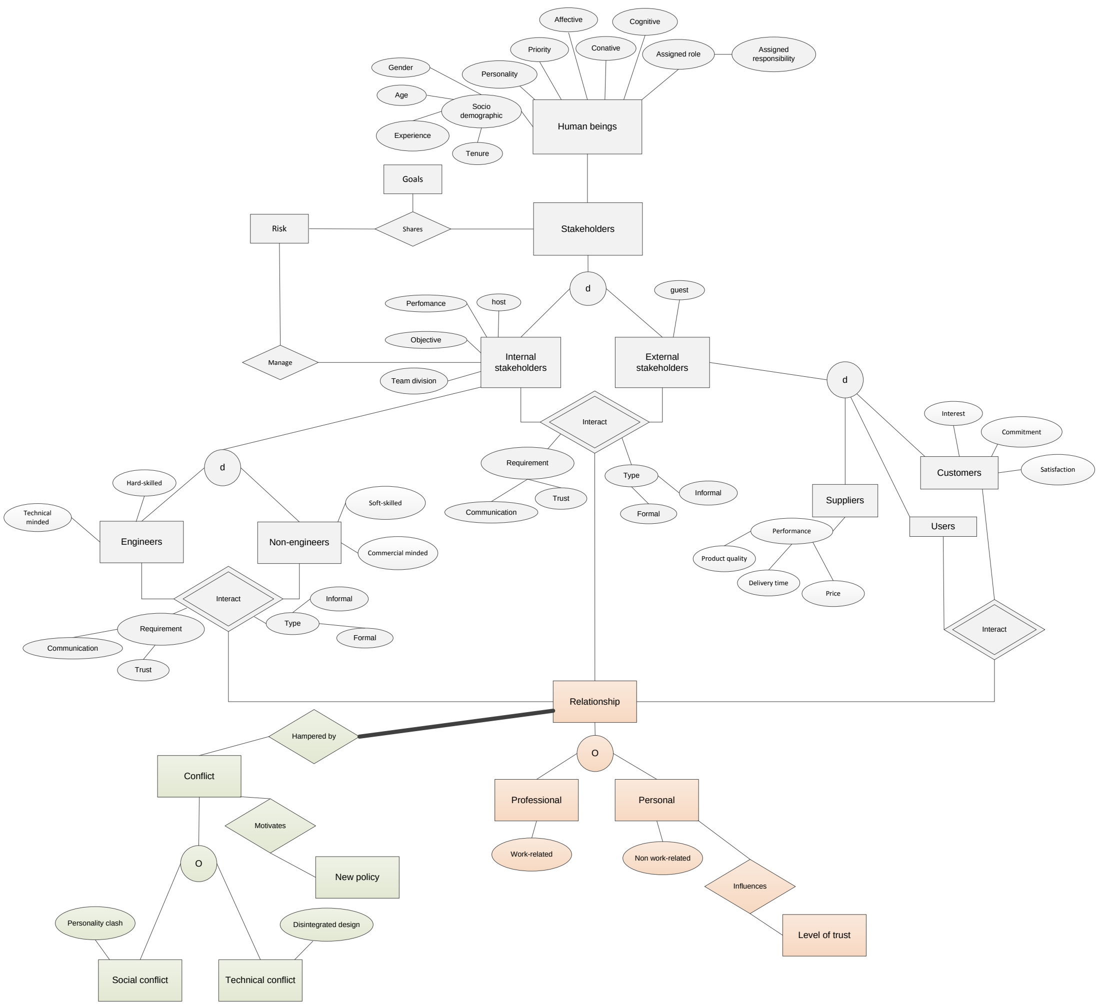


Figure 44 Combining the architectural model of conflict to the STAM of CED

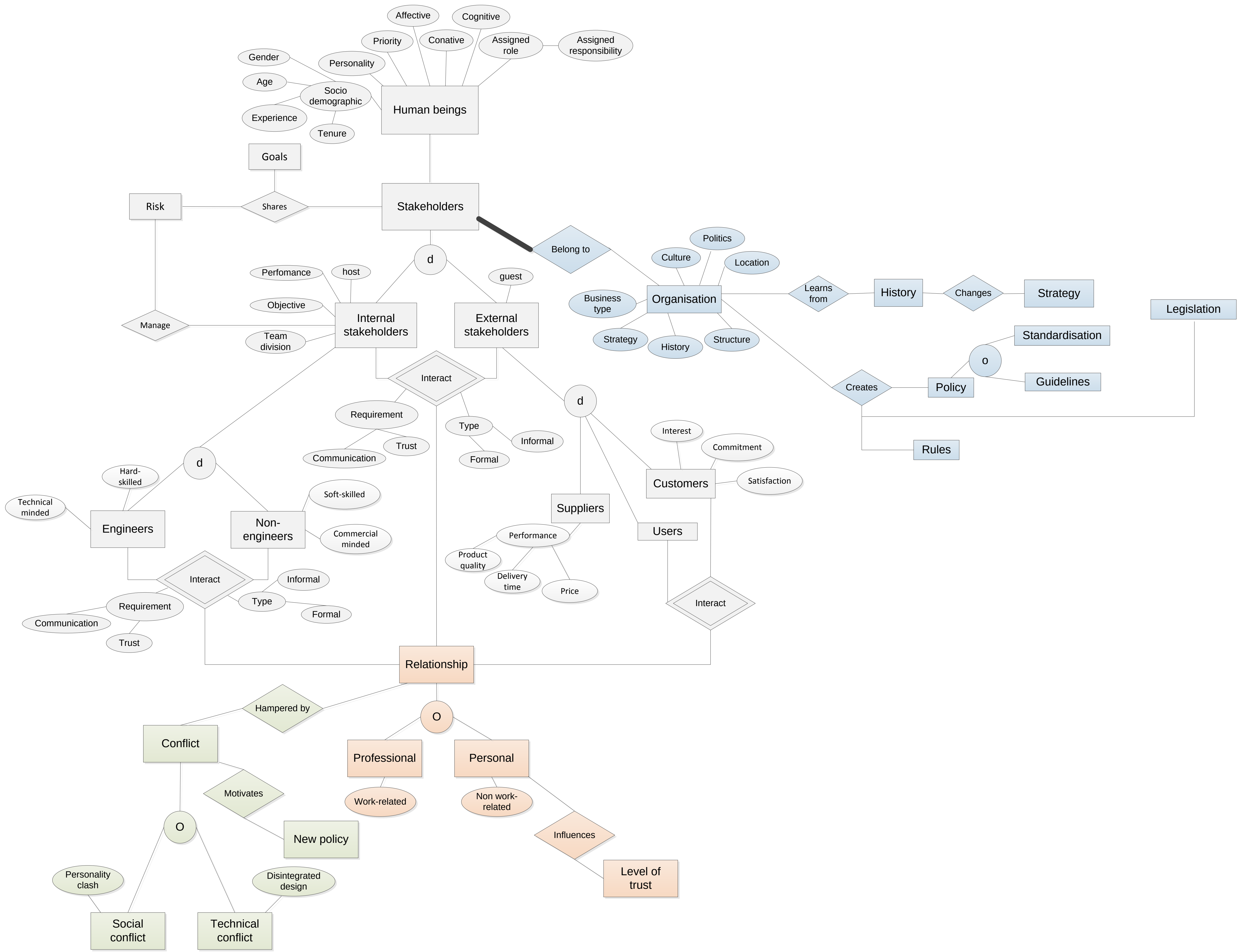


Figure 45 Combining the architectural model of organisation to the STAM of CED

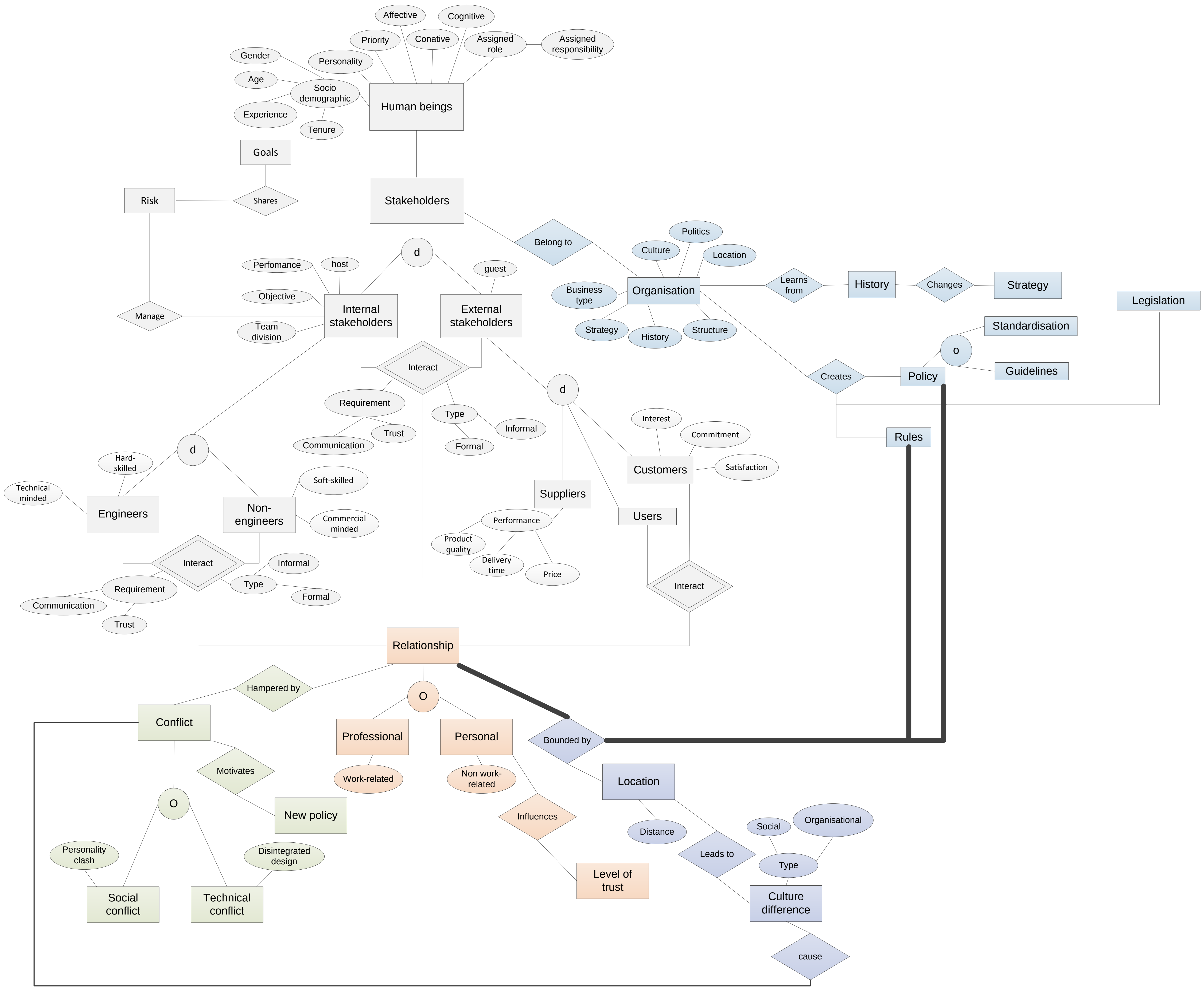


Figure 46 Combining the architectural model of boundaries to the STAM of CED

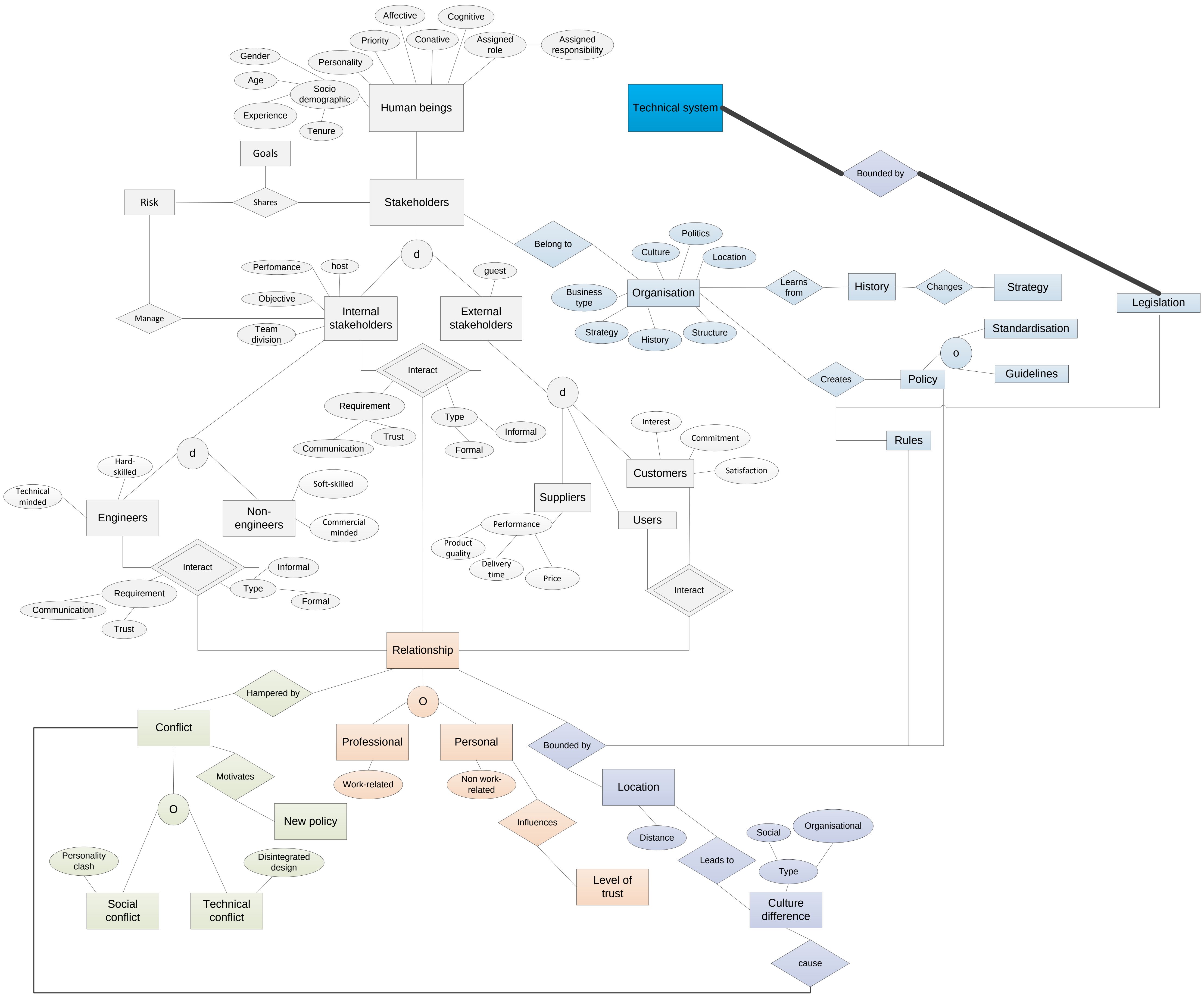


Figure 47 Combining the architectural model of technical system boundary to the STAM of CED

As discussed in Section 5.3.2.6, stakeholders exchange design information throughout collaborative design practice. To combine the architectural model of <u>design information</u> with the socio-technical architectural model, its relationship with <u>stakeholders</u> was used. This can be viewed in Figure 48.

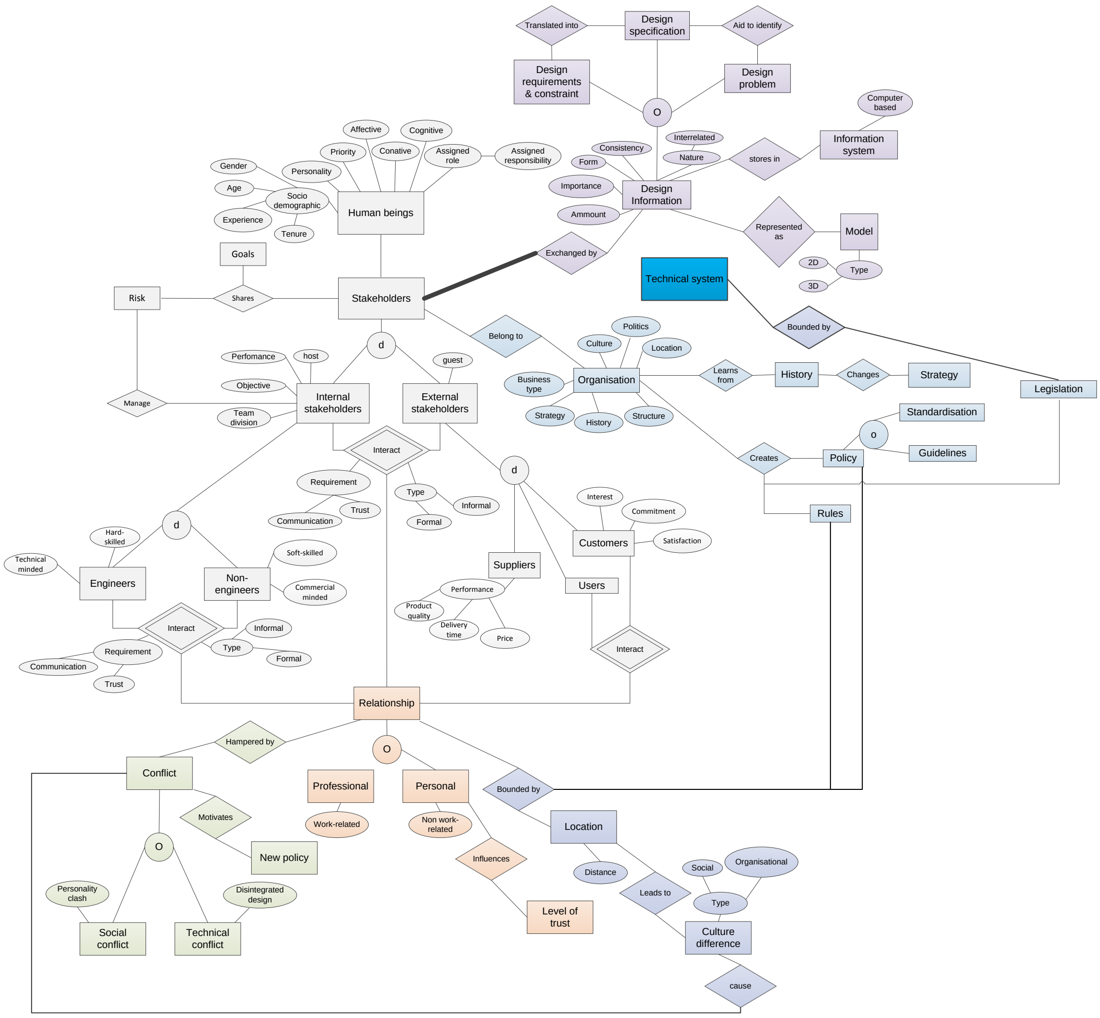


Figure 48 Combining the architectural model of design information to the STAM of CED

The industrial investigation indicated that stakeholders use tools to undertake their tasks (Section 5.3.2.7). Two types of tools were discussed in Section 5.3.2.7: technical tools and communication tools. Technical tools are generally used to process design information and create representations (i.e. models). From this perspective, <u>technical tools</u> are related with two entities: <u>design information</u> and <u>model</u>. This relationship between <u>technical tools</u> and the two entities is used to combine the architectural model of <u>tools</u> to the socio-technical architectural model, as depicted by Figure 49.

Communication tools are used to communicate design information and facilitate communication between different locations (see Section 5.3.2.7). From this perspective, communication tools are related with two entities: design information and location. Hence, in addition to the above, the architectural model of tools was combined with the socio-technical architectural model through the relationship between communication tools with design information and location, depicted by Figure 50.

Four relationships between the technical system and the other themes of collaborative design practice can be identified from Section 5.3.2.8: 1) the technical system is bounded by legislation. This was already presented in the socio-technical architectural model (see Figure 46); 2) the technical system is designed by stakeholders; 3) the technical system has to comply with design requirements and constraints; and 4) the technical system is influenced by conflict. The relationships from the architectural model of the technical system that are not already combined with the socio-technical architectural model are now included, as can be seen in Figure 51.

As identified and discussed in Section 5.3.2.9, there are five relationships between the elements of the design process and the elements of other themes. They can be summarised by the following points: 1) the design process is managed by stakeholders; 2) the design process is influenced by new policy; 3) the design process is influenced by conflict; 4) the design review process (i.e. an element of the design process) resolves design problems (i.e. a sub-element of design information); and 5) the design review process utilises models (i.e. an element of design information). These relationships were combined to the architectural model of collaborative design, depicted by Figure 52.

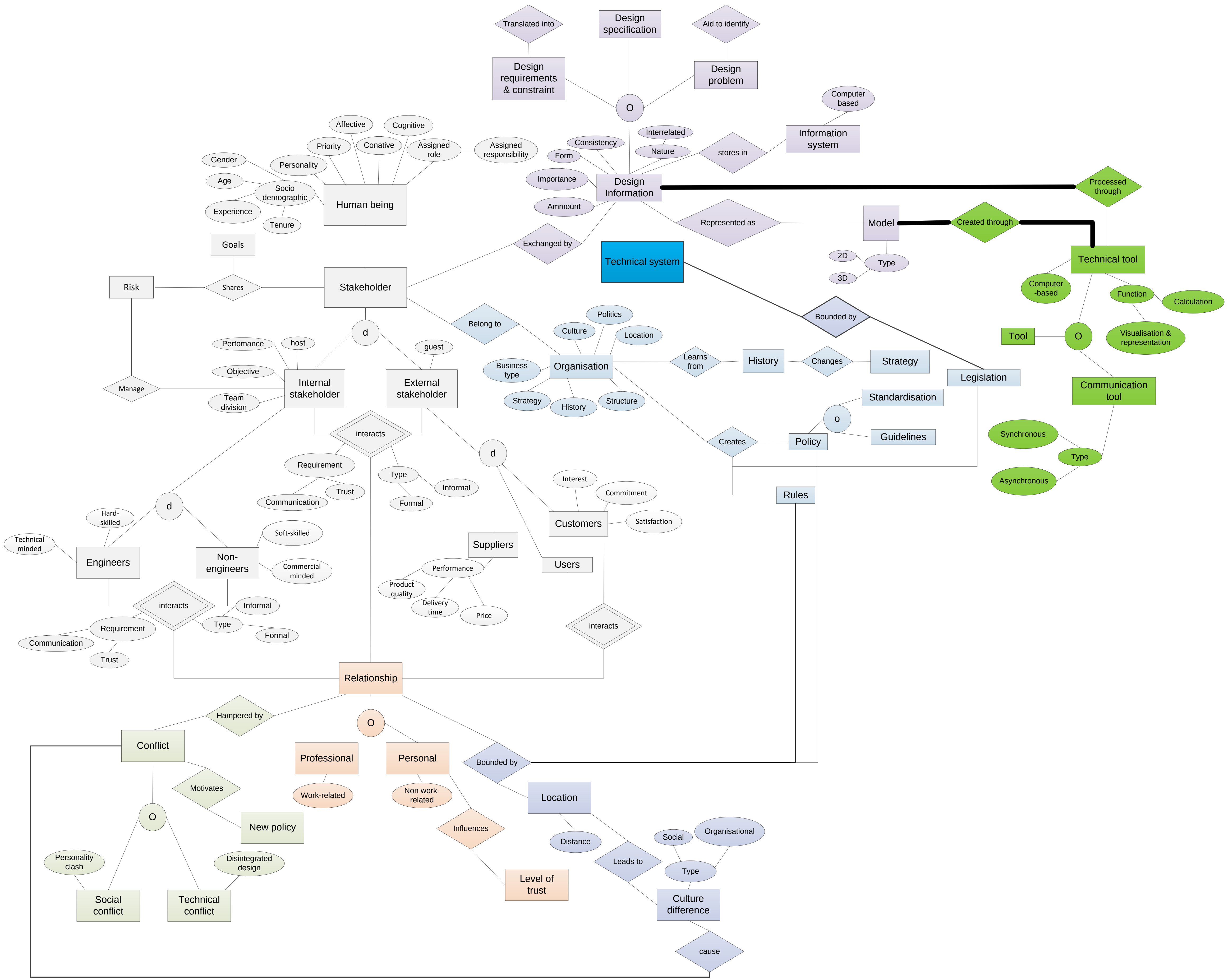


Figure 49 Combining the architectural model of tools to the socio-technical architectural model of collaborative design (1)

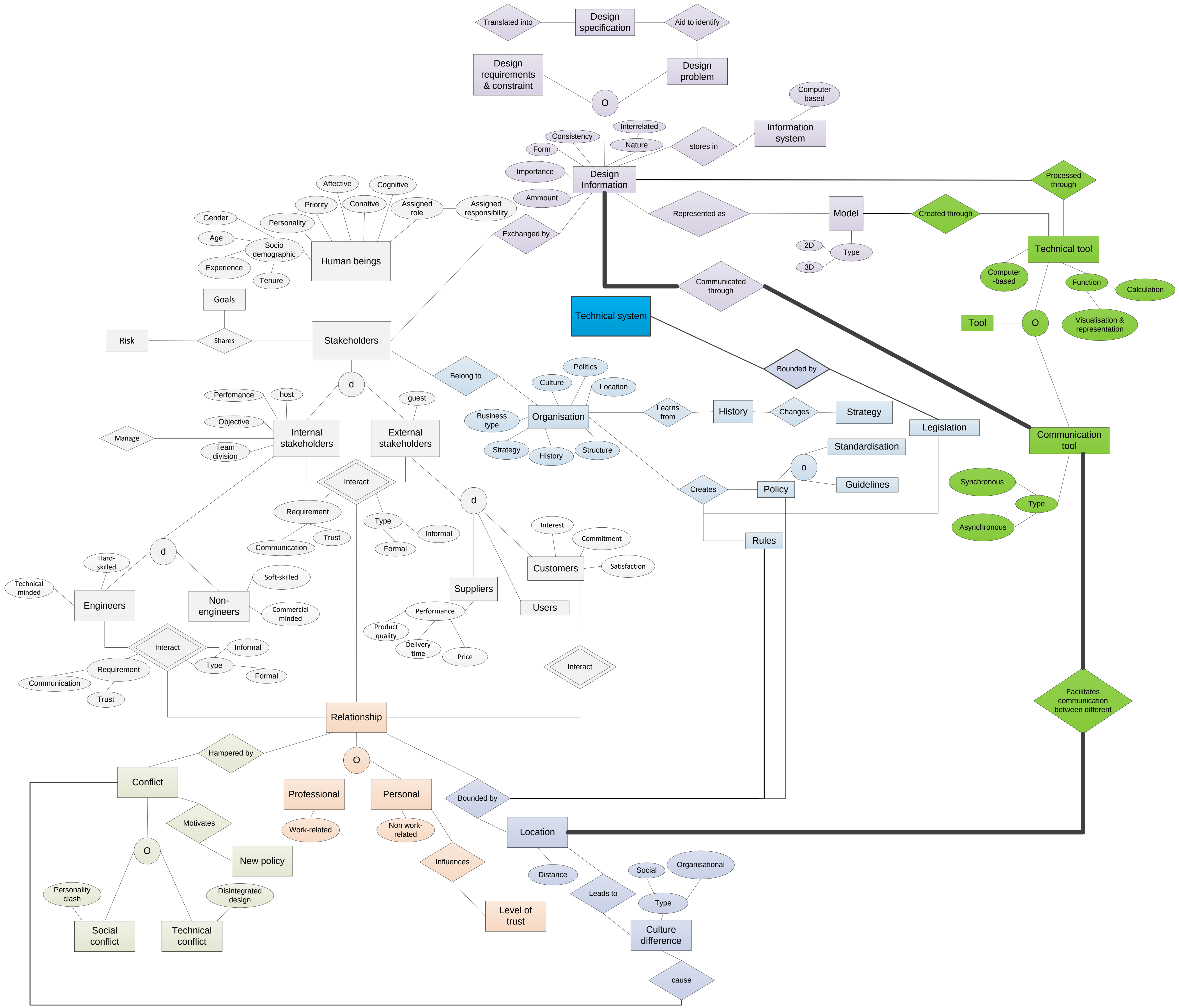


Figure 50 Combining the architectural model of tools to STAM of CED (2)

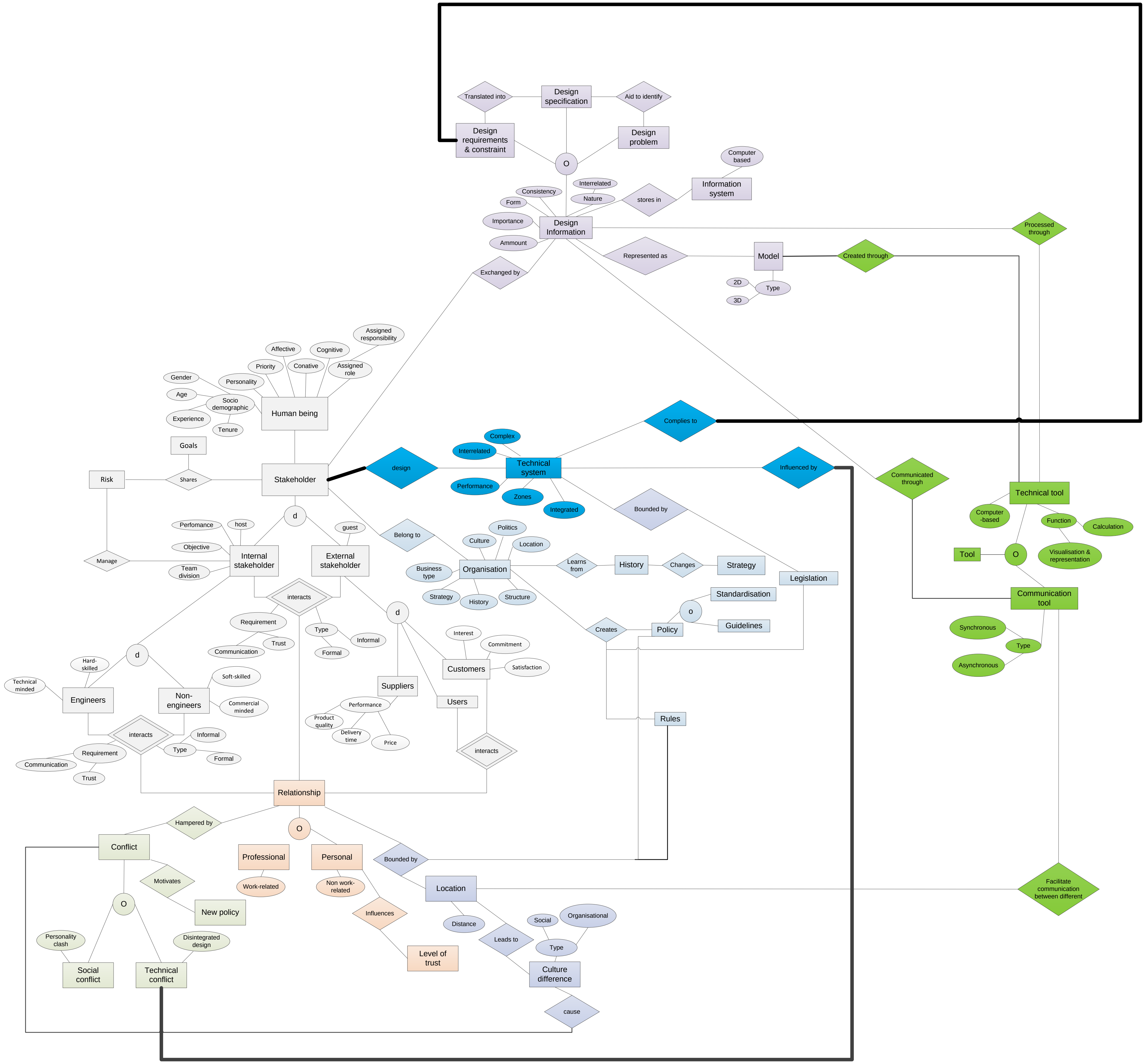


Figure 51 Combining the architectural model of technical system to the STAM of CED

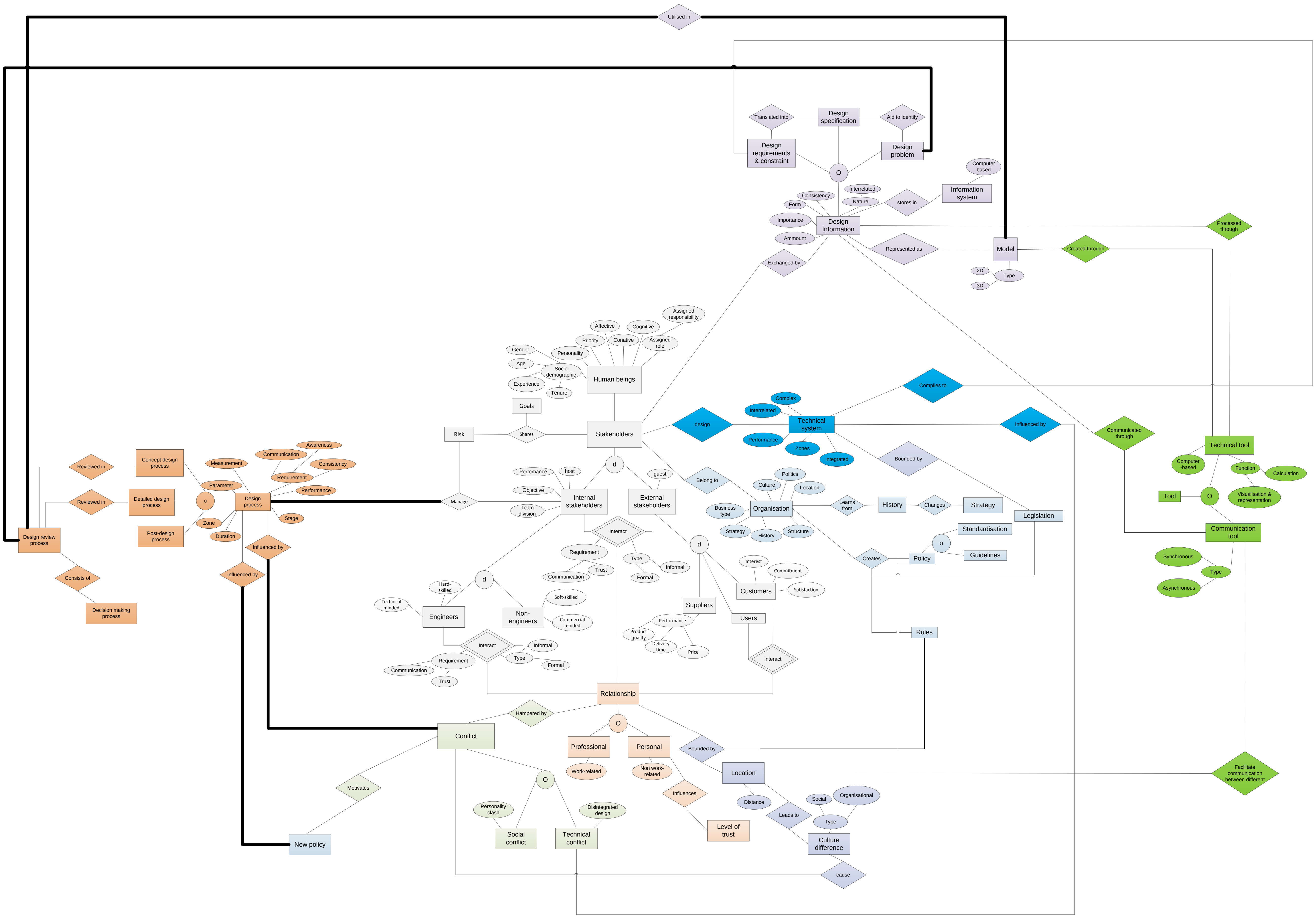


Figure 52 Combining the architectural model of design process to the STAM of CED (STAM-2)

With all combinations complete (as shown from Figure 43 to Figure 52), the second version of the socio-technical architectural model of CED (STAM-2) was constructed (Figure 52).

5.5 Differences between STAM-1 and STAM-2

In section 5.4, the second version of the socio-technical architectural model of CED was presented. The model was a refinement of STAM-1, presented in Section 4.5.2. The differences between model version 1 and version 2 are presented in this section, divided into two sub-sections. The two sub-sections are based on the area of refinements: 1) concept of the model, presented in Section 5.5.1, and 2) content of the model, presented in Section 5.5.2.

5.5.1 Concept of the model

From the literature, six socio-technical elements of CED were derived (Chapter 3). The number of elements was considered low with relatively simple relationships between each of them (i.e. non-intertwined relationships). Considering this, to develop the first model, only boxes and lines were used as graphical notations. However, the industrial investigation revealed 116 socio-technical elements and 33 types of relationship between the elements. Furthermore, the identified elements cannot be clustered in one category, as they are not all equal in importance/weighting. Considering the large number of elements and relationships, as well as the categorisation of elements, to develop the second model, a formal information modelling language called EER was adapted (see Appendix 8: Information modelling language review). In EER, the main elements of collaborative design were presented as entities, sub-elements as sub-entities, properties as attributes. The final category was relationships, which came from meaning categorisation. Each of the four categories was represented by a graphical notation, as explained in Appendix 8: Information modelling language review.

5.5.2 Content of the model

Concerning the content of the model, in a general sense, four main differences between the first and the second version of the socio-technical architectural model of CED were identified.

The first difference relates with the categorisation of the socio-technical elements. As aforementioned, from the literature exploration, six socio-technical elements of collaborative design were derived. These elements were seen equally as main elements. From the industrial investigation, 116 elements were obtained. In contrast with the first version of the model, these elements cannot all be seen as main elements. Instead, they must be split into four different categories: main elements, sub-elements (i.e. division of main element), properties that characterise main elements and sub-elements, and relationships between them all.

The second difference concerns the relationship between socio-technical elements of collaborative design. When developing the first version of the model, the relationships between the socio-technical elements were not identifiable. Thereby, the first model consists of two segregated social (Figure 14) and technical models (Figure 15). However, when developing the second version of the model, the relationships between the socio-technical elements were identified. Hence, the second version of the model consists of one consolidated model, containing interrelated socio-technical elements of CED.

The third difference refers to the existence of attributes in the model. From the preliminary investigation, attributes of (i.e. properties that characterise) the elements of CED were identified in a general manner (e.g. personality, behaviour) (Chapter 6). Nonetheless, they were not recognised as attributes, and they were not presented in the first version of the model. From the industrial investigation, attributes were identified in a more detailed manner (e.g. the existence of sub-attributes). According to Woodland and Hutton (2012, p.269), "Collaboration… must be characterised by specific attributes and variables so that its development, quantity, quality, and/or effects can be measured and observed". From this perspective, the attributes of collaboration need to be defined to support its development, and measurement of quantity, quality, and/or effects. On this basis, it seems reasonable to conclude that representing the attributes of socio-technical elements of CED can support the enhancement of said attributes. For this reason, the identified attributes were represented in the second version of the model.

Lastly, the fourth difference relates to the terminologies used in the model. The definitions of five terms were refined in the second version of the model. The definition refinements were based on the evolved understanding of socio-technical elements, gained from the industrial investigation. As an example, in model version 1, technical tools were defined as tools that support the creation of visualisation. However, the industrial investigation revealed that technical tools were also used to perform technical calculations (as discussed in Section 5.3.2.2). Accordingly, the definition of technical tools was refined. In Table 11, the refined terms are outlined and the difference in their definitions in model version 1 and model version 2 are presented.

Table 11 Definitions refinements of terms used in model version 1 and model version 2

Terms	Model version 1	Model version 2
Assigned role	Roles that relate with the human being's assigned function and/or hierarchical position in an organisation	Function in the collaborative design practice or in the company as appointed by the company, often relates with hierarchical position
Boundary	Acts/objects that limit collaborative design activity	Acts/objects that regulate or restrict relationship (between human beings) and/or the design of technical system
Tools	Devices that are used to support the design process	Instruments and/or application that execute a particular function(s)
Technical tools	The tools that are used to support creating visualisations of design	A type of tools to design (i.e. calculate and visualise) technical system
Communication tools	The tools that are used to support communication between collaborative design participants	A type of tools to exchange information between stakeholders

5.6 Summary and discussion

An industrial investigation was conducted to identify socio-technical elements of collaborative design from practitioners. The investigation was conducted in Company 1. The investigation was divided into two stages: data collection and data analysis. A semi-structured interview was adopted for data collection in which, 28 collaborative design practitioners were interviewed. The course of the interview was outlined in Section 5.1. For analysis purposes, each interview was audio recorded. The audio recordings were transcribed by the researcher and reviewed by a professional English transcriber to ensure accuracy (as described in Section 5.2.1). To analyse the interview transcriptions, they were *coded* and *condensed* (Section 5.2.2).

Coding involves applying specific codes to the interview transcriptions. Using meaning coding, 116 codes were derived. The codes consist of social and technical elements of collaborative design. They can be categorised into main elements, sub-elements, and the properties that characterise them (i.e. elements and sub-elements). Furthermore, considering the context of the codes, they can be clustered into nine themes: human being, interaction, conflict, organisation, boundary, design information, tools, technical system and design process.

Condensing involves summarising the statement of the interviewees to elicit the main theme of the statement. From this, 33 types of relationships, which connect the derived social and technical elements of collaborative design, were obtained. The elements and relationships were used as the basis to develop the socio-technical architectural model of CED (Section 5.3).

To develop the model, a formal information modelling language i.e. EER was adapted (Section 5.3.1). In EER, the main- and sub-elements of collaborative design were regarded as “entities”; properties that characterise the main- and sub-elements were regarded as “attributes”; and the relationship between the elements as “relationships”. Each was represented by a graphical notation (Appendix 8: Information modelling language review). Applying EER, the identified elements and their relationships were utilised to develop the model (presented from Section 5.3.2.1 to Section 5.3.2.9). From this, STAM-2 was generated (Section 5.4).

In Figure 53, the approach of industrial investigation, as summarised above, is depicted.

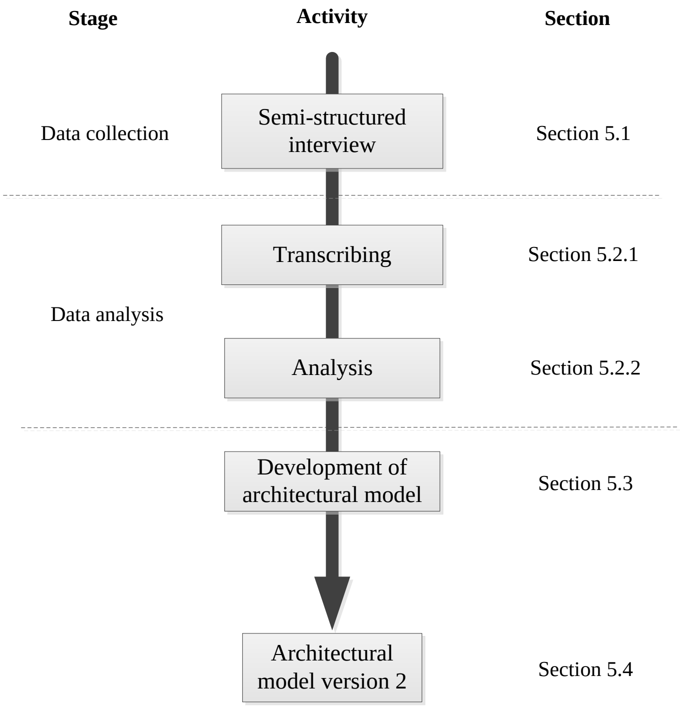


Figure 53 Industrial investigation approach

In comparison with STAM-1, five main differences can be identified in STAM-2 (Section 5.5). Firstly, STAM-2 was developed using a formal modelling language, while STAM-1 was developed without using a formal modelling language. Secondly, the socio-technical elements identified from the industrial investigation, presented in STAM- 2, were categorised into main elements, sub-elements, and attributes. The elements identified from the literature review, presented in STAM-1 can be categorised into main elements only. Thirdly, STAM-2 consists of one model, containing socio-technical elements of collaborative design and their interrelationships, while STAM-1 consists of two models, one consisting of the social elements and their relationships, and the other consisting of the technical elements and their relationships. From this perspective, the relationships between the socio-technical elements can be considered interrelated in STAM- 2, and segregated in STAM-1. Fourthly, in STAM-2, the attributes of socio-technical elements were presented, whereas in STAM-1, the attributes were absent. Table 12 summarises the differences between STAM-1 and STAM-2. Finally, the definitions of five terms were refined in model version 2: assigned role, boundary, tools, communication tools, and technical tools. The differences in definitions between the terms used in STAM-1 and STAM-2 were outlined in Table 11.

Table 12 Summary of differences between STAM-1 and STAM-2

Category	STAM-1	STAM-2
Information modelling language	No	Yes
Category of elements	Main elements	Main elements, sub-elements, and attributes
Relationship between socio-technical elements	Segregated	Interrelated
Attributes of socio-technical elements	No	Yes
Terms definition	See Table 11	

5.6.1 Discussion

While the industrial investigation revealed more detailed socio-technical elements of CED compared to the preliminary investigation, there are still lessons that can be learned from it and improvements, which can be made.

Within the industrial investigation, all participants can be considered as leaders in their team (e.g. supervisor, manager, director). Due to this, STAM-2 was developed based on a single perspective (i.e. a leader’s perspective). Furthermore, although the participants understand the overall practice of collaborative design in the company, their understandings tend to be general. For these reasons, involving non-leaders in the next model iterations were considered.

STAM- 2 was built from the perspective of internal stakeholders with relatively little perspective from external stakeholders. Only one external stakeholder (i.e. customer) could be interviewed due to the limited access given by Company 1, and the time available to collect the data. For a more multi-perspective approach, gaining insight from external stakeholders (i.e. suppliers and users) is needed. As such, involving external stakeholders was also considered for the next iteration of the model.

Reflecting upon the way the industrial investigation was conducted, interviews can be considered as a time-costly approach (e.g. approximately one-year duration covered for 28 interviews). As the available time to conduct the research was limited, other data collection approaches that require less time, such as focus groups needed to be explored to obtain further insights from CED practitioners.

Concluding from the lessons learned on the model development discussed above, to enhance the model's representativeness, the model needed further development. For this, multiple data-collection approaches such as focus group, involving various sources (e.g. non-leader and external stakeholders) for multi-perspectives purposes, were needed.

Part 3. Model evolution

6. Technical perspective

To enhance the representativeness of the model, multiple methods, involving various sources, were needed (Section 5.6.1). The first method selected was focus groups aiming at reviewing STAM-2 as the first part of the model review and refinement phase.

In a focus group method, opinions are elicited by giving a group of participants a specific topic to discuss (Chapter 2). To facilitate the discussion, the focus groups were conducted in a workshop form. In which, the participants were engaged in a set of activity pertinent to the topic of the discussion. Two independent workshops were conducted involving two groups of participants: 1) industrial practitioners, and 2) academics. In this chapter, how the model was reviewed and refined through these workshops is presented.

To ensure that the workshops were organised appropriately and therefore the desire aims could be achieved, a pilot study was conducted prior to the actual focus groups, explicated in Section 6.1. Based on the feedback given by the pilot group participants, the structure of the workshops was refined, outlined in Section 6.2. In Section 6.3, feedback (findings) derived from the participants of the workshop is summarised. These findings were used as the basis to review the model. In Section 6.5, how these findings were applied to refine STAM-2 is described along with how STAM-3 was generated (Section 6.6). This chapter is concluded with a summary of work, shown in Section 6.7.

6.1 Pilot study

A pilot study was conducted to ensure that the workshop was well structured and its aim, i.e. to review the model of CED could be achieved. The study was conducted in the Department of Design, Manufacture and Engineering Management (DMEM), at the University of Strathclyde. Six DMEM researchers participated in the study. They were selected based on their expertise in the fields pertinent to the study presented in this thesis, i.e. engineering design, design management, and system engineering. In addition, four of the participants were selected as they had experience of working with engineering designers in Company 1, where the workshop 1 (regarded as W1 throughout the thesis) was conducted.

The study started with a 15 minutes introductory presentation explaining the research, the socio-technical architectural model, the purpose of the workshop, and the organisation of the workshop (i.e. activities and allocated time). The workshop consisted of two main activities. The first activity was focussed on evaluating the architectural model, and the second activity was focussed on identifying the current state of collaborative design practice in the company.

For the first activity, the participants were divided into two groups. An A1 printed model was distributed to each group. Participants were asked to review the model, and make any necessary changes they thought applicable. Seventy-five minutes were allotted for this first activity. For the second activity, each participant was requested to fill in a set of questionnaires that queried the current state (i.e. strengths, challenges, and room for improvement) of collaborative design practice. Sixty-five minutes were allocated for this second activity.

During the course of the pilot study, an audio and video recorder were utilised so analysis could be undertaken later. After conducting the first and second activities, the participants were asked to provide feedback. The feedback provided by the participants can be grouped into three categories: 1) the organisation of the workshop, 2) the architectural model, and 3) the questionnaire. The feedback and how it was applied to refine the workshop is summarised in the following table (Table 13), based on the aforementioned categories.

Table 13 Refinement on the workshops organisations

Category	Feedback	Refinement
The organisation of the workshop	Increase the duration of introductory presentation.	Due to time limitation, the duration of the introductory presentation cannot be increased. However, the content of the presentation, particularly the explanation of the model, was refined.
	Distribute consent forms at the beginning of the workshop.	To maintain the flow of the workshop, a verbal consent to utilise recording device was asked prior to the introductory presentation. The distribution of consent forms followed subsequently to formalise the consent.
	Eliminate video recording.	To avoid discomfort, the use of video recording was eliminated. Audio recording was still used considering that during the industrial investigations, only one out of the 28 participants refused to be recorded. As such, the potential of discomfort was considered low.
	Add facilitator.	Considering the complexity of the model and the expected number of participants (i.e. more than 10), more than one person would facilitate the workshops. This, according to Saunders et al.(2007) would allow the discussion to be managed fully and at the same time, the data to be recorded appropriately.

The architectural model	Simplify the model presentation.	To simplify the model presentation, the model was divided into 5 zones. Each zone represents a theme. For example, Zone 1 represents the theme of "human being". The model was marked based on each zone, as can be seen in Appendix 7. Each group was assigned to review a zone in an allocated time. Once the time finished, they would be assigned to a different zone. This allowed the participants to focus on one zone at a time, and thus, not be overwhelmed by the size of the model. However, it meant that participants did not lose the overall concept of the model.
	Add direction arrows to the model.	In the EER concept (the formal information modelling language utilised to develop the model), all relationships are considered bi-directional. Thus, arrows are not used. Adding arrows to the model may infringe the concept of EER For this reason, arrows were not added in the architectural model.
	Add a glossary (i.e. explaining the definition of terms used in the model).	A glossary was written and distributed to the workshop participants to ensure that they had a shared understanding of the terms used in the model.
	Add a legend (i.e. explaining the graphical notations used in the model).	A legend was attached in a separate paper and distributed to the participants to facilitate their understanding of the model.
The questionnaire	Eliminate questionnaire and find an alternative.	The questions asked in the questionnaire were considered open-ended. According to Saunders et al. (2007), a questionnaire may be inappropriate to ask open-ended questions. Thus, the questionnaire was eliminated from the workshop. It was replaced with a group discussion.

6.2 Structure of workshops

As aforementioned, two workshops were conducted to review the model. In this section, the structure of the workshops is presented, divided into two sections: Section 6.2.1, presents the structure of the workshop with industrial practitioners (hereafter W1), and Section 6.2.2, presents the structure of the workshop with academics (hereafter W2).

6.2.1 W1

W1 was conducted in Company 1, the same company as the industrial investigation (Chapter 5). The workshop was attended by eight engineering design practitioners. These practitioners (regarded as IP-2 from here on), were not involved in the interviews for the industrial investigation. To capture the participants' profile (e.g. personal information and experience), a form was distributed to the participants. Seven out of the eight forms were returned. The profile of W1 participants are outlined in Appendix 10 based on the participants' current position in the company (Table 81), years of experience in the company (Table 82), and years of experience in the current position (Table 83).

As can be seen in Appendix 10.1, three participants were identified as managers, and four as non-managers. In terms of experience, three participants have less than ten years while the rest (i.e. four participants) have more than ten years of experience working with the company. From these numbers, two participants have more than 10 years of experience in their current position, whilst the others (i.e. five participants) have less than 10 years of experience in their current position. Additionally, it was mentioned during the workshop that all participants have an engineering background.

The workshop started with a five-minute opening speech from the company's Engineering Director. This was done to emphasise the importance of the workshop for the company and the expected contributions from the participants. Subsequently, a fifteen-minute introductory presentation was given by the researcher. The presentation covered a brief explanation of the study, the developed architectural model, and the organisation of the workshop. The participants were then divided into four groups to conduct the two main activities in the workshop.

The first activity was focussed on reviewing the architectural model. For this, an A1 printed model was distributed to each group. Each group was assigned to a different zone so that the views of one group were not affected by the views of the other groups. Each group was asked to review the model for any missing, irrelevant, and/or inappropriate elements (i.e. entities, sub-entities, attributes, and relationships). Ten minutes were allotted for each zone. Once the ten minutes finished, the groups were asked to move to the next zone and continue reviewing. Fifty minutes were allocated for this activity. During the following twenty minutes, each group was asked to present their feedback allowing other groups to clarify, to challenge and/or to discuss the feedback.

The second activity focussed on identifying the current state of collaborative design practice in Company 1. This was requested by the company for their evaluation purposes. The second activity did not provide any additional information that would be useful for further model development. It merely provided reflection for Company 1's CED performance. For this reason, results from this activity are not included in this thesis.

W1 was concluded with a summary of work. In total, W1 lasted for approximately three hours.

6.2.2 W2

W2 was conducted at an international conference of engineering design, considering that the conference's attendees were experts in the field of engineering design. The workshop was attended by twenty-two academics from various research fields.

To capture the participants' profile (e.g. personal information and experience) a form was distributed to the participants. Fourteen out of the twenty-two forms were returned. Based on the returned forms, the profiles of the participants are outlined in Appendix 10: Profile of workshops participants. They are categorised based on the profession of the participants (Table 84), research field of the participants (Table 85) and the duration in the field (Table 86).

As can be seen in the Appendices, eight attendees were identified as PhD students, and six were identified as "others", which includes lecturers and researchers. In terms of the research field, three attendees came from the design process research field, two from design theory, three from collaborative design, two from product development, three from innovation, and one from design management. Six attendees were researching in their field for less than two years; two attendees between two to four years; three between four to six years, and three attendees were researching in their field for more than six years.

The workshop opened with a fifteen-minute introductory presentation. This covered an overview of the CED concept, the developed architectural model, and the organisation of the workshop. The participants were then divided into five groups to conduct the two activities in the workshop.

Similar with W1, the first activity focussed on reviewing the model. The same version of the model used in W1 was printed in A1, and distributed to each group in W2. As conducted in W1, in W2, each group was assigned to a zone, and they were asked to review the elements of the model in the assigned zone only to reduce potential cross-discussion between different groups. Considering the number of participants in each group (i.e. five to six participants), twenty minutes was allocated to evaluate each zone. Once the allocated time finished, the groups were asked to move to the next zone and continue reviewing. Due to the time limitation allotted by the organiser of the conference, this activity was restricted to one hour only. After one hour, each group was asked to present their feedback and discuss it with the other groups of participants.

Similar with W1, in W2, two activities with different focus areas (i.e. one focussed on reviewing the model, and one focussed on identifying the current state of CED) were planned. However, due to the limited time (less than three hours) and the larger number of participants (i.e. twenty-two) when compared to W1, it was not possible to conduct the second activity.

The workshop concluded with a summary of work. In total, W2 lasted for approximately two hours and thirty minutes.

6.3 Feedback from the participants

During the first activity in W1 and W2, the participants were asked to review the elements (i.e. entities, sub-entities, attributes and relationships) presented in the model. From this activity, feedback from the participants was obtained. The feedback can be grouped into three categories: addition, deletion, and refinement. Each category can be described as follows:

1. **Addition** refers to the category of feedback for any element that was missing, however the participants considered essential to be included. For example, the participants argued that "technical drawing" is the main result of the design process, and thus considered an essential part of collaborative design activity. However, this was not present in the model. For this reason, the participants suggested to add "technical drawing" to the model.
2. **Deletion** refers to the category of feedback for any element that the participants considered unnecessary to be in the model and thus, needs to be deleted. For example, a group of participants claimed that although engineers mainly consider technical aspects (e.g. dimension) when designing the technical system, they also consider commercial aspects (e.g. material price). For this reason, the participants believed that the engineer should not be characterised as being technical[ly]-minded. For this reason, they suggested to delete technical minded from the model.
3. **Refinement** can be divided into:
   - **Category refinement** refers to the category of feedback for any element that was considered inappropriately categorised. For example, the relationship between stakeholder and its sub-classes was perceived as disjointed instead of overlapping. As such, the participants suggested refining the category of the relationship accordingly.

- **Term refinement** refers to the category of feedback for the element *term* that was considered inappropriately used. For example, conflict and design process were linked by the term influences. A group of participants recommended refining the term influences into impacts for two reasons. Firstly, the term influence was considered too general. Secondly, the group argued that the relationship between conflict and design process needs to be emphasised and the term impact was considered appropriate.

Fifty-one feedback points were derived from W1, consisting of forty-one additions, six deletions, two category refinements, and two term refinements.

In addition to the above categories, one further category, i.e. expansion, was identified by participants in W2 only. Expansion refers to the category of feedback for any element that was considered inadequately represented. However, the specifications of the refinements were not articulated. For example, a group of participants believed that the theme “design process” needs further investigation, and thus, they suggested expanding this theme. However, they did not specify how the theme should be expanded. Fifty-three feedback points related to the content of the model were identified from W2, consisting of twenty-nine additions, nine deletions, nine category refinements, four term refinements, and two expansions.

In W2, the identified feedback was merely related to the elements of the model (i.e. content). However, in W2, the identified feedback was also related to the ideas of the model (i.e. concept). The concept feedback can be grouped into four categories: 1) purpose, relating to the reason behind the model development; 2) emphasis, relating to the focus of the model; 3) presentation, relating to the appearance and the organisation of the model; and 4) development, relating to the approach of the model development. Eight concept feedback points were derived from W2, consisting of one purpose, two emphases, four presentations, and one development of the model.

6.4 Applicability of feedback

As aforementioned, from W1, fifty-one feedback points were derived. These feedback points are all related to the content of the model. From W2, sixty-one feedback points were derived, consisting of fifty-three that are related to the content of the model and eight that are related to the concept of the model. The feedback points were reviewed for their applicability to refine the model based on five premises (referred to as **P1** to **P5** throughout the thesis). These premises were constructed upon the following three aspects.

Firstly, justification, which refers to the rationale of the feedback or the reason why the feedback was conveyed. This includes elaboration on the feedback and examples used for justification. Justification was considered an essential aspect to warrant the reliability of the feedback. As reliability is one of the criteria that determines the quality of research (Zhang and Wildemuth, 2009), if a feedback point is not justified, then it cannot be applied in the model.

If a feedback point is justified, there are two other aspects that need to be reviewed: 1) alignment to research approach, such as alignment to the concept of the information modelling language used, 2) alignment to research findings, such as alignment to findings from the literature review and/or the industrial investigation. These two aspects were considered important. Alignment to research approach was deemed important to ensure that the model was developed in a consistent manner and that the aim of the model could be achieved, while alignment to findings was to minimise any potential bias. However, as not all feedback points were related to both research approach and research findings, the alignment to research approach and research findings were reviewed depending on the context of the feedback point. For example, if a feedback point related to research approach, to conclude that said feedback point was applicable or not, it was reviewed in line with the research approach aspect only.

Three categories of applicability were derived from the review:

Firstly, **applicable**, when the result of the review shows that the feedback point is appropriate for inclusion in the model. This category stands on the premise that *if feedback is justified and aligned to the research approach and/or research findings, then it is applicable* (regarded as **P1**). For example, the participants in W1 disagreed that risks are managed by the internal stakeholder solely. According to them, both internal and external stakeholders have risks that they need to manage. They provided an example that the internal stakeholder needs to manage the risk of design failure by testing different types of prototypes, while the external stakeholder needs to manage the risk of late delivery by having frequent design progress meetings[1]. This example was perceived as a justification as it provides evidence for the feedback given. Based on this justification, they suggested to delete <u>manage</u> that connects <u>risk</u> and <u>internal stakeholder</u> and add <u>manage</u> to connect <u>risk</u> and <u>stakeholder</u>. This suggestion was aligned with the findings from the industrial investigation, which indicated that the internal stakeholders manage the risk of rework and the external stakeholders manage the risk of having a failed product[2]. As the feedback point was justified and aligned to findings, it was deemed applicable.

In Table 14, the example presented above is summarised.

Table 14 Example of applicability conclusion based on P1

Feedback	**Applicability rule**		**Conclusion**
	Justification	**Alignment to research findings**	
Delete "manage " that connects "risk" and "internal stakeholder"	✓([1])	✓([2])	Applicable

Secondly, **partly applicable**, meaning that the feedback point was inappropriate for full inclusion in the model, however, it was still insightful. This category was based upon the premise that *if feedback is justified and aligned to the research approach and/or findings, however the suggestion on how to change the model does not align to the research approach and/or findings, or vice versa, then it is partly applicable* (regarded as **P2)**. For example, in W1, the participants mentioned that technical conflict can be differentiated by its cause. They provided an example that technical conflict caused by miscommunication is different with technical conflict caused by customer's technical requirements. In other words, technical conflict can be described by its cause[3]. Thus, they suggested adding <u>cause</u> as an attribute of <u>technical conflict</u>. Similar examples were also identified from the industrial investigation findings[4]. However, it was found from the industrial investigation that <u>cause</u> can be used not only to describe <u>technical conflict</u> but also <u>conflict</u> in general[5]. For example, personality difference can be used to describe social conflict, while incorrect information can be used to describe technical conflict. Based on this, instead of adding <u>cause</u> as an attribute of <u>technical conflict</u> as suggested by the participants, it was instead added as an attribute of <u>conflict</u>.

In Table 15, the example presented above is summarised.

Table 15 Example of applicability conclusion based on P2

Feedback	**Applicability rule**		**Suggestion**	**Conclusion**
	Justification	**Alignment to research findings**	**Alignment to research finding**	
Add "cause" as an attribute of "technical conflict"	✓([3])	✓([4])	×([5])	Partly applicable

Thirdly, **inapplicable**, when the result of the review concludes that the feedback point is not appropriate for inclusion in the model. Contrarily to the premise that defined the applicable category, the premise that defined the inapplicable category was that *if feedback is unjustified and/or not aligned to the research approach and/or not aligned to the research findings then it is inapplicable* (regarded as **P3**). For example, the participants from W2 mentioned that the relationship between stakeholders was not properly represented in the model. However, the feedback was given without suggestions of how to alter the model, nor the reason for the feedback. In other words, this feedback point was unjustified. Furthermore, relationship between stakeholders has been shown by the term interact in the model, based on the findings from the industrial investigation (see Chapter 5). The existence of different types of relationship was not apparent. Thus, the feedback was also considered not aligned with the research findings. Based on these points, the feedback was deemed inapplicable.

Additionally, during the review, it was found that several feedback points had already been included in the model, making the repetition of said feedback points inapplicable. For this reason, the following premise was also used to define inapplicable feedback: *if feedback is already applied in the model, then it is inapplicable* (regarded as **P4**). As an example, according to the participants of W1, one of the main interactions between external and internal stakeholder relates to the activity of evaluation. In this activity, external stakeholders provide feedback towards the design of the technical system, normally presented by internal stakeholders. Such activity (providing feedback) was identified during the design review process, and this process had been represented in the model by the entity design review process. Therefore, adding feedback loops in the interaction between the "internal stakeholders" and "external stakeholders" entities were deemed unnecessary, and thus, inapplicable.

Finally, as there are many dependencies in the model, if a feedback point alters the applicability of one entity, it could also alter the applicability of any children that the entity has (sub-entities, attributes, etc). Therefore, the final premise stated that *if feedback is linked to prior or other feedback, then the equivalent outcome applies* (regarded as **P5**). For example, participants from both workshops suggested deleting engineer entity. After reviewing the feedback (see Appendix 11 – HS1), it was concluded that the suggestion was deemed applicable. In the model, engineer entity has two attributes, technical minded and hard skill, which the participants also suggested to be deleted. Since these attributes are attached to the engineer entity (or in other words, they are parts of other feedback points), the applied suggestion to delete the engineer entity resulted in the technical minded and hard skill attributes also being deleted.

The detailed review of the feedback based on the applicable rules can be seen in Appendix 11: Review on the applicability of the feedback.

6.5 The refinements of the architectural model

In Section 6.3, feedback obtained from the two workshops and the conclusions from the analysis were presented. Their applicability was reviewed, summarised in Section 6.4. The applicable and partly applicable feedback points were used as the basis to refine the model, which denote the differences between STAM-2 and STAM-3. In this section, how the model was refined based on these points is presented, divided into two sub-sections: Section 6.5.1 describes the refinements on the concept (e.g. structure) of the model, while Section 6.5.2 describes the refinements on the content (e.g. entities) of the model.

6.5.1 Concept of the model

From the analysis summarised and presented in Section 6.4, three feedback points were considered applicable for use to refine the concept of the architectural model. They are all related to the presentation of the model. In this section, how the model was refined based on these feedback points is described. Each feedback point was assigned with an identified code as can be seen in Appendix 11. The descriptions are divided into three sections. In Section 6.5.1, the refinement related to the complexity of the presentation of the model (CO-5) is presented. In Section 6.5.1.2, the model refinement related to the consistency of the model attributes (CO-7) is given. In Section 6.5.1.3, the model refinement related to the direction of relationship between entities (CO-8) is outlined.

In addition to the above, one feedback point was considered partly applicable, i.e. purpose of the model (CO-1). The reason for this point was due to the inadequate initial explanation of the model's purpose by the researcher, not due to an inherent issue with the model itself. Based on the analysis in Appendix 11.1, a refinement to the verbal model explanation by the researcher during presentation was necessary. Since this is not an issue of the model, this refinement is not documented in this thesis, and thus, is excluded from this section.

6.5.1.1 The complexity of the model's presentation

The participants in W2 concluded that the model was overly complex due to its high level of detail, and thus, the model was difficult to understand. To provide a simpler presentation of the model, several participants suggested reducing the number of elements in the model.

However, the elements of the model (i.e. entity, sub-entity, attributes and relationship) are considered compulsory to properly explicate the phenomena of CED activity (See Section 7.4.1). Brooks & Tobias (1996, p.2) remarked, "A model that is too simple will be unrealistic and so its results will be, at best, of little use, and at worst, misleading". For this reason, reducing the number of elements in model was considered inappropriate and thus, was not applied to the model.

According to Brooks & Tobias (1996, p.11), "If the main purpose of the study is gaining an understanding of a system [i.e. CED activity] then the benefits of building models at several levels of detail may be well worth the additional effort involved". Furthermore, building a model at different levels of detail can accommodate the preferences of multiple users. For example, a simple model is often favoured by those who have less experience and limited knowledge on the model being developed (Brooks and Tobias 1996) while those with more experience and knowledge of the model often prefer more detail. On this basis, to accommodate the concern over the model's complexity, without reducing the number of elements, the model was presented at two levels of detail, which can be explained as follows:

At the greatest level of detail (i.e. Level 2), the model consists of entities, sub-entities, relationships, and attributes. It was developed from the literature review and industrial investigation, and reviewed in the workshops.

At the lowest level of detail (i.e. Level 1) the model consists of entities and relationships aimed at describing CED in a general sense. To develop the model in level 1, parts of the level 2 model were aggregated. For example, as can be seen in Figure 54, to develop the level 1 model, all elements of the model that can be categorised as "human being" (e.g. stakeholder and its attributes) are aggregated as "human being", while all elements of the model that can be categorised as "organisation" (e.g. history, strategy, policy and, their attributes) are aggregated as "organisation". To identify the relationship between "human being" (Entity A) and "organisation" (Entity B), i.e. relationship C, all relationships that link the elements of the theme "human being" and the elements of the theme "organisation" were aggregated.

It should be noted that model level 1 was developed for ease of communication purposes and/or if a more high-level of model abstraction is needed by the users.

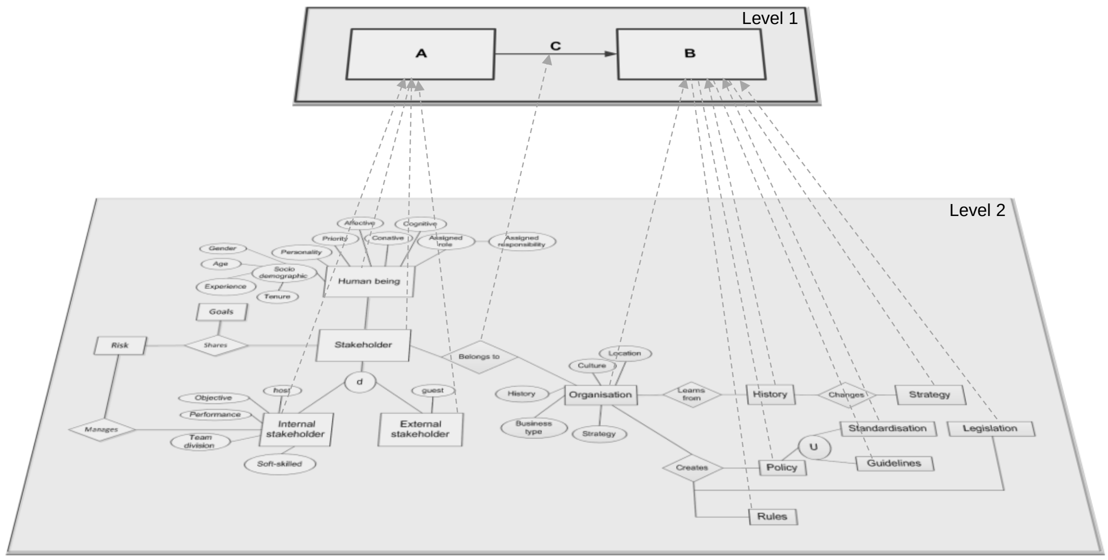


Figure 54 Example of model aggregation from model level 2 to model level 1

6.5.1.2 The consistency of attributes

The participants in W2 identified inconsistencies of the attributes presented in the model. For example, function was presented as an attribute of technical tool. In this view, function can be seen as a property that describes a technical tool. This is aligned with the basic definition of an attribute. However, computer-based was also presented as an attribute of technical tool. The participants argued that computer-based and function could not be put into the same definition category. Computer-based cannot be seen as a property of technical tool, and thus, cannot be categorised as an attribute. The participants questioned the basic definition of attribute and suggested to review all attributes presented in the model based on this definition to ensure its consistency. For this reason, the concept of attribute in EER was revisited.

During the development of version 2 of the architectural model (Chapter 5), the concept of an attribute was identified in a basic sense, i.e. the identification of the concept was limited to the definition of *attribute* (i.e. a property that describes an entity or relationship), and *sub-attribute* (i.e. a division or sub-class of attribute). However, in addition to this basic concept, there is a concept of value attribute that was not considered. An attribute has value(s) that describe it (Elmasri and Navathe, 2011), regarded as value attribute. For example, a student has a name, i.e. John Doe. Based on the concept of EER (Appendix 8), "a student" can be defined as an entity and "name" as an attribute. "John Doe" describes the said attribute (i.e. name), and thus, it is regarded as a value attribute. In EER concept, the existence of *value attribute* is not graphically represented.

Adding the concept of value, the attributes presented in the architectural model were analysed. To exemplify this, the attribute of technical tool is used. As presented in the model, a "technical tool" is described by its "function". Based on the industrial investigation, there are two main functions of technical tool: "calculation", and "visualisation representation". In this sense, calculation, visualisation and representation describe the functions (i.e. attributes) of a technical tool. As such, they can be categorised as *value attributes*. However, "calculation" and "visualisation and representation" were presented as sub-attributes in version 2 of the model (as depicted by Figure 55) and thus, need to be refined accordingly.

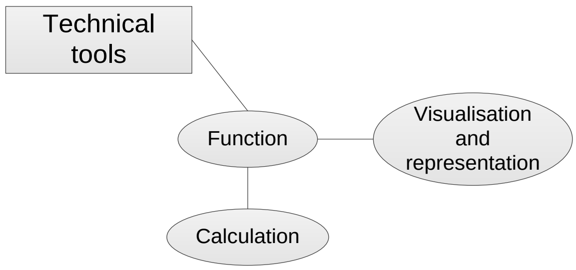


Figure 55 Example of inappropriate application of attribute

The results of the analysis are presented in conjunction with the content refinement of the model, from Section 6.5.2.1 to Section 6.5.2.9.

6.5.1.3 The directions of relationships between entities

The participants from W2 concluded that the directions of relationships between entities in the model cannot be intuitively understood. For example, from the industrial investigation, stakeholders were viewed as the designers of a technical system (see Section 5.3.2.8). To present this relationship in the model, stakeholders and technical system were linked by the term design (depicted by Figure 56). However, according to the participants in both workshops, such presentation can lead to misinterpretation. For example, a participant remarked, if the model (Figure 56) is viewed from right to left, with limited knowledge of the EER concept, the relationship between stakeholders and technical system can be read as: "a technical system designs stakeholders". The model is however developed for general readers, which can have varying levels of knowledge on the concept of EER. To avoid misinterpretation and to clarify the direction of relationship between entities, directional arrows were added, as depicted by Figure 57. Such refinement was applied throughout the architectural model.

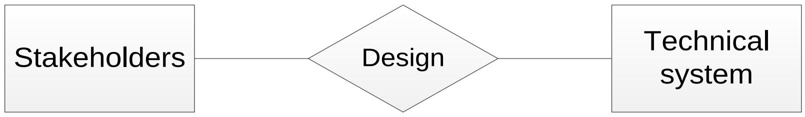


Figure 56 Relationship between stakeholders and technical system as shown in STAM-2

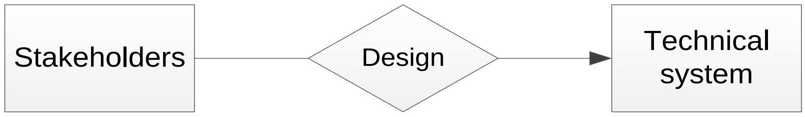


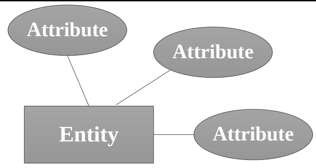
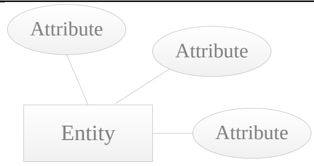
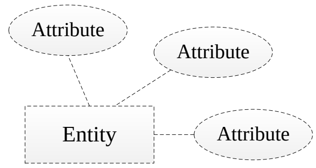
Figure 57 Refinement of the relationship between stakeholders and technical system based on the feedback from participants

In addition to the above feedback, the participants also recommended evaluating the terms used to represent relationships. For this reason, the terms were reviewed and inconsistencies were identified. Several terms were identified as active verbs (e.g. designs, influences) while others were passive (e.g. bounded by, utilised in). The utilisation of passive and active verbs can be related to the tone intended to convey a sentence. According to Sigel (2009, p.478), an active voice allows the reader to understand the meaning of a sentence as it clearly shows the subject, the verb and the object (i.e. who is doing what to whom) of a sentence. Contrarily, a passive voice can prevent the reader from understanding the meaning of a sentence, as the subjects, the verb, and the object are rather unclear. Since the aim of the model is to allow the readers and/or users to gain a better understanding of CED (Chapter 1), the model needs to be easily understood. As such, an active voice was preferred within the model. To present an active voice, active terms were used to connect entities throughout the model.

6.5.2 Content of the model

In this section, how the contents (i.e. elements) of the model (i.e. entity, sub-entity, attributes and relationship) were refined based on the **applicable** and **partly applicable** feedback points (presented in Section 6.4) is described from Section 6.5.2.1 to Section 6.5.2.9, following the theme identified in Section 5.2.2 (i.e. human being, relationship, conflict, organisation, boundary, design information, tools, technical system and design process). Four categories of refinements can be identified: **addition**, when content was added to the model, **deletion**, when content was removed, **category refinement**, when the category of certain content was refined (e.g. from entity to attribute), and **term refinement**, when the term used to represent the content was refined (e.g. “influence” to “impact”). To signify these refinements in the model, the following notations were applied: 1) a dark colour for addition, 2) part-transparency for deletion, and 3) a dotted line for category and term refinement. Table 16 depict these notations.

Table 16 Representations of the feedback applications to the architectural model

Addition	Deletion	Refinement
		

6.5.2.1 Human being

On the theme "human being", twelve refinements were made based on the feedback analysis, presented in Section 6.4. Ten of these were made based on the applicable feedback (Table 17) and two were made based on partly applicable feedback (Table 18).

Table 17 List of refinements on human being from applicable feedbacks

Element of model	Category of refinement	Description of refinement
Sub-entity	Deletion	Delete "engineer" sub-entity.
Sub-entity	Deletion	Delete "non-engineer" sub-entity.
Attribute	Addition	Add "skill" as attribute of stakeholders.
Attribute	Deletion	Delete "technical minded", an attribute of "engineer".
Attribute	Deletion	Delete "commercial minded", an attribute of "non-engineer".
Attribute	Deletion	Delete "hard skilled", an attribute of "engineer".
Attribute	Deletion	Delete "soft skilled", an attribute of "non-engineer" entity.
Relationship	Addition	Add "manages" to connect "risk" and "stakeholder".
Relationship	Addition	Add "supply" to connect "supplier" and "design information".
Relationship	Deletion	Delete "manage" that connects "risk" and "internal stakeholder".

Table 18 List of refinements on human being from partly applicable feedback

Element of model	Category of refinement	Description of refinement
Sub-entity	Deletion	Delete "users".
Sub-entity	Term refinement	Refine "customers" into "customers and users".

In addition to the refinement listed in Table 17 and Table 18, thirty-two further refinements were made. These were motivated by the refinements listed above and feedbacks from participants on the concept of the model (discussed in Section 6.5.1). For example, from the literature review, “human beings” was identified as the main actor of CED activity (Chapter 4). A sub-class of human being, i.e. “stakeholders” was identified from the industrial investigation as a specific name for actor of CED activity. In the model, “human beings” and “stakeholders” were presented separately, as entity and sub-entity, respectively. However, presenting human being and stakeholder as mentioned have created confusions amongst the participants of both workshops. A question on why the presentation of human being and stakeholder were raised by the participants. Although the participants did not make further comment, it motivated further exploration. For this reason, the existence of human being and stakeholder as two separate entities was re-evaluated. Based on the re-evaluation (explained in Appendix 11.2), the entity “human being” was deleted from the model.

The type of refinements derived as exemplified above are described in Appendix 12: Additional refinements.

Table 19 List of additional refinements on human being

Element of model	Category of refinement	Description of refinement
Entity	Deletion	Delete “human being” entity.
Entity	Addition	Add “opinions” as an entity.
Attribute	Deletion	Delete “performance”, an attribute of “internal stakeholder”.
Attribute	Deletion	Delete “objective”, an attribute of “internal stakeholder”.
Attribute	Deletion	Delete “host”, an attribute of “internal stakeholder”.
Attribute	Deletion	Delete “guest”, an attribute of “external stakeholder”.
Attribute	Deletion	Delete “product quality”, a sub-attribute of “suppliers”.
Attribute	Deletion	Delete “delivery time”, a sub-attribute of “suppliers”.
Attribute	Deletion	Delete “price”, a sub-attribute of “suppliers”.
Attribute	Deletion	Delete "requirement", an attribute of "interact".
Attribute	Deletion	Delete "requirement", an attribute of "interact" that connects “engineers” and “non-engineers”.
Attribute	Deletion	Delete "type", an attribute of "interact" that connects “engineers” and “non-engineers”.
Attribute	Deletion	Delete “communication”, a sub-attribute of “interact” that connects “engineers” and “non-engineers”.
Attribute	Deletion	Delete “trust”, a sub-attribute of “interact” that connects “engineers” and “non-engineers”.
Attribute	Category refinement	Refine “personality” from an attribute of “human being” to an attribute of “stakeholders”.
Attribute	Category refinement	Refine “priority” from an attribute of “human being” to an attribute of “stakeholders”.
Attribute	Category refinement	Refine “affective” from an attribute of “human being” to an attribute of “stakeholders”.

Attribute	Category refinement	Refine “cognitive” from an attribute of “human being” to an attribute of “stakeholders”.
Attribute	Category refinement	Refine “conative” from an attribute of “human being” to an attribute of “stakeholders”.
Attribute	Category refinement	Refine “assigned role” from an attribute of “human being” to an attribute of “stakeholders”.
Attribute	Category refinement	Refine “assigned responsibility” from a sub-attribute of “human being” to a sub- attribute of “stakeholders”.
Attribute	Category refinement	Refine “socio demographic” from an attribute of “human being” to an attribute of “stakeholders”.
Attribute	Category refinement	Refine “gender” from a sub-attribute of “human being” to a sub- attribute of “stakeholders”.
Attribute	Category refinement	Refine “age” from a sub-attribute of “human being” to a sub- attribute of “stakeholders”.
Attribute	Category refinement	Refine “experience” from a sub-attribute of “human being” to a sub- attribute of “stakeholders”.
Attribute	Category refinement	Refine “tenure” from a sub-attribute of “human being” to a sub- attribute of “stakeholders”.
Relationship	Addition	Add “communicate” as a relationship loop attached to “internal stakeholders”.
Relationship	Addition	Add “communicate” as a relationship loop attached to “customers and users”.
Relationship	Addition	Add “provide” to connect “customers and users” and “design requirement and constraint”.
Relationship	Deletion	Delete “interact” that connects “customers” and “users”.
Relationship	Deletion	Delete “interact” that connects “engineers” and “non-engineers”.
Relationship	Term refinement	Refine “interact” that connects “internal stakeholders” and “external stakeholders” into “communicate”.

The refinements of the “human being” architectural model based on Table 17, Table 18, and Table 19 are depicted in Figure 58, using the graphical notations as shown in Table 16.

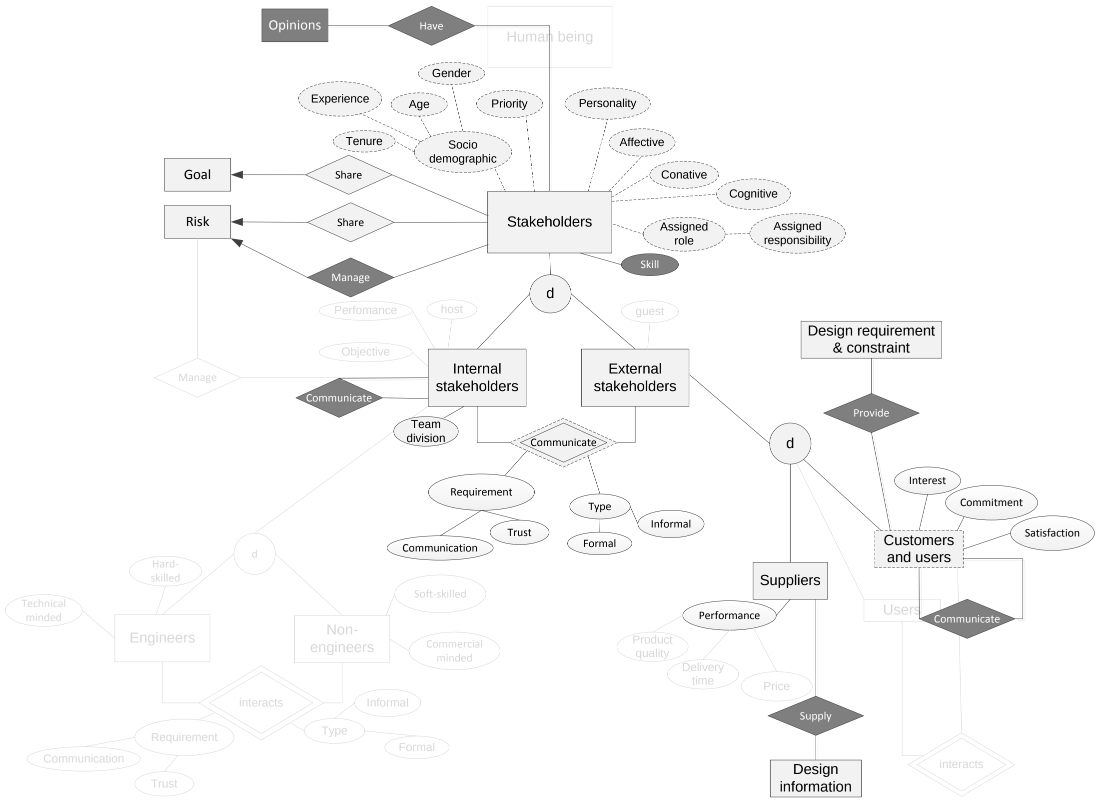


Figure 58 Refined architectural model of human being

6.5.2.2 Interaction

Four refinements on the "interaction" theme were made. Table 20 presents these refinements.

Table 20 List of refinements on interaction

Element of model	Category of refinement	Description of refinement
Entity	Addition	Add "communication" entity
Attribute	Addition	Add "value" as an attribute of "relationship"
Relationship	Addition	Add "influence" to connect "relationship" and "level of trust"
Relationship	Deletion	Delete "influence" that connects "personal relationship" and "level of trust"

In addition to the refinements listed in Table 20, Table 21 summarises nine refinements that were a result of the above refinements (discussed in Section 6.5.1).

Table 21 List of additional refinements on interaction

Element of model	Category of refinement	Description of refinement
Entity	Term refinement	Refine "level of trust" to "trust"
Attribute	Addition	Add “level” as an attribute of “trust”
Attribute	Addition	Add "formal" and "informal" as sub-entities of "communication" with "disjointed" relationship
Attribute	Addition	Add "way of establishment" as an attribute of "relationship"
Attribute	Deletion	Delete "work related", a sub-attribute of "professional" relationship
Attribute	Deletion	Delete "non-work related", a sub-attribute of "personal" relationship
Relationship	Addition	Add "perform" to connect "stakeholder" and "communication
Relationship	Addition	Add "create" to connect "communication" and "relationship"
Relationship	Category refinement	Refine "communicate" from identifying relationship to relationship

The changes to the “interaction” architectural model based on Table 20 and Table 21 can be seen in Figure 59 below.

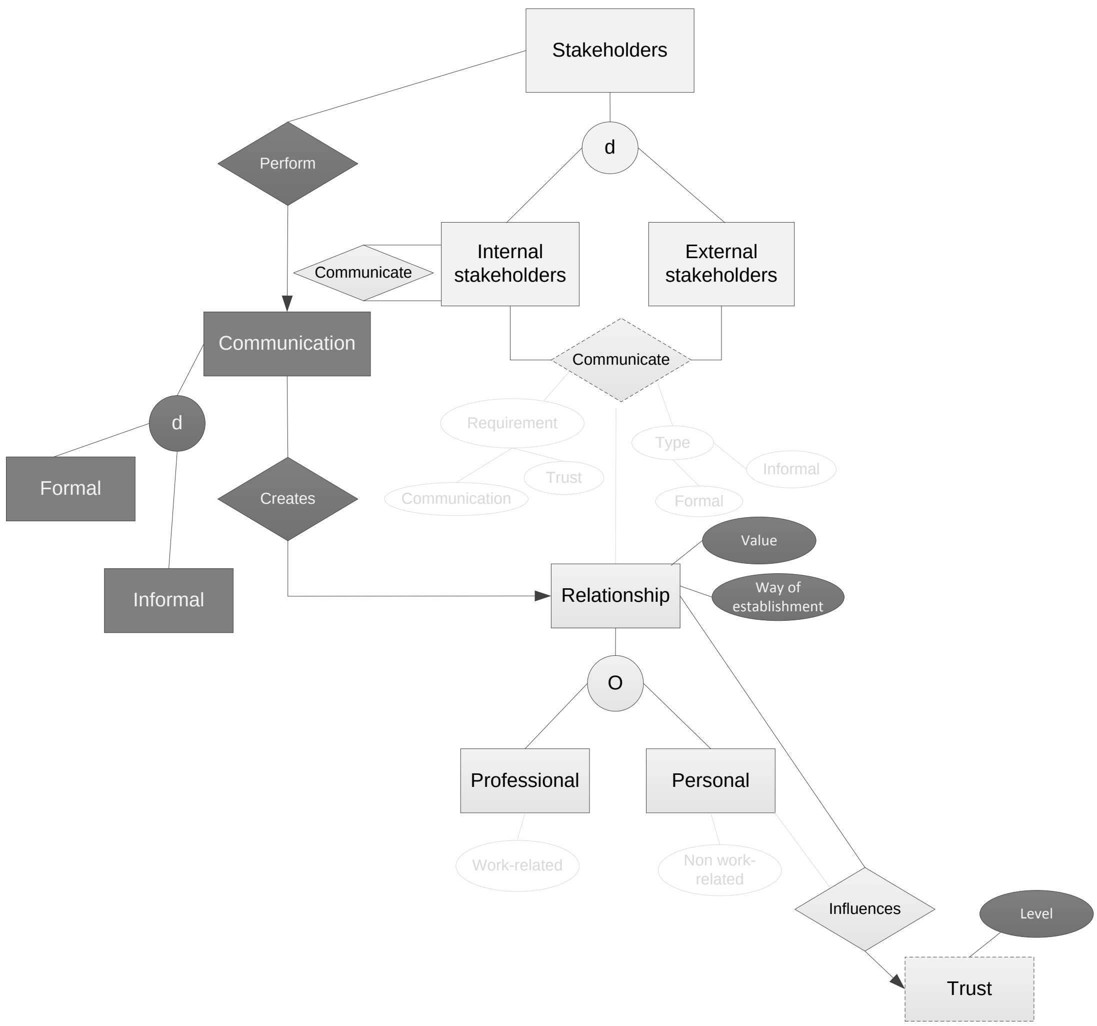


Figure 59 Refined architectural model of interaction

As can be seen from the figure above (Figure 59), "communication" had become the main theme of the architectural model, instead of "interaction". Thus, the theme was changed from "interaction" to "communication".

6.5.2.3 Conflict

Within the "conflict" theme, one refinement was made based on one applicable feedback, presented in Table 22. Three refinements were made based on partly applicable feedback points, listed in Table 23.

Table 22 List of refinements on conflict based on applicable feedback

Element of model	Category of refinement	Description of refinement
Relationship	Term refinement	Refine "influenced by" that connects "conflict" and "design process" to "impact"

Table 23 List of refinements on conflict based on partly applicable feedbacks

Element of model	Category of refinement	Description of refinement
Attribute	Addition	Add "cause" as an attribute of "conflict"
Attribute	Deletion	Delete "disintegrated design"
Attribute	Deletion	Delete "personality clash"

In addition to the above, four refinements were made as a result of the refinements listed in Table 22 and Table 23 and the feedbacks from participants on the concept of the model. The refinements consisted of one entity deletion, one relationship addition, one relationship deletion, and one term refinement. These refinements are listed in Table 24.

Table 24 List of additional refinements on conflict

Element of model	Category of refinement	Description of refinement
Entity	Deletion	Delete the term "new policy"
Relationship	Addition	Add "influences" to connect "conflict" and "policy"
Relationship	Deletion	Delete "motivates" that connect "conflict" and "new policy"
Relationship	Term refinement	Refine "hampered by" that connects "to "hampers"

The refinements listed in Table 22, Table 23 and Table 24 were applied in the architectural model, as can be seen in Figure 60 below.

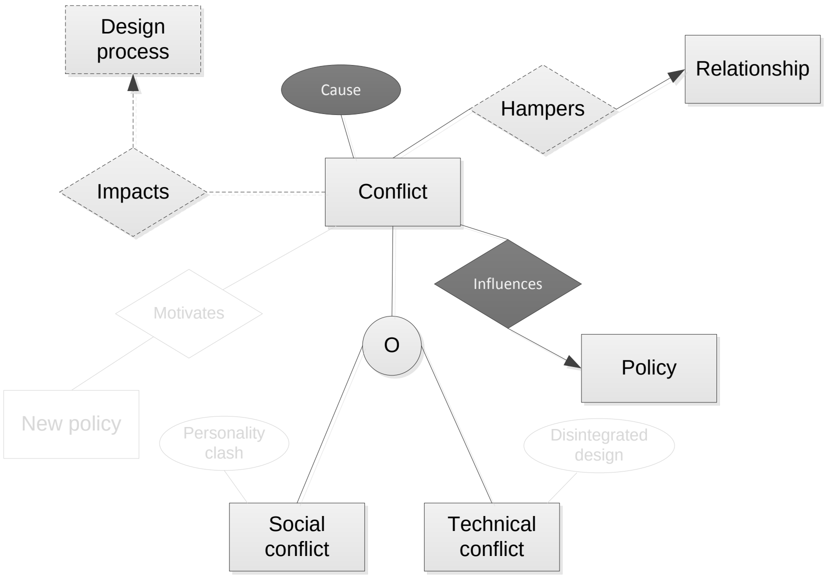


Figure 60 Refined architectural model of conflict

6.5.2.4 Organisation

One refinement was applied from one applicable feedback relating to the “organisation” theme. The refinement is presented in Table 25 below.

Table 25 List of refinements on organisation

Element of model	Category of refinement	Description of refinement
Attribute	Deletion	Delete “history”, an attribute of organisation

In addition, seven further refinements were made, motivated by the feedback from participants on the concept of the model (discussed in Section 6.5.1). These refinements are summarised in Table 26.

Table 26 List of additional refinements on organisation

Element of model	Category of refinement	Description of refinement
Attribute	Addition	Add "influences" to connect “politics” and “organisation”
Attribute	Category refinement	Refine “politics” from attribute to entity
Relationship	Addition	Add “underpins” to connect “opinion” and “history”
Relationship	Addition	Add “has” between “stakeholder” and “opinion”
Relationship	Term refinement	Refine “learns from” that connects “history” and “organisation” into “influences” relationship
Relationship	Term refinement	Refine “belongs to” that connects “stakeholders” and “organisation” to “employs”
Relationship	Term refinement	Refine “creates” that connects “organisation” and “legislation” to “applies”

The refinements listed in Table 25 and Table 26 were applied to refine the “organisation” architectural model, depicted by Figure 61.

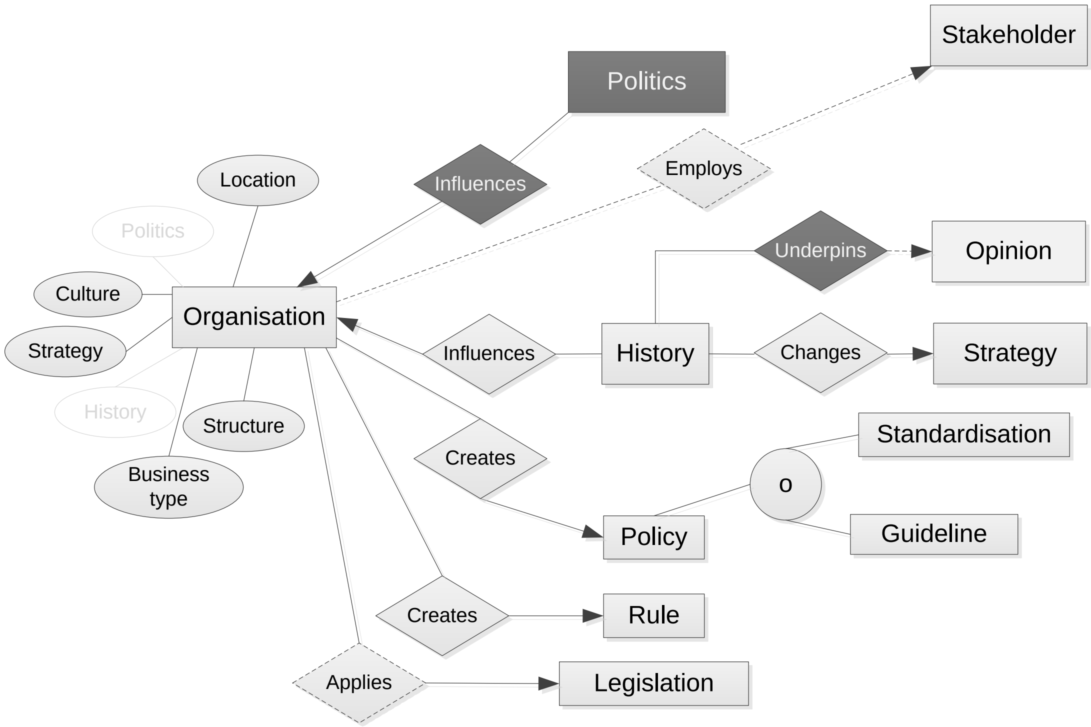


Figure 61 Refined architectural model of organisation

6.5.2.5 Boundary

One refinement was derived from one applicable feedback on the "boundary" theme. The refinement can be seen in Table 27 below.

Table 27 List of refinements on boundary

Element of model	Category of refinement	Description of refinement
Attribute	Addition	Add "time zone" as an attribute of "location"

In addition to the above refinement, in Table 28, thirteen additional refinements, resulting from the refinements listed above, the feedbacks from participants on the concept of the model (discussed in Section 6.5.1), are listed.

Table 28 List of additional refinements on boundary

Element of model	Category of refinement	Description of refinement
Entity	Term refinement	Refine "culture difference" to "culture"
Attribute	Deletion	Delete "type", an attribute of "culture"
Attribute	Category refinement	Refine "social" from a sub-attribute of "culture difference" to a sub-class of "culture", with "disjointed" relationship

Attribute	Category refinement	Refine “organisational” from a sub-attribute of “culture difference” to a sub-class of “culture” with “disjointed” relationship
Relationship	Addition	Add “has” to connect “organisation” and “location”
Relationship	Addition	Add “has” to connect “organisation” and “organisational” culture
Relationship	Addition	Add “bounds” to connect “location” and “communication”
Relationship	Addition	Add “has” to connect “organisation” and “organisational culture”
Relationship	Deletion	Delete “may causes” that connects “culture differences” and “conflict”
Relationship	Term refinement	Refine the term “leads to” that connects “location” and “culture” to “influences”
Relationship	Term refinement	Refine “bounded by” that connects “relationship” and “location” to “bounds”
Relationship	Term refinement	Refine “bounded by” that connects “relationship” and “policy” to “bounds”.
Relationship	Term refinement	Refine “bounded by” that connects “relationship” and “rule” to “bounds”.

The refinements listed in Table 27 and Table 28 were applied to refine the “boundary” architectural model, as depicted in the following figure:

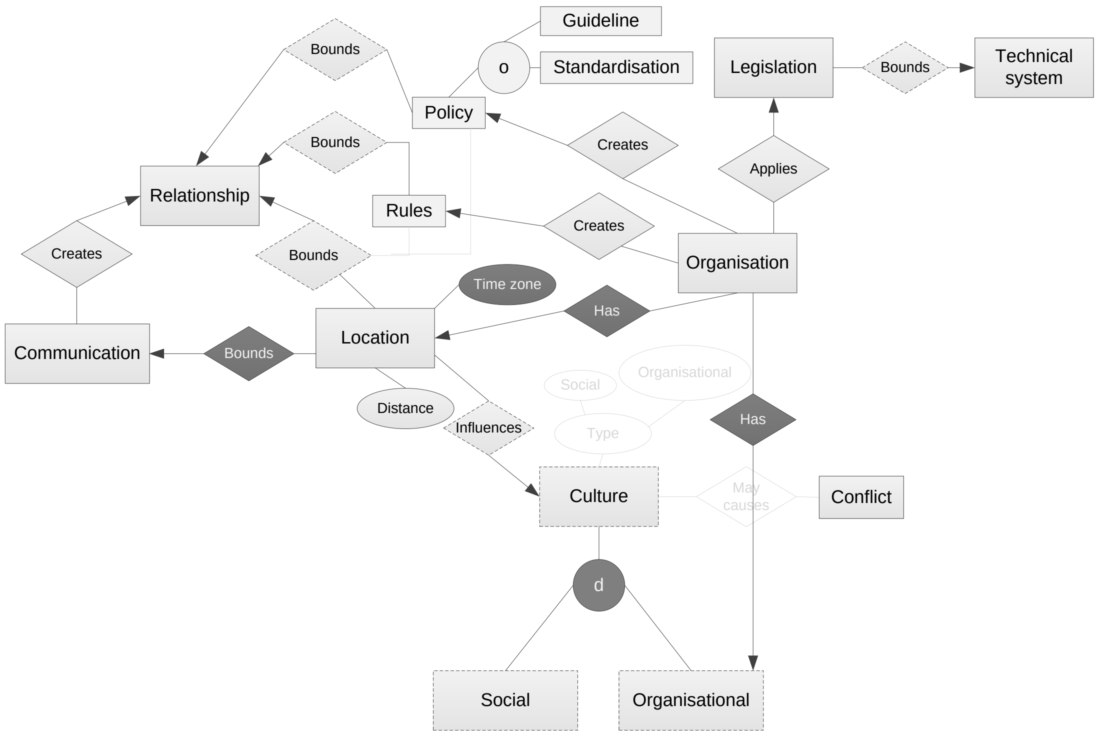


Figure 62 Refined architectural model of boundary

In addition to the refinements to the “boundary” architectural model, it should be noted that the inclusion of elements into the “boundary” theme was intended to present: 1) the boundaries of CED activity; and 2) how these boundaries limit the activity. However, in the refined model, these boundaries can be presented by the relationship between two entities in the model, without the need to categorise the elements into the “boundary” theme. For example, from the following relationships: “policy” bounds “relationship”; and “location” bounds “communication”, it can be seen that policy and location are boundaries for collaborative design activity as they bind other entities (i.e. relationship and communication). For this reason, categorising the elements as “boundaries” was viewed unnecessary and thus, the “boundary” theme was eliminated. Additionally, as the members of the “boundary” theme are also members of the “organisation” theme (see Table 29), hereinafter, they are categorised under the “organisation” theme only.

Table 29 Members of boundary theme

Entity	Themes	
	Boundary	Organisation
Location	√	√
Rules	√	√
Policy	√	√
Legislation	√	√

6.5.2.6 Design information

Within the theme of “design information”, one refinement was made based on one applicable feedback. This refinement is listed in Table 30. Four refinements were made based on four partly applicable feedback points. These refinements are listed in Table 31.

Table 30 List of refinements on design information based on applicable feedback

Element of model	Category of refinement	Description of refinement
Relationship	Addition	Add "determines" to connect "design requirements constraints" and "design problems"

Table 31 List of refinements on design information based on partly applicable feedbacks

Element of model	Category of refinement	Description of refinement
Attribute	Deletion	Delete "2D"
Attribute	Deletion	Delete “3D”
Relationship	Addition	Add "stores" to connect "information system" and "model"

Relationship	Addition	Add "utilises" to connect "design process" and "design information"

In addition to the refinements listed above, fourteen further refinements that resulted from the refinements listed above, the feedbacks of participants on the concept of the model (discussed in Section 6.5.1), were made. These refinements are outlined in Table 32.

Table 32 List of additional refinements on design information

Element of model	Category of refinement	Description of refinement
Attribute	Addition	Add "quality" as an attribute of "design information"
Attribute	Addition	Add "value" as an attribute of "design information"
Attribute	Addition	Add "function" as an attribute of "tools"
Attribute	Deletion	Delete "amount", an attribute of "design information"
Attribute	Deletion	Delete "importance", an attribute of design information
Attribute	Deletion	Delete "consistency", an attribute of "design information"
Attribute	Deletion	Delete "inter-related", a sub-attribute of "nature"
Attribute	Deletion	Delete "computer-based", an attribute of "design information"
Relationship	Term refinement	Refine "exchanged by" that connects "stakeholder" and "design information" to "exchanges"
Relationship	Term refinement	Refine "represented as" that connects "design information" and "model" to "represents".
Relationship	Term refinement	Refine "stored in" that connects "information system" and "design information" to "stores"
Relationship	Term refinement	Refine "utilised in" that connects "design process" and "design information" to "utilises"
Relationship	Term refinement	Refine "translated into" that connects "design requirements and constraints" and "design specification" to "translates"
Relationship	Term refinement	Refine "aid to identify" that connects "design specification" and "design problem" to "identifies"

Applying the refinements listed in Table 30, Table 31, and Table 32, a refined architectural model on design information was constructed, depicted by Figure 63.

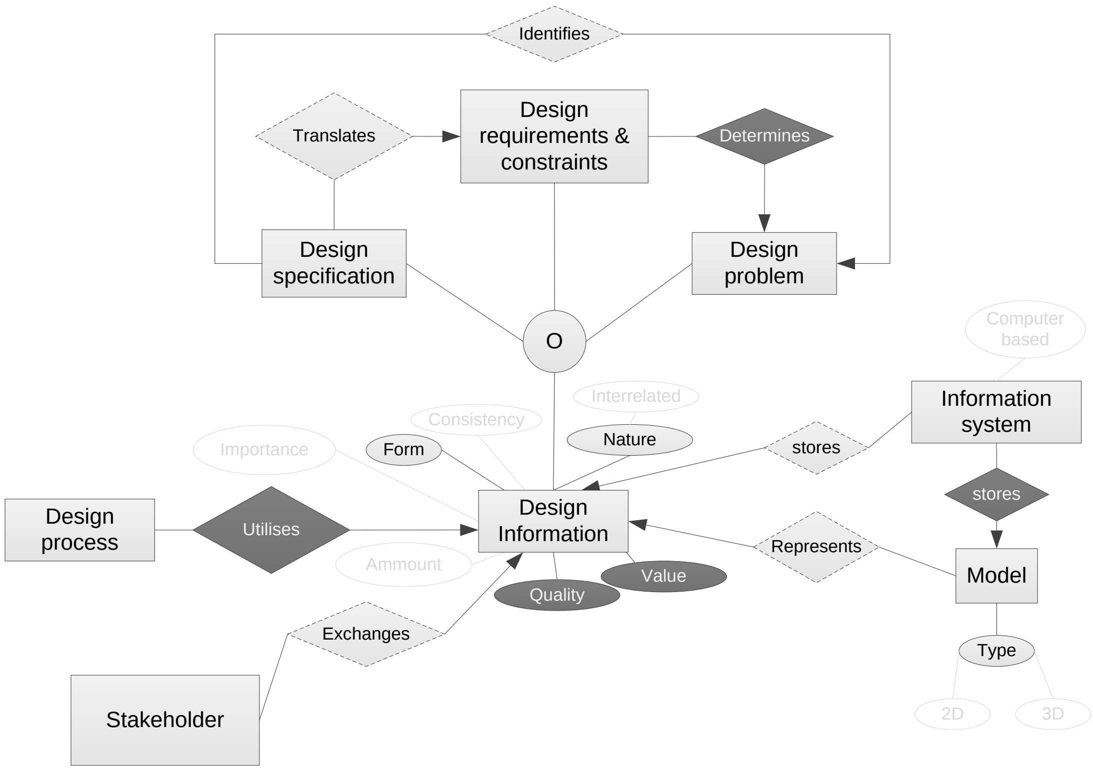


Figure 63 Refined architectural model on design information

6.5.2.7 Tools

Under the "tools" theme, two refinements were made based on partly applicable feedback. The refinements are listed in Table 33.

Table 33 List of refinements on tools

Element of model	Category of refinement	Description of refinement
Sub-entity	Category refinement	Refine "information system" from an entity to a sub-entity of "tools"
Sub-entity	Term refinement	Refine the term "information system" to "information tools"

In addition to the above refinements, eleven refinements were made, motivated by the refinements listed above and the feedbacks from participants on the concept of the model (discussed in Section 6.5.1). These refinements are listed in Table 34.

Table 34 List of additional refinements on tools

Element of mode	Category of refinement	Description of refinement
Attribute	Deletion	Delete "function", an attribute of "technical tools"
Attribute	Deletion	Delete "type", an attribute of "communication tool"
Attribute	Deletion	Delete "calculation", a sub-attribute of "technical tools"
Attribute	Deletion	Delete "visualisation and representation", a sub-attribute of "technical tools"
Attribute	Category refinement	Refine "synchronous" from a sub-attribute to a sub-class of "communication tools" with "overlapping" relationship
Attribute	Category refinement	Refine "asynchronous" from a sub-attribute to a sub-class of "communication tools" with "overlapping" relationship
Relationship	Addition	Add "facilitates" to connect "communication tools" and communication"
Relationship	Addition	Add "utilises" to connect "stakeholders" and "tools"
Relationship	Deletion	Delete "facilitate communication between" that connects "communication tools" and "location"
Relationship	Term refinement	Refine "processed through" that connects "design information" and "technical tools" to "processes"
Relationship	Term refinement	Refine "created through" that connects "technical tools" and "model" to "creates"

Applying the refinements listed in Table 33 and Table 34, a refined architectural model of tools was constructed, depicted by Figure 64.

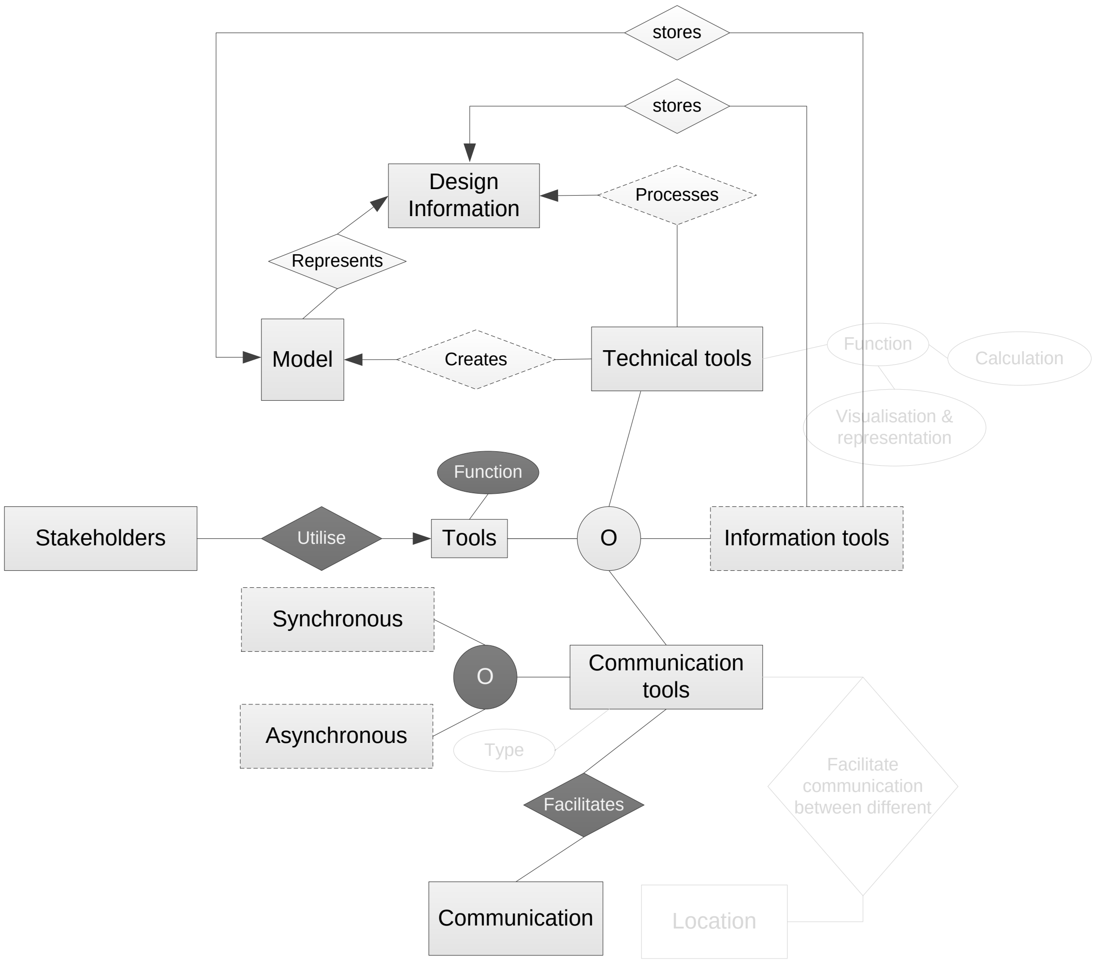


Figure 64 Refined architectural model of tools

6.5.2.8 Technical system

Within the theme of "technical system", one applicable feedback can be derived from the workshops, outlined in Table 35. In addition, six refinements were further made based upon feedback from participants on the concept of the model (discussed in Section 6.5.1). The additional refinements are listed in Table 36.

Table 35 List of refinements on technical system

Element of model	Category of refinement	Description of refinement
Relationship	Addition	Add "underpins" to connect "design information" and "technical system"

Table 36 List of additional refinements on technical system

Element of model	Category of refinement	Description of refinement
Attribute	Addition	Add “nature” as an attribute of “technical system”
Attribute	Deletion	Delete “interrelate”, an attribute of “technical system”
Attribute	Deletion	Delete “complex”, an attribute of “technical system”
Attribute	Deletion	Delete “integrated”, an attribute of “technical system”
Relationship	Deletion	Delete “complies to” that connects “technical system” and “design requirements and constraints”
Relationship	Term refinement	Refine “influenced by” that connects “technical system” and “technical conflict” to “influences”

Figure 65 illustrates the refined architectural model of technical system by applying the refinements listed in Table 35 and Table 36.

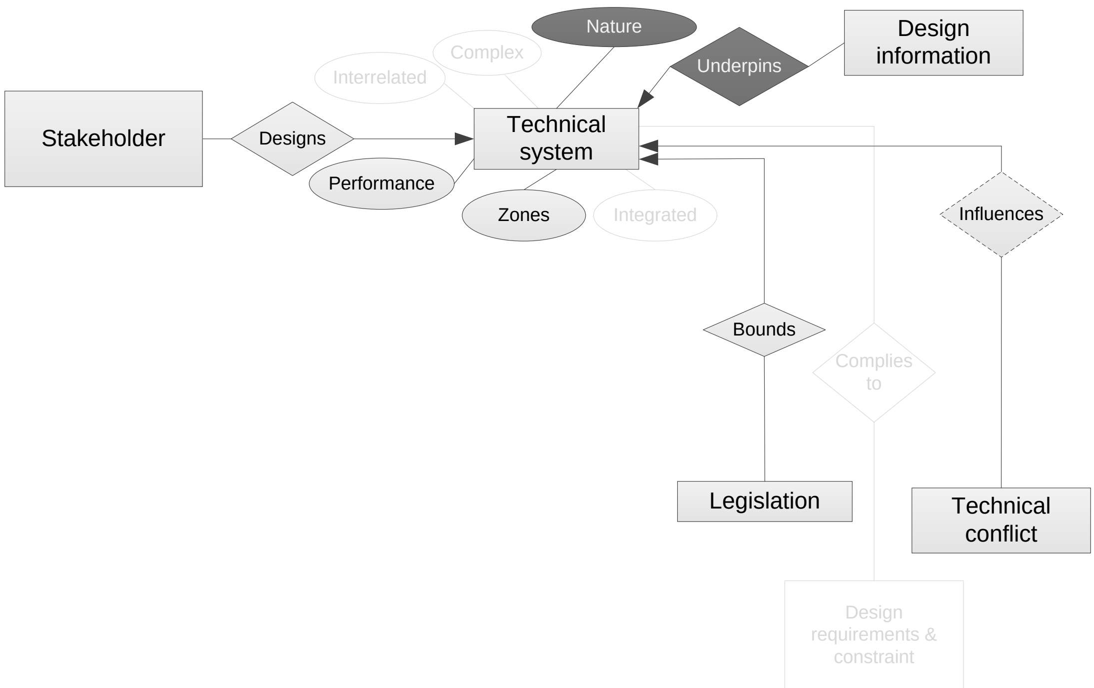


Figure 65 Refined architectural model of technical system

6.5.2.9 Design process

Within the "design process" theme, two refinements were made based on the applicable feedback and one was made based on the partly applicable feedbacks from the workshops. The refinements are presented, in Table 37 and Table 38.

Table 37 List of refinements on design process based on applicable feedbacks

Element of model	Category of refinement	Description of refinement
Attribute	Addition	Add "schedule" as an attribute of "design process"
Attribute	Term refinement	Refine the term "zone" to "area"

Table 38 List of refinements on design process based on partly applicable feedbacks

Element of model	Category of refinement	Description of refinement
Attribute	Deletion	Delete "parameter", an attribute of "design process"

In addition to the above, twelve further refinements were made, triggered by the refinements listed above and the feedback from participants on the concept of the model (discussed in Section 6.5.1). In Table 39, these additional refinements are listed.

Table 39 List of additional refinements on design process

Element of model	Category of refinement	Description of refinement
Sub-entity	Addition	Add "design review process" as a sub-entity of "design process"
Attribute	Addition	Add "cost" as an attribute of "design process"
Attribute	Deletion	Delete "communication", a sub-attribute of "requirement"
Attribute	Deletion	Delete "awareness", a sub-attribute of "requirement"
Attribute	Deletion	Delete "consistency", a sub-attribute of "requirement"
Relationship	Addition	Add "has" to connect "design process" and "risk"
Relationship	Addition	Add "has" to connect "design process" and "goal"
Relationship	Deletion	Delete "reviewed in" that connects "concept design process" and "design review process"
Relationship	Deletion	Delete "reviewed in" that connects "detailed design process" and "design review process"

Relationship	Term refinement	Refine "resolved in" that connects "design review process" and "design problem" to "resolves"
Relationship	Term refinement	Refine "utilised in" that connects "design review process" and "model" to "utilises"
Relationship	Term refinement	Refine "influenced by" that connects "design process" and "conflict"

Applying the refinements listed in Table 37, Table 38, and Table 39, the revised architectural model of "design process" was constructed, depicted by Figure 66.

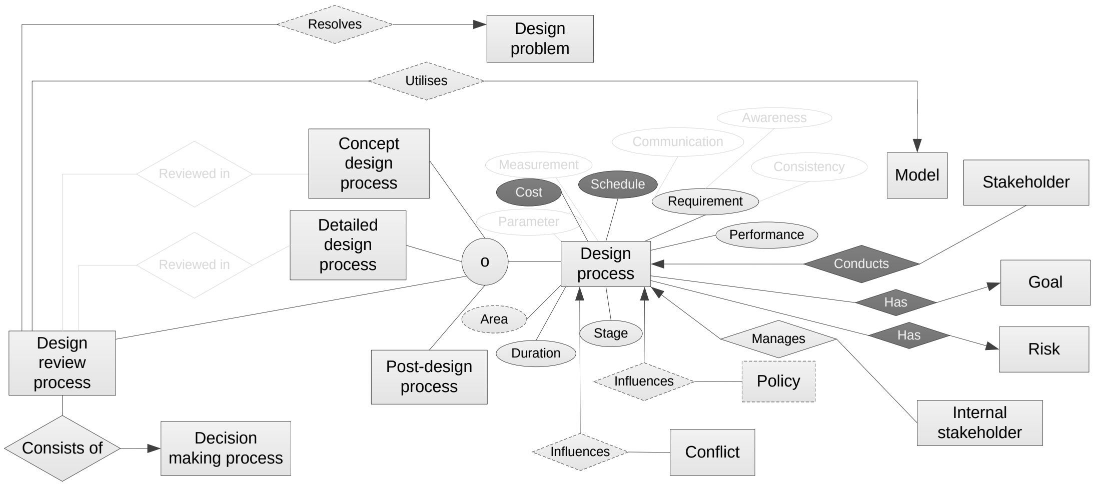


Figure 66 Refined architectural model of design process

6.6 STAM-3

The refinements of the model presented in Section 6.5 are combined as STAM-3 and provided in this section. As discussed in Section 6.5.1.1, the refined architectural model was developed in two levels of detail, based on the feedback given by the workshops participants. The model developed at the greatest level of detail (level 2) is presented in Section 6.6.1, while the model developed at the lowest level of detail (level 1) is presented in Section 6.6.2.

6.6.1 STAM-3 Level 2

In Section 6.5, the refinements to the model were presented. The results were categorised according to the identified theme of each socio-technical element of collaborative design (as can be seen in Section 6.5.2). From each theme, a fragment of the refined architectural model that consists of entities, sub-entities, attributes and relationships, was generated. To construct the level 2 version of the third architectural model, the fragmented architectural models were combined. In this section, how each fragment was combined is presented.

To aid visualisation, colours were assigned to each theme (see Nomenclature), and to highlight the connection between the themes, the appropriate line(s) have been widened in each figure.

In Figure 59 (Section 6.5.2.2), it can be seen that the theme "human being" the first theme discussed in Section 6.5.2 and "communication" the second theme discussed in Section 6.5.2 were connected through the term perform (i.e. stakeholders perform communication). This was used to combine the refined architectural model in the initial level 2 version of the third architectural model. This combination is depicted by Figure 67.

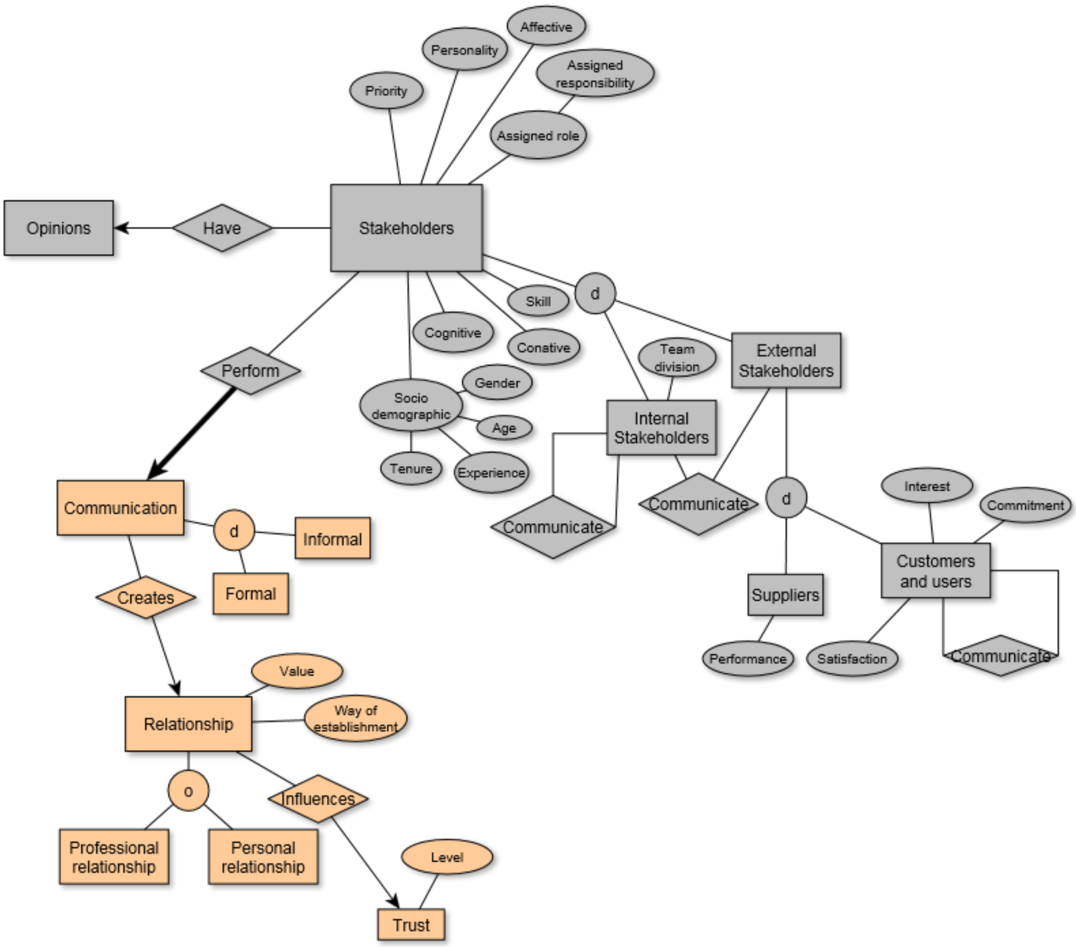


Figure 67 The combination of the refined architectural model of human being and communication

From the list of refinements presented in Table 22, Table 23, and Table 24 (Section 6.5.2.3), represented in Figure 60, three relationships between "conflict" and other themes of CED can be identified. The relationships are: 1) between conflict and relationship (i.e. a member of the "communication" theme), which is connected by the term hampers; 2) between conflict and policy (i.e. a member of the "organisation" theme), which is connected by the term influences; and 3) between conflict and design process, which is connected by the term impacts. These relationships were used to add the refined architectural model of "conflict" to the initial architectural model version 3 (Figure 67). The addition is depicted by Figure 68.

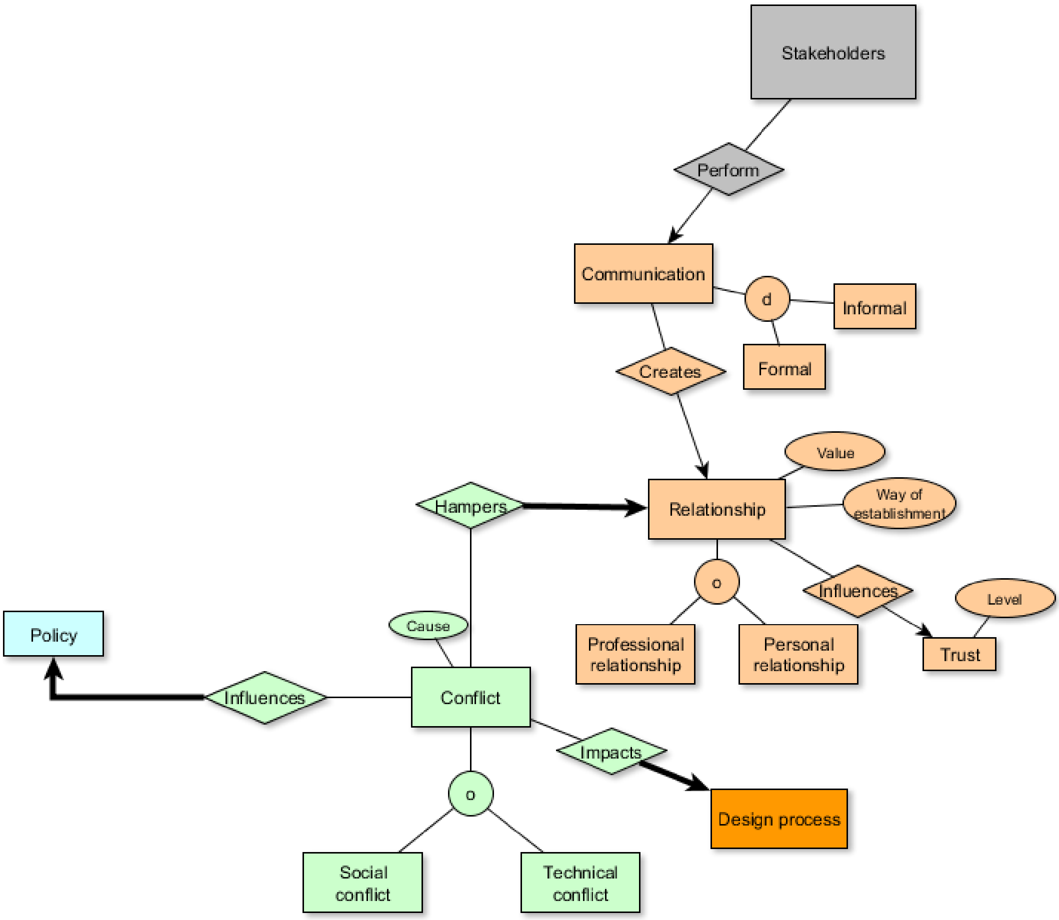


Figure 68 The addition of the refined architectural model of "conflict" to the STAM-3

Three relationships between "organisation" and other themes of CED can be derived from Section 6.5.2.4. The first is the relationship between policy and conflict, which is connected by the term influences. The second is the relationship between organisation and stakeholders, which is connected by the term employs. The third is the relationship between opinions (a member of the "stakeholders" theme) and history (a member of "organisation" theme), which is connected by the term underpins. Additionally, as discussed in Section 6.5.2.5, the theme "boundary" was eliminated and the members of the theme were included in "organisation" theme. Four relationships between the new members of "organisation" and the other themes of CED can be identified: 1) the relationship between location and communication, which is connected by the term bounds, 2) the relationship between location and relationship, which is connected by the term bounds, 3) the relationship between legislation and technical system, which is connected by the term bounds, and 4) the relationship between rule and relationship, which is connected by the term bounds. The refined architectural model of "organisation" was added into the third version of the architectural model, as depicted in Figure 69.

Seven relationships between the "design information" theme and the other themes of collaborative design practice can be derived from the list of refinements outlined in Table 30, Table 31, and Table 32, depicted by Figure 63:

1. The relationship between design information and stakeholders (i.e. a member of "human being" theme), which is connected by the term exchange.
2. The relationship between design specification and suppliers, which is connected by the term supply.
3. The relationship between design requirement and constraints and customers and users, which is connected by the term provide.
4. The relationship between design information and technical systems, which is connected by the term underpins.
5. The relationship between model and information tool (i.e. a member of "tools" theme), which is connected by the term stores.
6. The relationship between design information and information tool, which is connected by the term stores.
7. The relationship between design information and design process, which is connected by the term utilises.

The above relationships were used to combine the "design information" theme to the third architectural model. The addition is shown in Figure 70.

Three connections between the theme "tools" and the other themes of CED can be derived from the list of refinements, presented in Table 33 and Table 34, depicted by Figure 64 (Section 6.5.2.7). Firstly, the relationship between tools and stakeholders (i.e. a member of the "human being" theme), connected by the term utilise, secondly the relationship between communication tool and communication, connected by the term facilitates; and thirdly the relationship between technical tools and design information, connected by the term process.

These relationships were utilised to integrate the refined architectural model of "tools" into the architectural model version 3. The integration is shown in Figure 71.

Four relationships between the "technical systems" theme and the other themes of CED can be derived from the list of refinements as outlined in Table 36, depicted by Figure 65 (Section 6.5.2.8). The relationships are: 1) between technical system and stakeholders, connected by the term design; 2) between technical system and design information, connected by the term underpins; 3) between technical system and legislation, connected by the term bounds; and 4) between technical system and technical conflict, connected by the term influences. Using these connections, the refined architectural model of the "technical system" was integrated into the architectural model version 3, as depicted by Figure 72.

Eight relationships between the theme "design process" and the other themes of collaborative design practice can be identified from the list of refinements, presented in Table 37, Table 38, and Table 39, depicted by Figure 66 (Section 6.5.2.9). The relationships are:

1. Between design process and stakeholders, connected by the term conduct.
2. Between risk and stakeholders, connected by the term manage.
3. Between risk and stakeholders, connected by the term share.
4. Between goal and stakeholders, connected by the term share.
5. Between design process and internal stakeholders, connected by the term manage.
6. Between design process and design information, connected by the term utilises.
7. Between design process and conflict, connected by the term impacts.

These relationships were utilised to integrate the refined architectural model of "design process" into the architectural model version 3, as depicted by Figure 73.

Having connected the refined architectural model of each theme (depicted from Figure 67 to Figure 73), an architectural model for version 3, level 2, was constructed. The model is depicted by Figure 74.

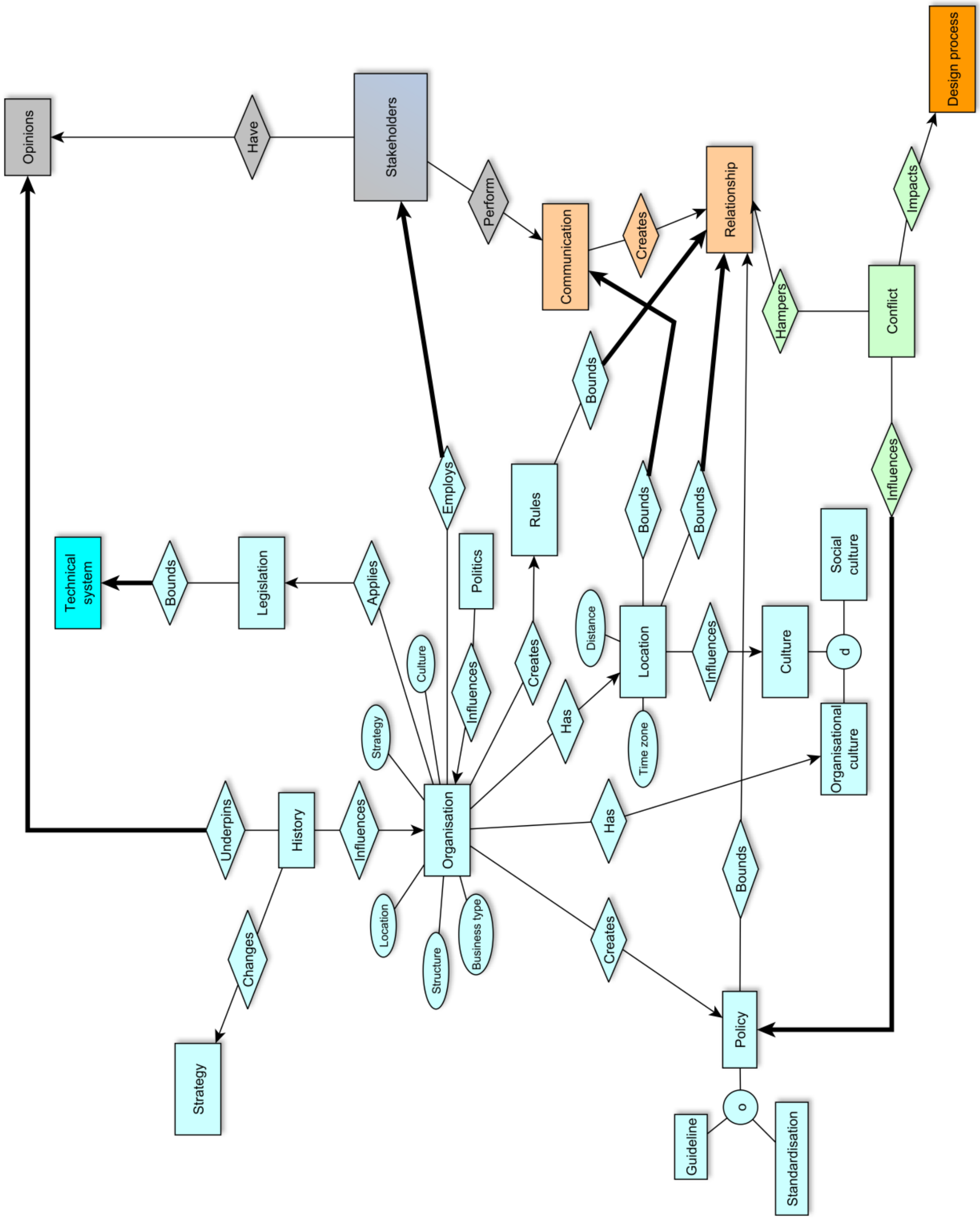


Figure 69 The addition of the refined architectural model of "organisation" to the STAM-3

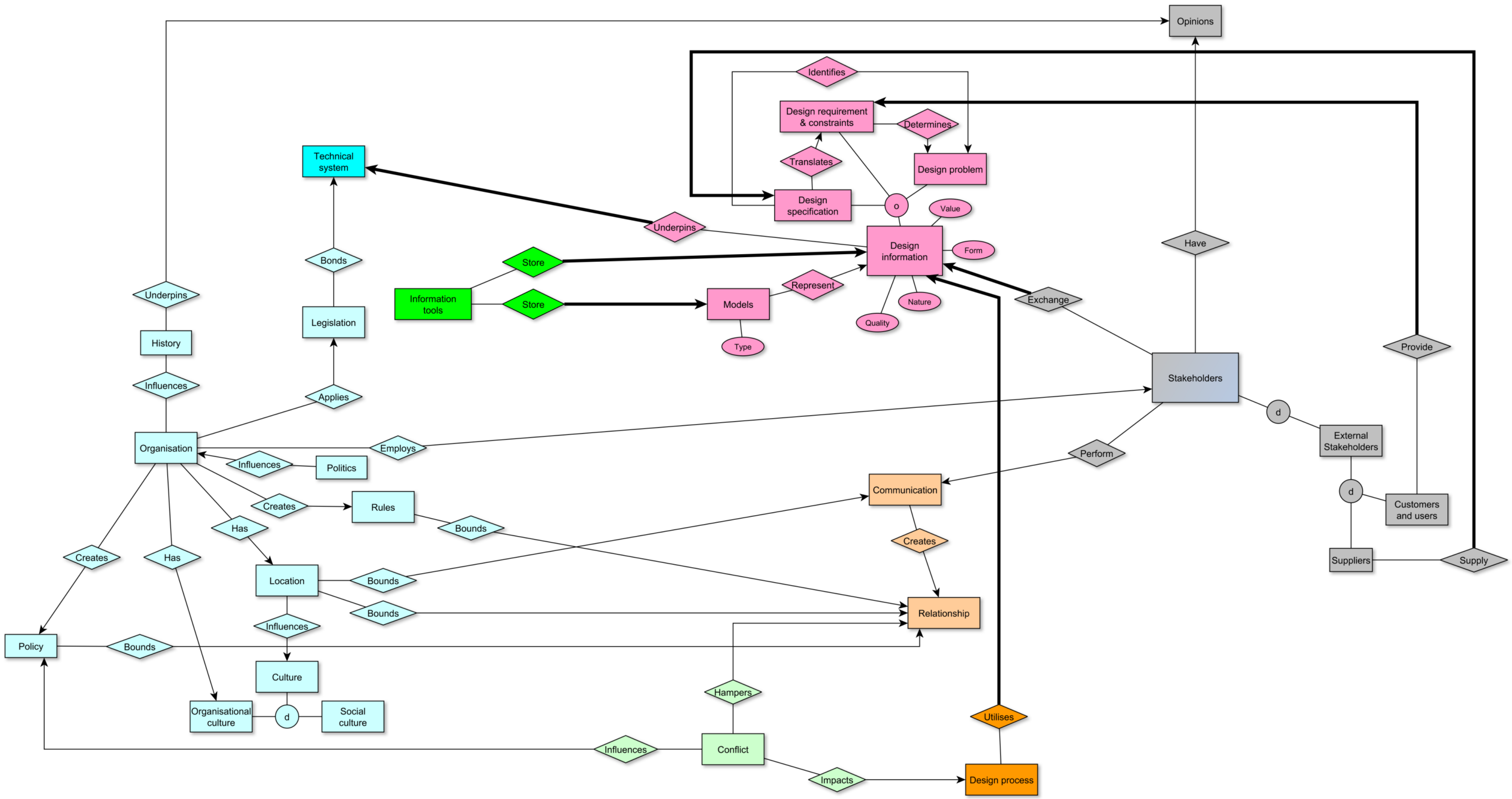


Figure 70 The integration of design information theme to STAM-3

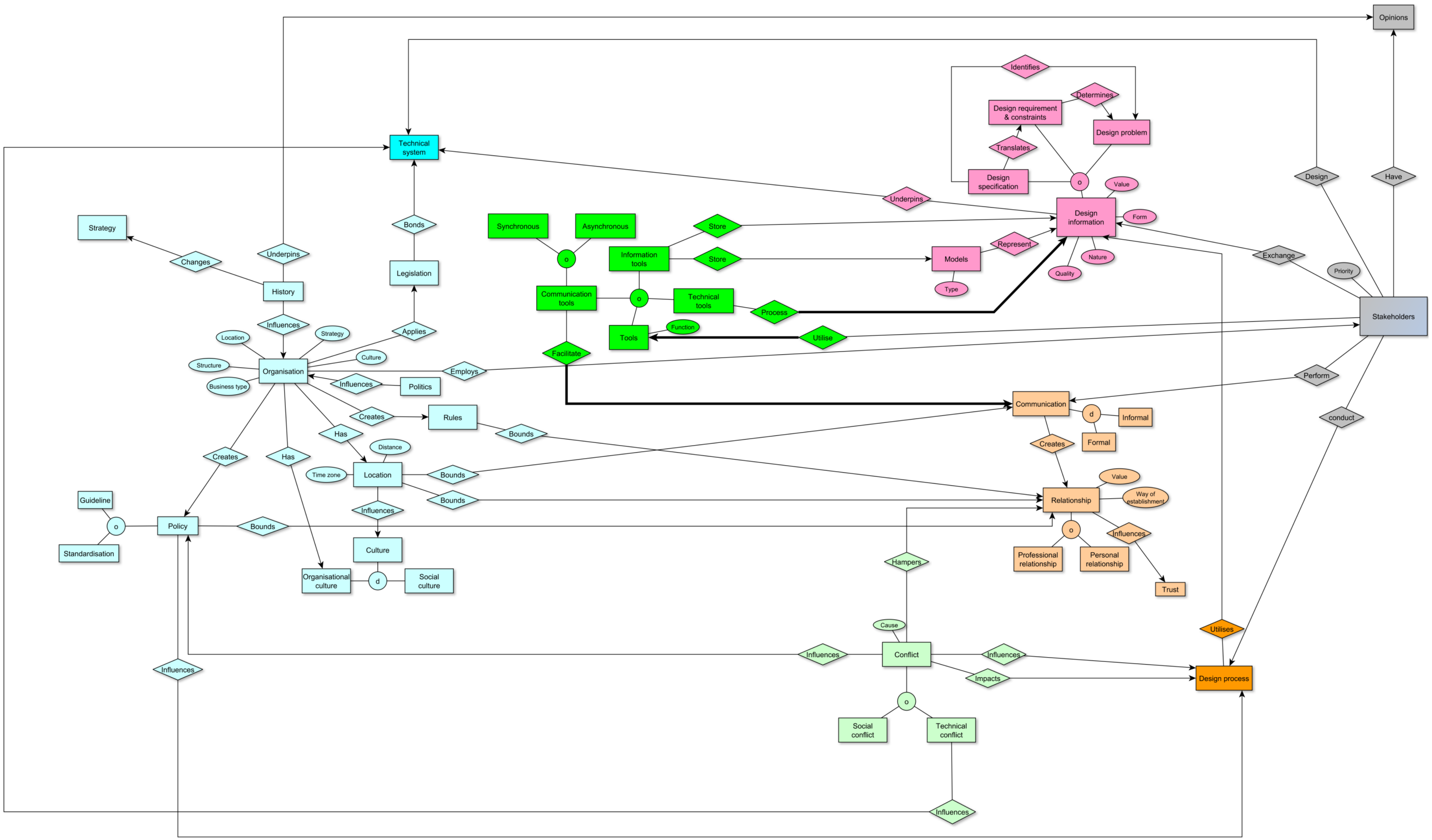


Figure 71 The integration of the refined architectural model of tools to STAM-3

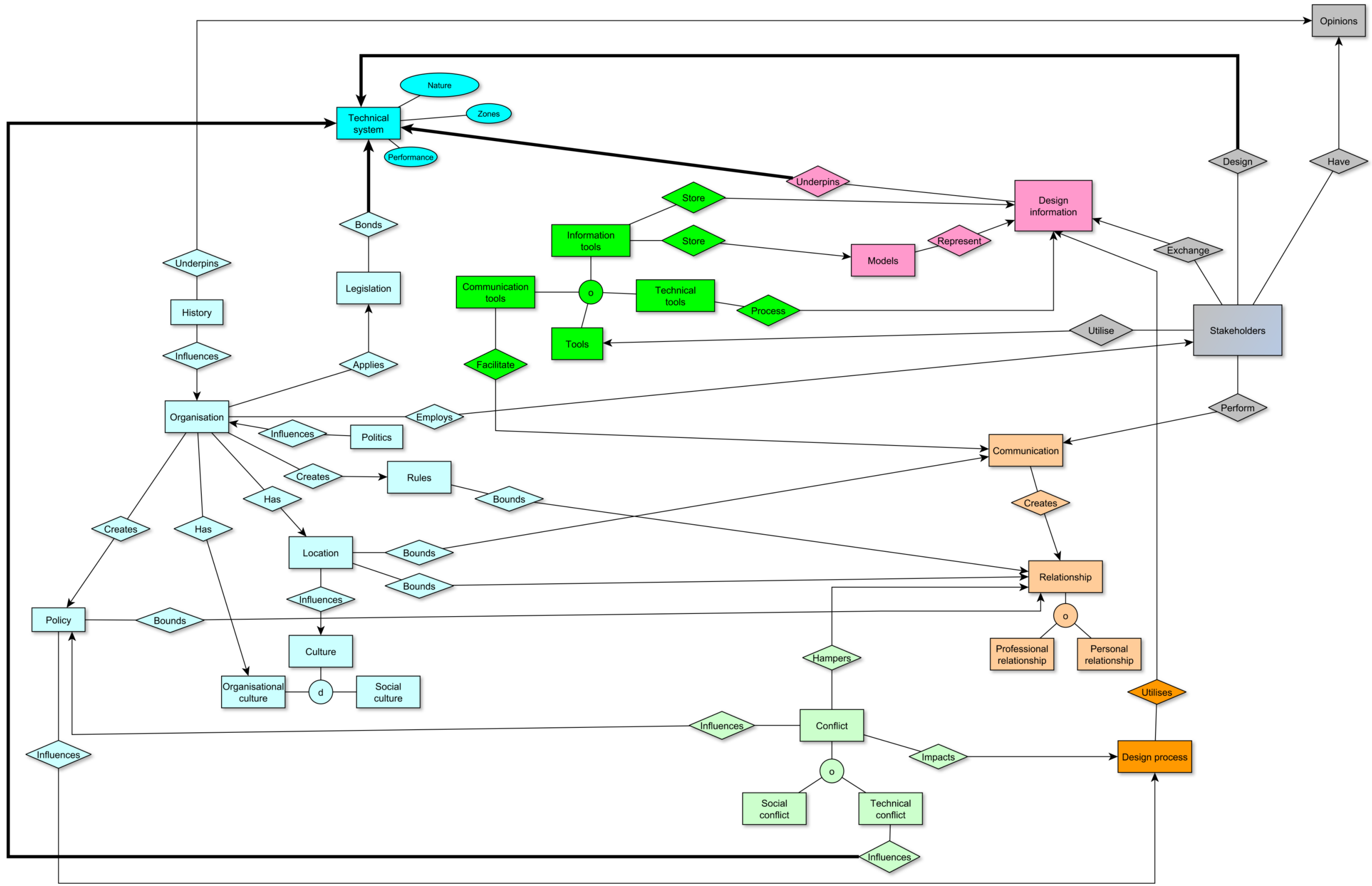


Figure 72 The integration of the refined architectural model of technical system to STAM-3

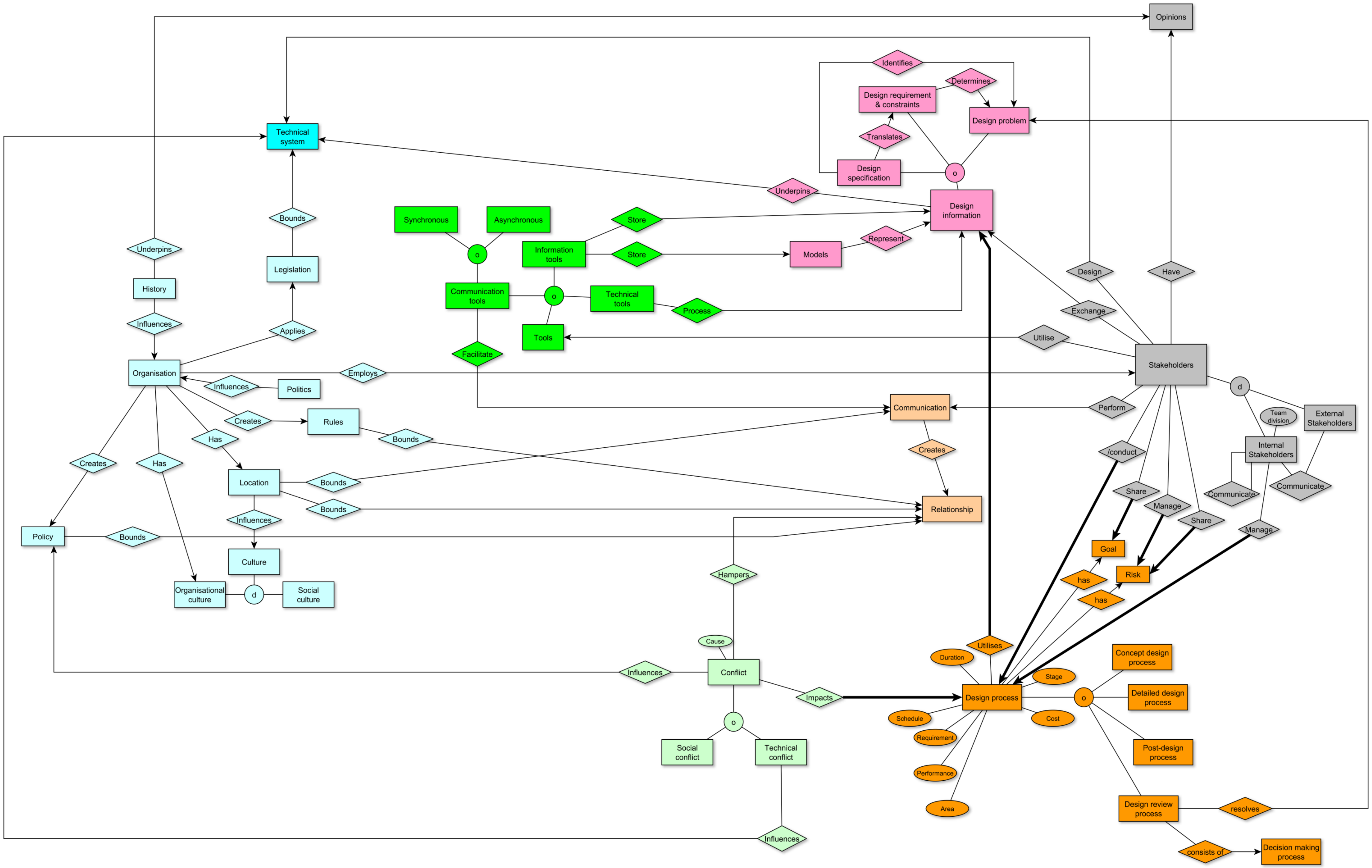


Figure 73 The integration of design process theme to STAM-3

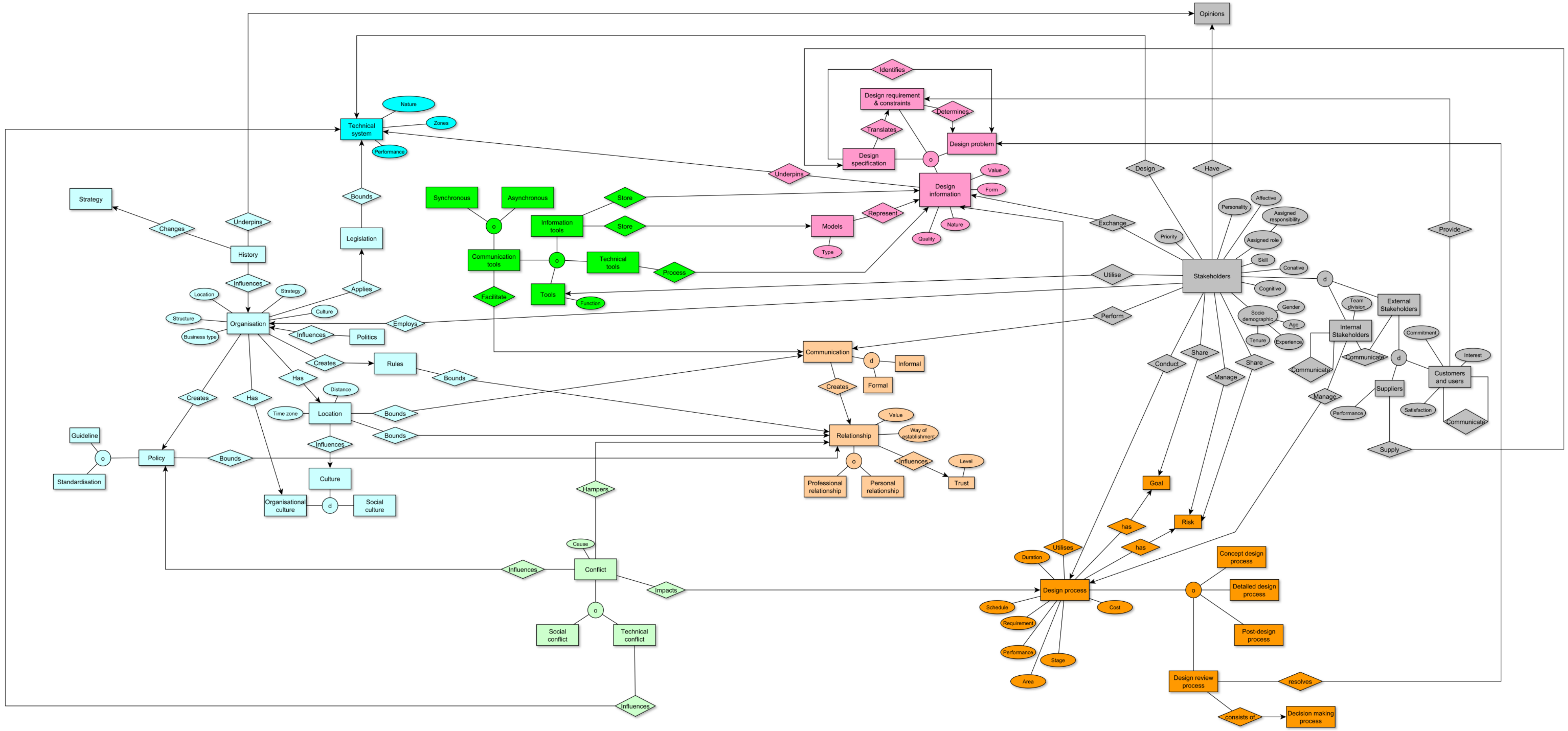


Figure 74 STAM-3 Level 2

6.6.2 STAM-3 Level 1

Section 6.6.1 described how the second level of the model (i.e. high level of detail) was developed. In this section, how the first level of the model (i.e. low level of detail) was developed, is described. To develop the first level of the model, the second level of the model was aggregated (as mentioned in Section 6.5.1.1).

The main purpose of aggregation is to provide a more abstract model with fewer elements and relationships. This is done to make the model easier to comprehend (Iwasaki and Simon, 1994). An aggregated model may be viewed as a "summary of the information contained at the lower level of abstraction" (Benjamin et al. 1998, p. 392). According to Iwasaki and Simon (1994), aggregation mainly involves two processes: 1) grouping together of different elements of the model through, for example, the combination of what is considered to less significant elements to other elements (Polyvyanyy et al. 2008), and the reclassification of current elements based on their similarities (Archer et al. 1996); and 2) defining relationships between the new groups of elements.

In Section 5.5.2, refined in Section 6.5.2, the (socio-technical) elements of CED were already grouped together into different themes. This can be considered as the first process of aggregation as aforementioned. The themes are human being, communication, conflict, organisation, design information, tools, technical system, and design process. To define the relationships between different themes, the relationship(s) that includes two entities that belongs to different themes such as the relationship between stakeholders (a member of "human being" theme), and communication (a member of "communication" theme) were identified. Each entity was then clustered based on its themes. For example, location, rules and policy are grouped as "organisation" theme. The groupings are listed in Table 40. Each theme grouping is set in **bold** face.

Table 40 List of relationship between themes

#	Themes		Relationship
1	**Human being**	**Communication**	**Perform**
	Stakeholders	Communication	Perform
2	**Human being**	**Design information**	
	Stakeholders	Design information	Exchange
	Suppliers	Design specification	Supply
	Customers and users	Design requirements and constraints	Provide
3	**Human being**	**Tools**	**Utilise**
	Stakeholders	Tools	Utilise
4	**Human being**	**Technical system**	**Design**

	Stakeholders	Technical system	Design
5	**Human being**	**Design process**	
	Stakeholders	Design process	Conduct
	Stakeholders	Goal	Share
	Stakeholders	Risk	Share
	Stakeholders	Risk	Manage
	Internal stakeholders	Design process	Manage
6	**Communication**	**Tools**	**Facilitate**
	Communication	Communication tool	Facilitate
7	**Conflict**	**Organisation**	**Influences**
	Conflict	Policy	Influences
8	**Conflict**	**Technical system**	**Influences**
	Technical conflict	Technical system	Influences
9	**Conflict**	**Communication**	**Hampers**
	Conflict	Relationship	Hampers
10	**Conflict**	**Design process**	**Impacts**
	Conflict	Design process	Impacts
11	**Organisation**	**Human being**	
	Organisation	Human being	Employs
	History	Opinion	Underpins
12	**Organisation**	**Communication**	**Bounds**
	Location	Communication	Bounds
	Rules	Relationship	Bounds
	Policy	Relationship	Bounds
	Location	Relationship	Bounds
13	**Organisation**	**Technical system**	**Bounds**
	Legislation	Technical system	Bounds
14	**Design information**	**Technical system**	**Underpins**
	Design information	Technical system	Underpins
15	**Tools**	**Design information**	
	Technical tools	Design information	Process
	Information tools	Design information	Store
16	**Design process**	**Design information**	
	Design process	Design information	Utilises
	Design review process	Design problem	Resolves

From Table 40, it can be seen that ten of the sixteen theme groupings only have one entry. For example, the relationship between human being and communication (#1), only involves stakeholders from the "human being" theme and "communication" theme. Therefore, in each of these twelve theme groupings, a relationship can be directly obtained. These relationships come directly from the second (higher detail) level of the model.

Looking again at Table 40, it can be seen that theme grouping #11 (the “organisation” and “communication” theme) has more than one entry. However, each entry has the same relationship regardless of the two entities within the relationship (i.e. bounds). Therefore, the “organisation” and “communication” theme grouping can also be given the “bounds” relationship.

For the remaining five theme groupings, further investigation was needed, as the relationships between the themes cannot be directly obtained from the second (higher detail) level of the architectural model. These remaining five theme groupings are shown in red bold. The relationships are between 1) “human being” and “design process”; 2) “human being” and “design information”; 3) “organisation” and “human being”; 4) “tools” and “design information”; and 5) “design process” and “design information”. To define these relationships, further investigation was conducted. Defining the relationship between the themes “human being” and “design process” is used to exemplify the investigation. In Table 41, the relationships between the members of the “human being” theme and the members of the “design process” theme are listed. A “human being” is identified as the main actor of collaborative design practice (Chapter 4). As the main actor, they conduct the design process. When conducting the design process, the human being performs multiple activities as shown in the model (i.e. sharing goals, sharing and managing risk, and managing the design process) (Section 5.3.2.1). From this perspective, representing the relationship between “human being” and “design process” with the term “conduct” can represent these other activities that a human being performs (e.g. sharing goals, managing risk) when undertaking the design process. On this basis, the term “conduct” was utilised to connect the “human being” and “design process” theme.

Table 41 List of relationship between human being and design process

Themes		**Relationship**
Human being	**Design process**	
Entities		
Stakeholders	Design process	Conduct
Stakeholders	Goal	Share
Stakeholders	Risk	Share
Stakeholders	Risk	Manage
Internal stakeholders	Design process	Manage

The detailed investigation to define the relationships between the remaining five themes can be seen in Appendix 13. The socio-technical themes (i.e. elements) of collaborative design and the relationships, aggregated from the second level of the architectural model are outlined in Table 42.

Table 42 List of relationship between the CED themes

Themes		Relationship
Human beings	Communication	Perform
Human beings	Design information	Exchange
Human beings	Tools	Utilise
Human beings	Technical system	Design
Human beings	Design process	Conduct
Conflict	Communication	Hampers
Conflict	Organisation	Influences
Conflict	Technical system	Influences
Conflict	Design process	Impacts
Organisation	Human beings	Employs
Organisation	Communication	Bounds
Organisation	Technical system	Bounds
Design information	Technical system	Underpins
Tools	Communication	Facilitate
Tools	Design information	Serve
Design process	Design information	Utilises

Based on the table above, a socio-technical architectural model of CED Level 1 is developed. The model is depicted by Figure 75.

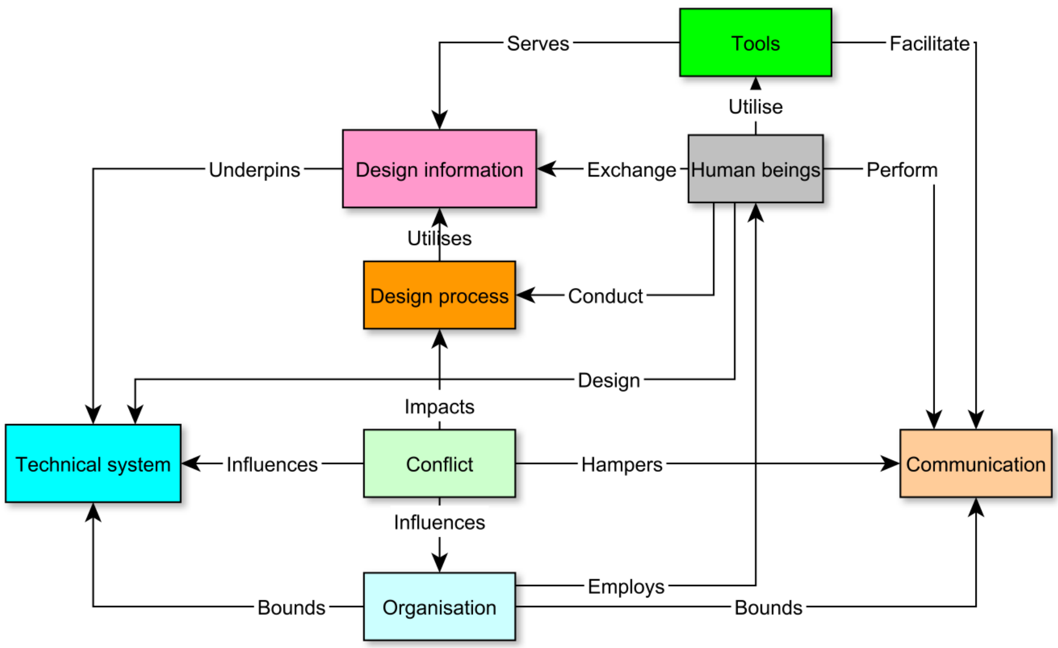


Figure 75 STAM- 3 Level 1

6.7 Summary

Two workshops (i.e. W1 and W2) were conducted to review the socio-technical architectural model of CED that was developed based on the literature (Chapter 4) and the industrial investigation (Chapter 5), following a pilot study with six DMEM's researchers (Section 6.1). W1 was conducted at Company 1 and attended by eight collaborative design practitioners (Section 6.2.1) while W2 was conducted at an international conference of engineering design and attended by twenty-two engineering design academics (Section 6.2.2).

In both workshops, participants were divided into different groups. Each group was asked to evaluate the elements of the model (i.e. entities, sub-entities, attributes, and relationships) and present their feedback to the other groups. From the participants of W1, the feedback can be grouped into four categories: "addition", "deletion", "term refinement", and "category refinement" (Section 6.3). The feedback from W2 can be grouped into these four categories, and one additional category, "expansion". While the feedback from the participants of W1 only relates to the content of the model (e.g. entities), the feedbacks from the participants of W2 also relates to the concept of the model (e.g. presentation). This further feedback from W2 can be categorised into "purpose", "emphasis", "development", and "presentation" (Section 6.3). The feedback values from W1 and W2 are summarised in Table 43.

Table 43 Feedback values from W1 and W2

	Category of feedbacks	W1	W2
Content	Addition	41	29
	Deletion	6	9
	Category refinement	2	9
	Term refinement	2	4
	Expansion	-	2
Concept	Purpose	-	1
	Emphasis	-	2
	Development	-	1
	Presentation	-	4

The feedback obtained from the workshops was reviewed for its applicability to refine the model based on five applicability premises. They are summarised in Table 44.

Table 44 Feedback applicability premises

	Premises	
Applicable (A)	P1	If feedback is justified and aligned to the research approach and/or research findings, then applicable
Partly Applicable (PA)	P2	If feedback is justified and aligned to research approach and/or findings, however the suggestion on how to change the model does not aligned to research approach and/or findings, and vice versa, then partly applicable
Inapplicable (I)	P3	If feedback is unjustified and/or not aligned to research approach and/or not aligned to research findings then, inapplicable
	P4	If feedback is already applied in the model, then inapplicable
A / PA / I	P5	If feedback is related to prior or other feedback, then corresponding outcome (i.e. applicable, partly applicable, or inapplicable)

From the review, the feedback can be concluded as being "applicable" when it is considered appropriate to be applied, "partly applicable" when it is somewhat relevant, or can motivate changes in other parts of the model, and "inapplicable" when it is considered inappropriate to be applied (Section 6.4). In Table 45, the number of feedback points per category is presented, categorised by the identified socio-technical theme.

Table 45 Number of feedbacks applicability according to the themes

Theme	Applicable	Inapplicable	Partly applicable
Human being	15	18	2
Interaction	6	5	-
Conflict	1	2	3
Organisation	1	4	-
Boundary	1	2	-
Design information	1	12	4
Tools	-	4	1
Technical system	1	1	-
Design process	3	16	1

Based on the "applicable" and "partly applicable" feedback points, the architectural model was refined (Section 6.5). The refinements apply to both the concept and the content of the model. With respect to the concept of the model, the refinements relate to the way the model was presented. Three such refinements were made: 1) the model was presented in two levels of details instead of one (Section 6.5.1.1), 2) the concept of a "value attribute" was identified and used to review the attributes of the model (6.5.1.2), and 3) directed arrows were added to show the direction of relationships between the entities (Section 6.5.1.3).

Concerning the content (element) of the model, similar categories of refinement were identified once the feedback was categorised. These are: 1) “addition” when content was added, 2) “deletion” when content was deleted, 3) “category refinement” when a content category was refined, and 4) “term refinement” when a term used to represent particular piece of content was refined. “Expansion”, however, was not identified in the refinements list. In the following table (Table 46), the refinements are summarised, based on the aforementioned categories, the elements of the model (e.g. entity, attribute), and the socio-technical theme (e.g. human being, interaction). Having applied these refinements, STAM-3 Level 2 consists of 101 elements, 15 elements less than STAM-2

Table 46 Summary of refinements

Theme	Element of model	Addition	Deletion	Category refinement	Term refinement
Human being	Entity	-	1	-	-
	Sub-entity	-	3	-	1
	Attribute	1	16	12	-
	Relationship	5	3	-	1
Interaction	Entity	1	-	-	1
	Sub-entity	-	-	-	-
	Attribute	4	2	-	-
	Relationship	3	1	1	-
Conflict	Entity	-	1	-	-
	Sub-entity	-	-	-	-
	Attribute	1	2	-	-
	Relationship	1	1	-	2
Organisation	Entity	1	-	-	-
	Sub-entity	-	-	-	-
	Attribute	1	1	1	-
	Relationship	2	-	-	3
Boundary	Entity	-	-	-	1
	Sub-entity	-	-	-	-
	Attribute	1	1	2	-
	Relationship	4	1	-	4
Design information	Entity	-	-	-	-
	Sub-entity	-	-	-	-
	Attribute	3	7	-	-
	Relationship	3	-	-	6
Tools	Entity	-	-	-	-
	Sub-entity	-	-	1	1
	Attribute	-	4	2	-
	Relationship	2	1	-	2
Technical system	Entity	-	-	-	-
	Sub-entity	-	-	-	-
	Attribute	1	3	-	-

	Relationship	1	1	-	1
Design process	Entity	-	-	-	-
	Sub-entity	1	-	-	-
	Attribute	2	4	-	1
	Relationship	-	-	-	3

In addition to the above refinements on the elements of the model, one theme of the socio-technical architectural model, i.e. “interaction”, was refined to “communication” (Section 6.5.2.2), and one theme was deleted, i.e. “boundary”. As a result, the theme of CED consists of human being, communication, conflict, organisation, design information, tools, and design process.

Having refined STAM-2, STAM-3 was constructed. At this point, the model was split into two levels of detail. The greater level of detail model was referred to as the second level of the third version of the architectural model (Section 6.6.1). This model was then aggregated, leading to the lower level of detail model, referred to as the first level of the third version of the architectural model (Section 6.6.2).

Finally, one lesson was learned during the workshops regarding to the participants of the workshop. As described in Section 6.2, two types/groups were involved in the model evaluation, i.e. industrial practitioners and academics. This was done to generate multi-perspective feedback. Although their contribution towards the model evaluation was considered important, these participants were overwhelmingly from the engineering field (see Section 6.2.1 and Section 6.2.2). Only one participant was identified as from a non-engineering field (i.e. management) (see Table 85). As such, their perspectives can be considered technical. If the aim of developing the model is to understand a phenomenon of the CED practice, from a socio-technical perspective (Chapter 1 and Chapter 6), then it is reasonable to conclude that the model needs to be evaluated by those coming from a non-engineering field to enhance the social perspective.

7. Social perspective

In Chapter 6, STAM-2 was reviewed using a focus group method, conducted in the form of a workshop. The workshop involved two groups of participants, i.e. industrial practitioners and academics. The outcome of the review was the third version of the architectural model (STAM-3). One of the lessons learned from the STAM-2 review was that the model was mainly reviewed from a technical perspective with relatively little input from a social perspective (Section 6.7). As the model is intended to encapsulate both social and technical elements (it is a socio-technical model) (Chapter 4), a view from the social perspective was needed. The social views were obtained from two sources. The first involved eliciting the opinion from a social science academic through a semi-structured interview. The second involved reviewing social collaboration literature. The results and how they were used to refine the model are provided in Section 7.1 and Section 7.2, respectively. The chapter concludes with a summary of work presented in Section 7.3.

7.1 Social science academic perspective

As mentioned in Chapter 2, CED involves human beings and their interaction. To study the phenomena of CED, studying human beings and their interaction is needed. Studying human beings and their interaction can also be found in a social science field. Thus, to obtain social perspective towards the model, it seems reasonable to involve social scientists. However, as the researcher conducts a research within an academic environment, they have limited connections to social science based on industry. Additionally, from the experience of conducting empirical study in Company 1, it was found that there is a lack of social scientist based on CED practice. For this reason, involving social science academic was deemed appropriate.

As mentioned in Chapter 3, the social element of CED is related to teamwork (design team) in an organisational context. On this basis, the social science academic selected to review the model was someone who specialised in organisational teamwork area. Additionally, for practicality reason the social science academic selected was someone located in the University of Strathclyde, Glasgow where the researcher is based. A recommendation was asked for from a member of the faculty of Humanities and Social Sciences at the University of Strathclyde, where the majority of organisational teamwork academics are based. From them, an academic in industrial-organisational psychology, from the Department of Human Resource Management at the University of Strathclyde, was suggested. To manage anonymity, the recommended academic is regarded as "the social science academic" throughout this thesis

The social science academic suggested is an industrial-organisational psychologist, specialising in the field of people management (team work) and organisational behaviour. The social science academic has been in the field for more than 10 years, has a number of publications, and is currently involved in a number of projects in collaboration with organisations in the aforementioned field. The social science academic is a peer reviewer of various pertinent journals such as the Group Processes and Intergroup Relations Journal, the Journal of Organizational Behaviour, Employee Relations, and British Journal of Industrial relations. Given the research background and experience, the academic was considered knowledgeable in the field of social science, particularly in the field of team work.

A semi-structured interview was used to elicit judgement from the social science academic. During the interview, the model was briefly presented to the social science academic to obtain their feedback. A set of open ended questions were prepared, such as, what constitute collaboration practice in an industry and need to be presented in the model, what elements need to be added/deleted/changed intended to open a discussion on the representativeness of the social elements in the model and their relationships with the technical elements.

During the interview, the viewpoint of the social science academic was held in the same regard as that of all previous interviewees. However, due to time and resource constraints, this social science academic was the only interviewee spoken to from the social science perspective. As such, despite their viewpoint being held in the same regard as all interviewees from the technical perspective, the suggestions from the social science academic were relied upon more heavily when reviewing the model than any individual from the technical perspective, as they were one of the few sources of information the author could access.

In this section, feedback derived from the interview (findings) and how the findings were applied used as the basis to refine the model are outlined In Section 7.1.1, the feedback derived from the social science academic is reviewed and presented. Based on this review, STAM-3 was refined, presented in Section 7.1.2, and STAM-4 was generated, presented in Section 7.1.3.

7.1.1 Feedback from the social science academic

After a three-hour interview with the social science academic, feedback on the social elements of the model was derived. The first two categories of feedback are similar with those in Chapter 7: the ideas of the model (i.e. concept of model) and the elements of the model (i.e. content of model). In addition to these, an additional category was identified, i.e. data source to further enhance the social perspective. They are presented in Section 7.1.1.1, Section 7.1.1.2, and Section 7.1.1.3, respectively.

7.1.1.1 Concept

Two feedback points were identified concerning the concept of the model.

Firstly, the social science academic remarked that the purpose of the model was inadequately articulated during the meeting. However, according to them, the purpose, i.e. to provide insights into CED from the socio-technical perspective, became clearer when the model was reviewed and discussed. The social science academic suggested that the purpose of the model needs to be clearly articulated in any presentation of the model so that the audience can appreciate what the model is for. As argued in Section 6.5.1, since the articulation of the model's purpose during a presentation was not considered an issue of the model itself, this refinement was not documented in this thesis.

Secondly, the social science academic commented on the complex structure of the model, which was also mentioned by the participants in W2 (Section 6.5.1). The social science academic argued that such complexity can lead to misinterpretation, and thus, the social science academic advised the researcher to break down the model into different layers, based on the levels of detail. As discussed in Section 6.5.1.1, the model was presented at two levels of detail to accommodate this concern over the model's complexity, mentioned by the participants in the W2. In this sense, the comment of the social science academic was already accommodated in the third version of the model. However, during the interview with the social science academic, only the second level of the third version of STAM (i.e. the greater level of detail) was presented, as the first level of STAM-3 (i.e. the low level of detail) had not yet been fully developed. When the plan to develop the first level of the model was presented to the social science academic, the social science academic agreed that the first level of the model reduces the complexity of the model. Additionally, the social science academic advised to ensure that the detailed elements and their relationships were properly aggregated in the first level model.

7.1.1.2 Content

With respect to the content of the model, the social science academic remarked that the social elements needing to be presented were organisational elements that affect the collaborative behaviour of human beings. According to the social science academic, there were four elements of organisation that affect collaborative behaviour of human beings. These elements and how they relate to the elements of the model based on the view of the social science academic can be further explained as follows:

7.1.1.2.1 Structure

According to the social science academic, "structure" can be referred as the way an organisation (i.e. a company) is organised. It can relate to various things such as the location of an organisation and the hierarchical structure of an organisation. A different arrangement of an organisation can affect collaborative behaviour. The social science academic believed that in the architectural model, the "structure" that they briefly explained, has been represented properly by the theme "organisation". As such, no alteration to the model was needed.

7.1.1.2.2 Human resource

"Human resource" was used by the social science academic to refer to all the human beings working in an organisation. Various attributes of human beings, such as "motivation" (relating to rewards), "personality", "knowledge", "skill", and "ability" can be considered to influence collaborative behaviour of human beings. The social science academic indicated that human resource had been represented comprehensively by the "human being" theme in the model. However, they remarked the absence of "motivation" in the model and suggested to investigate this further.

In a general sense, the term "motivation" can be defined as a reason(s) that underpins a particular behaviour (The Oxford English Dictionary, 2013). Along a similar stream, Ryan & Connell (1989) also referred to the term "motivation" as "reasons of action".

In the literature, it was identified that several authors used "motivation" in conjunction with other terms, including "behaviour" (Wiener and Vardi, 1990), "cognition" (Badke-Schaub, Dörner and Stempfle, 2005), "emotion" (McCrae and John, 1992; Badke-Schaub, Dörner and Stempfle, 2005; Durndofer, 2005), "skill" and "experience" (Evans, 2012). For example, in the field of psychology, "motivation" and "behaviour" are similarly mentioned as influences to a human being's actions (Wiener & Vardi, 1990). In the design field, "motivation" and the other personal factors such as "emotion" are similarly identified as an influence to the design process (Durndofer, 2005). Evans (2012) revealed "motivation" amongst other individual's factors, i.e. "skills", "experience", and "beliefs" as an enhancer of knowledge sharing. Behaviour (i.e. conation), cognition, emotion (i.e. affection), skills, and experience were identified as attributes of human beings (i.e. stakeholders) in the context of the study presented in this thesis. If “motivation” was perceived as similar with the aforementioned attributes, it seemed reasonable to therefore perceive “motivation” as an attribute of human beings.

The importance of motivation to the general design context has been acknowledged in the literature. Arias et al. (2000), for example, mentioned that an understanding of the people’s motivation is needed to engage them in design culture. From a different perspective, Adler & Chen (2011) perceived motivation as a challenge that individuals need to overcome when performing creative tasks (e.g. designing a complex system). Motivation can cause conflict when the motivation between one team member and another clashes (Goldschmidt, 1995). As conflict was viewed to influence CED practice (see Section 5.3.2.3) and itself is influenced by motivation, motivation can be considered as an influencing factor of CED practice.

The study of Bierhals et al. (2007, p. 89) revealed that when one team member lacked motivation, it “impeded the group process and exacerbated the other team members”. Along a similar vein, Frankenberger & Badke-Schaub (1998) argued that motivation of an individual can influence a s team work situation, together with emotion and cognitive abilities. In knowledge sharing, an essential activity to achieve shared understanding in collaborative work (Panteli and Sockalingam, 2005), “individual motivation” is perceived as a critical influencing factor, as it can “…either facilitate or inhibit…” it (Sondergaard et al. 2011, p. 426). Within the context of design team formation, motivation is identified as one of the factors that needs to be understood prior to forming a design team (Shen *et al.*, 2007). Grounding on the various roles of motivation aforementioned, <u>motivation</u> was seen as an essential attribute of a human being, and one that influenced different elements of CED practice, and thus, needed to be added to the model.

7.1.1.2.3 Culture

According to the social science academic, in an organisational context, “culture” can be divided into two types: 1) Structural culture, which relates to “systems, policies, procedures, and technology that the organisation has”, and 2) Attitudinal culture, which relates to “people’s perceptions, attitudes, feelings, and behaviour in response to the structural culture”. In this sense, structural culture can be viewed as an influence to attitudinal culture. The social science academic believed structural culture can be seen in the model under the term <u>organisational culture</u>, and attitudinal culture under can be seen in the attributes of <u>stakeholders</u>. However, the social science academic mentioned that the relationship between structural and attitudinal culture (i.e. stakeholders) cannot be identified from the model. The social science academic considered that this relationship was essential for representing the influence of culture to collaborative behaviour and therefore needed investigation. The following points described the result from the investigation:

The types of culture

In the literature, various types of culture were identified, presented by different authors. For example, “national or regional” culture, “ethnic”, “corporate”, “branch”, and “professional” culture (Riboulet, Marin and Gowers, 2005; Anticoli and Toppano, 2011). Hofstede & Hofstede (2005) added “gender”, “generation”, “social class”, and “organisation” to the culture types category. In the model, two types of culture were identified: “organisational”, which refers to customs that are embedded in an organisation, and “social”, which refers to customs that are embedded in the society (Section 7.4.2.5). In a general sense, “national”, “regional”, “ethnic”, “gender”, “generation”, and “social class” culture can be grouped into “social” culture as they are embedded in general society, while “corporate”, “branch”, and “organisation” can be categorised as “organisational” culture as they are embedded in an organisation. However, professional culture, which relates to the profession of an individual (Riboulet, Marin and Gowers, 2005), could not be categorised in either type of culture presented in the model. A CED team commonly consists of participants with different professions such as electrical engineers, mechanical engineers, and marketers. Each profession has customs embedded in it and can be referred to as professional culture (Delinchant *et al.*, 2002). These customs influence the individuals’ attributes such as their view (i.e. perspective) towards the design problem. For example, marketing people view a design problem from a commercial point of view while mechanical engineers view a design problem from structural point of view.

Professional culture can be identified as one of the main causes of “silos” (Senescu *et al.*, 2014), or as Company 1 recognised it, the “stiffed-pipe effect” (Section 7.4.2.5). This is the situation in which design participants are only concerned with their tasks, only share information and build relationships with members of their team (Section 7.4.2.5) who share similar professional culture, and build a wall that segregates them with the members of the other design teams. Silos (or the “stiffed-pipe effect”) are identified as an obstruction to communication (Evans, 2012), and thus, an obstruction to collaboration work (Stone, 2004). Considering its significance to collaborative behaviour, <u>professional culture</u> was added to the model, as a subclass of culture.

In addition to the above, as <u>organisational culture</u> and <u>professional culture</u> can be related to organisation, they can be viewed as a member of the “organisation” theme; <u>social culture</u> can be related to a larger field than organisation, i.e. society. For this reason, *social culture* cannot be viewed a member of the “organisation” theme. Regardless of this, as organisation can be perceived as a mini society, and furthermore, society cannot be included in any identified theme, and thus, social culture was included in the model as a member of the “organisation” theme. However, since social culture cannot be viewed as a member of “organisation” theme, any relationship that involves social culture cannot be seen as a relationship that involves “organisation” theme.

Relationship between social culture and organisational culture

From Hofstede & Hofstede 's (2005) cultural dimensions theory, relationships between social culture and organisational culture were identified. In cultural dimension theory, the relationship between social culture and organisational culture can be viewed based on its four social culture dimensions:

- Power distance
  Power distance refers to “the extent to which the less powerful members of institutions and organisations within a country expect and accept that power is distributed unequally” (Hofstede & Hofstede 2005, p.28). According to Hofstede & Hofstede (2005), power distance in society can be related with emotional distance between sub-ordinates and their superior in an organisation. They argued that in the countries (i.e. societies) where power distance is considered large (i.e. power inequality is highly accepted by the society), the emotional distance between subordinates and their bosses is also large, which means sub-ordinates are less likely to interact with their bosses directly. On the contrary, in the societies where power distance is considered low, sub-ordinates are more likely to interact with their bosses directly. The way sub-ordinates interact with their bosses can be viewed as an organisational culture, as it is a custom embeds in an organisation. In this sense, organisational culture is influenced by power distance (i.e. social culture).
- Individualism versus collectivism
  Individualism refers to societies where the interests of the individual are placed higher than the interests of the group, and thus, the connection between individuals are “loose”. In contrast, a collectivist society holds the interests of the individual below the interests of the group, and thus, the individuals are closely connected (Hofstede, Hofstede and Minkov, 2010). The relationship between social culture and organisational culture identified from Hofstede & Hofstede’s (2005) study can be seen in various settings, one of them being the management of the organisation.

According to Hofstede & Hofstede (2005), in the societies with high individualism, organisations typically have "management of individual" focussed policies. Contrarily, in societies with high collectivism, organisations commonly have "management of group" focussed policies. An example of such policy can be seen in the way organisations link their incentives, i.e. organisations with "management of individual" link their incentives to the individual's performance, while organisation with "management of group" link their incentives to the group's performance.

- Masculinity versus femininity

  In this dimension, masculinity refers to "the societies in which social gender roles are clearly distinct", (Hofstede & Hofstede 2005, p.82) while femininity refers to "the societies in which social gender roles overlap" (Hofstede & Hofstede 2005, p.83). The relationship between these cultures to the organisational culture can be seen during conflict resolutions (Hofstede & Hofstede 2005). They stated that in femininity societies, individuals tend to resolve conflict through negotiation and compromise, while in masculinity societies individuals tend to resolve conflict through a "good fight".

- Uncertainty avoidance

  Uncertainty avoidance relates to how a society tolerates uncertainty (Hofstede, Hofstede and Minkov, 2010). This relationship between social culture and organisational culture is identified in the establishment of formal rules, such as rules that govern the employee's rights and obligations. In societies that actively tolerate uncertainty, few formal rules can be identified in the organisation, as they are established depending on current needs. In societies that actively avoid uncertainty, many formal rules can be identified to control potential uncertainties.

Based on the above, it can be concluded that <u>social culture</u> is an influencing factor of <u>organisational culture</u>. This relationship was not presented in the model, and thus, was added.

Relationship between human beings and culture

As aforementioned, in the study presented in this thesis, "organisational culture" refers to the customs that are embedded in an organisation. In a more detailed view, Deshpande & Webster (1989, p.4) defined organisational culture as "the pattern of shared values and beliefs that help individuals understand organizational functioning and thus provide them norms for behaviour in the organization". In this sense, organisational culture can be viewed as an influencing factor of an individual. Similarly acknowledging the influence of organisational culture to an individual, Lozano (2008) remarked that organisational culture influences individuals in terms of their values and beliefs, while Lu & Cai (2001) mentioned the influence of organisational culture to the individuals' roles. The influence of organisational culture to individuals (i.e. stakeholders) is also identified with respect to their perspective, cognitive, affective, and conative attributes (Schein, 2004). The industrial investigation (Chapter 5) revealed how organisational culture drives a human being behaviour (e.g. INT-12, INT-14; INT-22, INT-24, INT-25, and INT-26). For example, the culture of indirect communication (e.g. through email) motivates the behaviour of "blaming each other" (indicated by INT-14). In addition to these, the influence of other types of culture (i.e. social and professional culture) to individuals was also identifiable in the literature (however, it must be noted that the description of "influence" was unclear). For example, Geertz (2000) described how the differences in social culture (e.g. between western culture and east Asian culture) affects individual's cognition, attitudes, and behaviours while Hofstede et al. (2010) argued that culture form human beings' personality.

Despite the relationship between culture and the attributes of human beings (e.g. behaviour, belief) described above, there was no evidence mentioning the relationship between culture and the socio demographic (e.g. age, gender) of human beings can be identified from the literature and the industrial investigation. Within the concept of EER, a relationship between two entities involves all attributes and subclasses that attached to the said entities. Based on this, although the influences of culture to human beings were acknowledged, this relationship was not represented in the model.

Winkler & Bouncken (2011) stated that culture differentiates a human being from another. From this perspective, culture can be considered as an attribute of human beings (stakeholders). This has not been included in the model. Considering the significance of culture (discussed above), culture was added in the model as an attribute of stakeholders. Furthermore, Hofstede et al. (2010) argued that human beings are not born with culture. They acquired it from the environment that they belong such as family where they grow up and the country where they live. Human beings also acquire culture from their interaction with other people (Winkler and Bouncken, 2011). In this sense, it can be concluded that there is a relationship between stakeholders and culture (i.e. stakeholders acquire culture). However, this relationship was not yet presented in the model, and thus, was added.

7.1.1.2.4 Conflict

The term "conflict" mentioned by the social science academic here referred to social conflict (i.e. conflict between two or more individuals), which can occur between different people in a team (i.e. interpersonal conflict) and/or between different teams (e.g. department, project team) in an organisation. This can be caused by various factors, such as differences in goals and the use of power (e.g. coercion). In the model, the social science academic identified that “conflict” was represented by the theme “conflict”, and therefore, no changes were needed.

In summary, four elements of organisation that influence the collaborative behaviour of human beings, elicited from the social science academic, were explained above. It was seen that elements “structure” and “conflict” required no further action (the only difference between the current model and the social science academic’s view being terminology differences). However, elements “human resource” (particularly “motivation”) and “culture” required refinement to the model.

7.1.1.3 Data source

With respect to the relationships between the socio-technical elements of the model, the social science academic argued that their expertise was within the domain of general collaboration within organisations. As such, they believed that their knowledge was limited to the relationships between the social elements. To review the relationship between the socio-technical elements, from a social perspective, the social science academic suggested obtaining insights from human resource staff in a company(s) conducting collaborative engineering design. One human resource staff in Company 1 was interviewed and their insights were used as the basis to develop the second version of the model (Chapter 5). As such, this suggestion was considered completed, and thus, can be excluded from the next stages of the model evolution. In addition, the social science academic also suggested two books (i.e. “Reframing organizations: artistry, choice, and leadership” by Lee G. Bolman and Terrence E. Deal, and “The secrets of successful team management: how to lead a team to innovation, creativity and success” by Michael A. West) that the researcher should read for further insight into the social perspective of collaboration. Finally, for the purpose of model generalisation, as the model was developed based on CED practice in a single company, the social science academic recommended to conduct study or evaluate the model based on CED practice in another company(s).

7.1.2 The refinements of STAM-3

In Section 7.1.1, feedback on STAM-3 elicited from the social science academic was presented. From the feedback, suggestions to further investigate two social elements (i.e. motivation and culture) were derived and discussed. Based on the discussion, four refinements were made. How these refinements were applied to the model is presented in this section. To highlight the refinements, the notations used in Section 6.5.2 were applied. Additionally, for visualisation purposes, the same colours as used in the second (Section 5.4) and the third version (Section 6.6) of the model were applied to the fourth version of the architectural model (STAM-4).

The first refinement was applied within the "human being" theme, an attribute of stakeholders, i.e. motivation was added. The refinement is shown in the Figure 76.

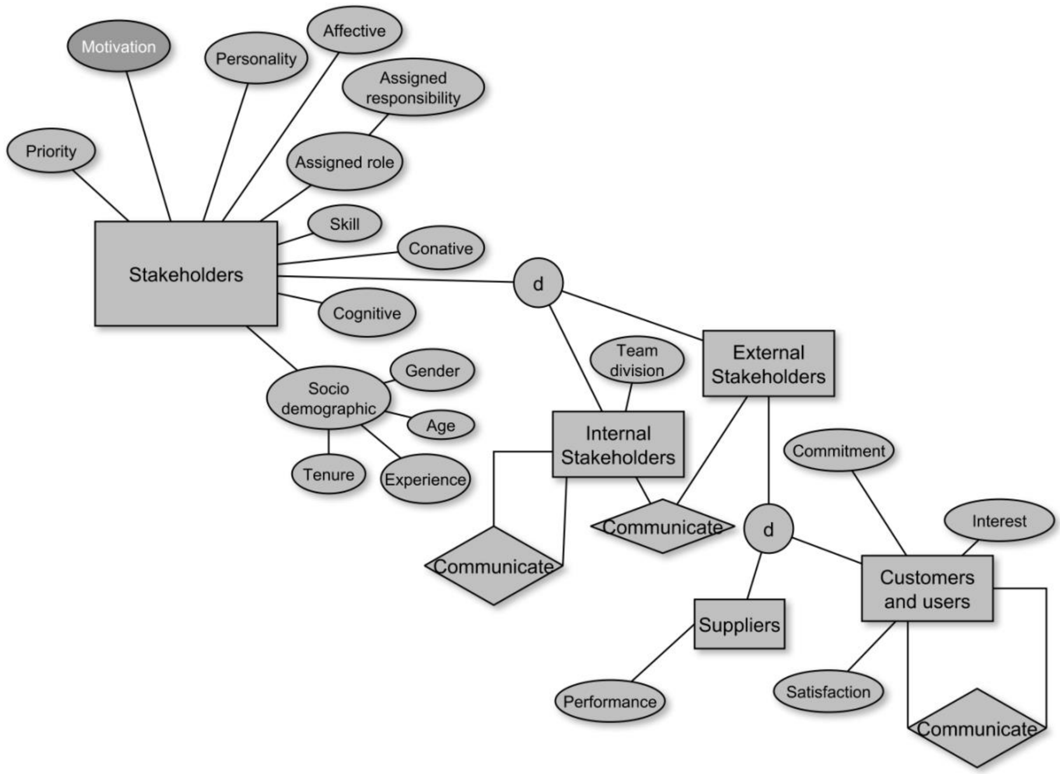


Figure 76 Refinement on the architectural model of the human being theme

The second refinement was applied within the "human being" and "organisation" theme, a relationship to connect stakeholders (i.e. a member of the "human being" theme) and culture (i.e. a member of the "organisation" theme) and, i.e. "acquire" was added. The refinement is presented in Figure 77

The third and fourth refinements were applied within the "organisation" theme, a sub-entity of culture, i.e. professional culture was added, and the relationship influences was added to connect social culture and organisational culture. The refinements are depicted by Figure 78.

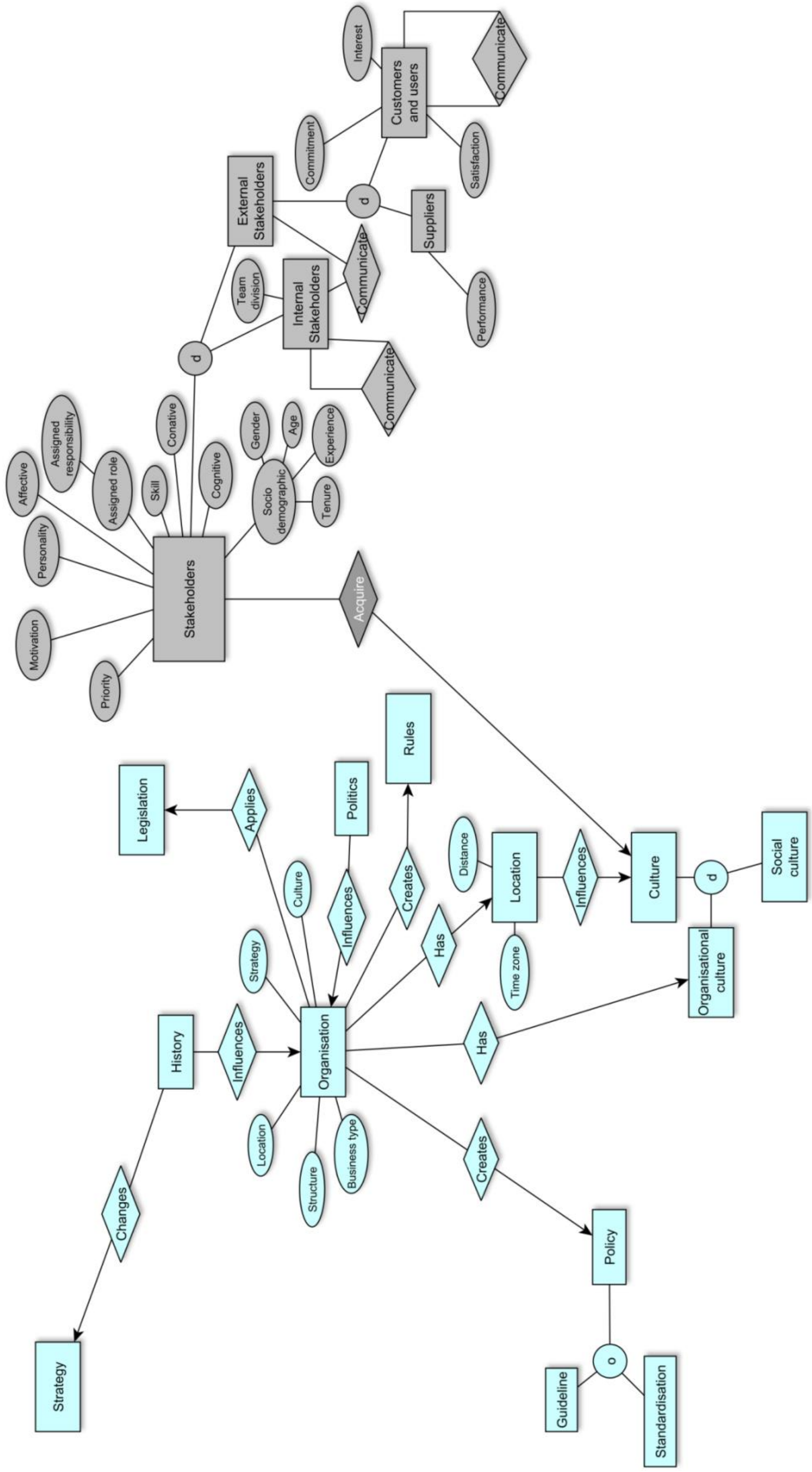


Figure 77 Refinement on the "organisation" and "human being" theme

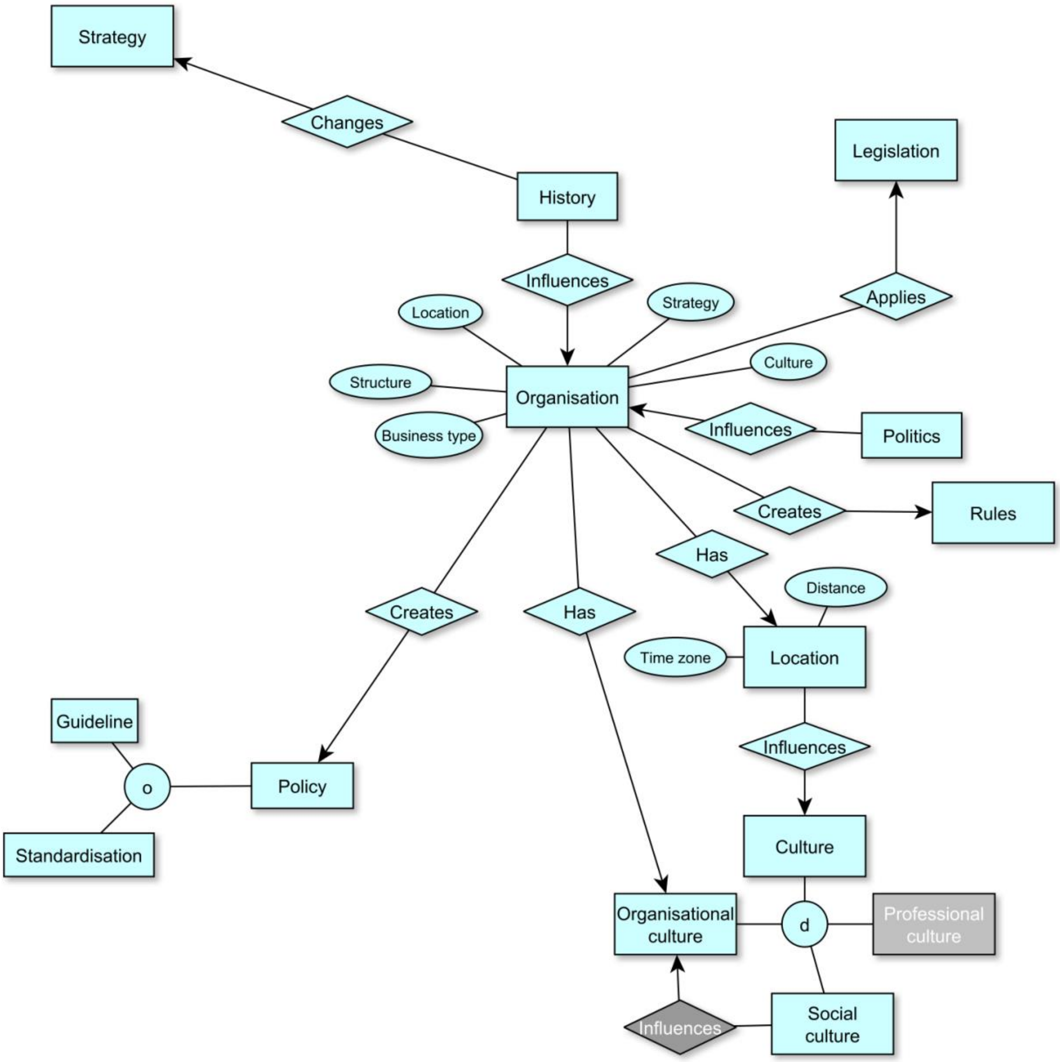


Figure 78 Refinements on the organisation theme

7.1.3 STAM-4

Applying the aforementioned refinements, STAM-4 of collaborative engineering design Level 2 was constructed, presented in Figure 79.

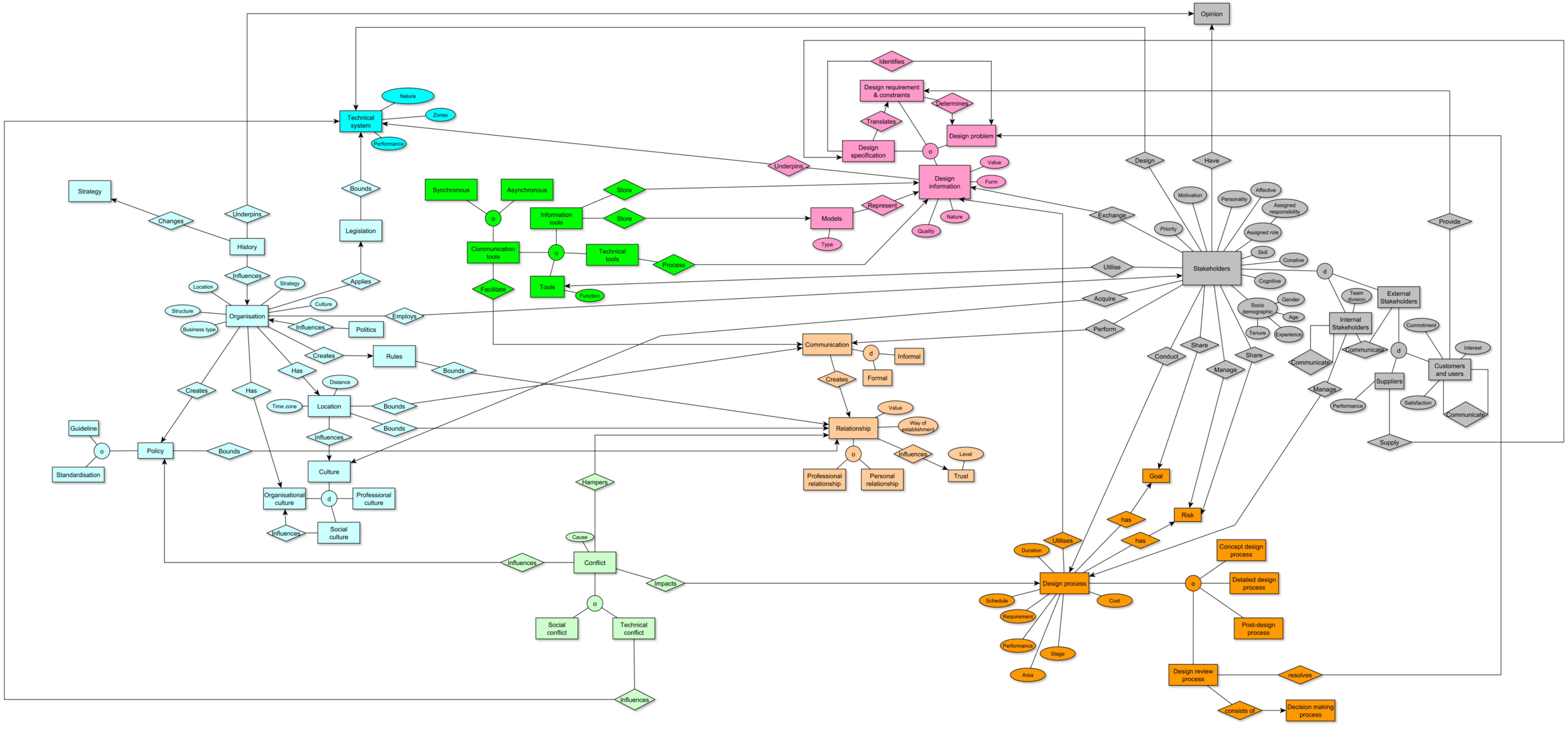


Figure 79 STAM-4 Level 2

In the fourth version of the architectural model, there was an additional relationship between the "human being" and "organisation" themes (i.e. stakeholders acquire culture). However, any relationship that involves *social culture* cannot be seen as a relationship that involves the *organisation* theme (discussed in Section 7.1.1.2.3). As social culture is a sub-entity of culture, and thus, the relationship between stakeholders and culture involves social culture, this relationship cannot be seen as a relationship that involves the "organisation" theme. For this reason, no aggregation was deemed needed, and the architectural model level 1 remained unchanged.

In addition to the above, in STAM-4, no new themes were identified and no refinement was made on the existing themes. Thus, it can be concluded that the model development has reached what it is recognised as *theoretical saturation* (see Section 2.3.2). However, according to Marshall et al. (2013) to confirm that new themes are indeed no longer identifiable, research needs to be conducted past the saturation point. Based on this, the iteration of model evolution was continued.

7.1.4 Summary

This section presents the second iteration of the model review and refinement phase, aiming to enhance the social perspective of the socio-technical architectural model. The model was reviewed using an expert judgement approach. The social science academic was selected through peer-recommendation, from which, an industrial-organisational psychologist was selected. To elicit their judgement, a semi-structured interview was conducted.

The social science academic described the four elements of organisation that affect collaborative behaviour of human beings, which according to the social science academic, can be considered relevant to the social elements of collaborative engineering design. The elements consisted of "structure", "human resource", "culture", and "conflict". The social science academic believed that these elements were generally represented in the model, under different terminologies (as outlined in Table 47). However, there were four suggestions that could be considered to refine the model. They are summarised in Table 48, grouped into concept (Section 7.1.1.1), content (Section 7.1.1.2), and data source (Section 7.1.1.3) of the model.

Table 47 Representations of the organisational elements in the socio-technical architectural model

Organisational elements	Elements of model
Structure	Organisation
Human resource	Human being
Culture	Culture

Conflict	Conflict

Table 48 Summary of refinement suggestions from the social science academic

	Suggestions
Concept	Clearly articulate the purpose of the model.
	Simplify the structure of the model by presenting it in different levels of detail.
Content	Investigate "motivation" as an attribute of a human being.
	Investigate relationship between "attitudinal culture" and "structural culture".

Based on these suggestions, four refinements to the architectural model were made. The refinements consist of one attribute addition and one relationship addition on the "human being" theme, one sub-entity addition, and two relationship additions on the "organisation" theme. The refinements are summarised in Table 49. Applying these refinements to the model, the STAM-4 level 2 was generated (Section 7.1.3). These refinements did not affect the architectural model level 1, and thus, it remained unchanged.

Table 49 Summary of refinements on the architectural model

Theme	Element of model	Category of refinement	Description of refinement
Human being	Attribute	Addition	Add "motivation" as an attribute of "stakeholders"
Human being	Relationship	Addition	Add "acquire" to connect "stakeholders" and "culture"
Organisation	Sub-entity	Addition	Add "professional culture" as a sub-entity of "culture"
Organisation	Relationship	Addition	Add "influences" to connect "social culture" and "organisational culture"

In addition to the above, on the basis of the suggestions from the social science academic and to further enhance the social perspective of the model, three actions needed to be undertaken: 1) social literature exploration on the books aforementioned and 2) conduct study in different companies for generalisation purposes. For this reason, the next iteration of the model review and refinement phase included social literature exploration and further industrial investigation(s). In the following section, the first action was addressed and the results are presented.

7.2 A review on the social literature

Two books (identified as social literature throughout this thesis) were recommended by the expert for a better insight into the social elements of collaborative work in an organisational context, from the social perspective. The first book was written by Lee G. Bolman and Terrence E. Deal, titled "Reframing organizations: artistry, choice, and leadership" (hereafter B1). The second book was authored by Michael A. West, titled "The secrets of successful team management: how to lead a team to innovation, creativity and success" (hereafter B2). The social literature was explored to elicit findings that could be used as the basis to review the model.

In this section, the third iteration of the model review and refinement phase through social literature is presented from Section 7.2.1 to Section 7.2.5. The chapter starts with a summary of the suggested books and their relevance to the model, presented in Section 7.2.1. In Section 7.2.2, findings elicited from the social literature and how these findings can be applied to the model are identified and presented. Based on the applicable findings, the model was changed, as described in Section 7.2.3. From the refinement, STAM-5 was developed, presented in Section 7.2.4. This chapter concludes with a summary of work, provided in Section 7.2.5.

7.2.1 Summary of the social literature

A summary of B1 and B2, as well as their relevancy to the model, are presented in Section 7.2.1.1and Section 7.2.1.2, respectively.

7.2.1.1 B1

This book offers an approach to understand the concept of an organisation by perceiving organisations through "frames". The term "frame" used in the book refers to "a mental model, a set of ideas and assumptions" that people have in their head to "help understand and negotiate a particular territory [of organisations]" (Bolman & Deal 2013, p.10). According to Bolman & Deal (2013), each frame represents different perspective, and thus, provides a different portrait of reality (i.e. organisations). Four frames to view the concept of an organisation were presented in the book:

1. **Structural frame**, relates to organisational structure, rules, policies and goals, regarded as the "architecture of organisation".
2. **Human resource frame**, relates to people, their needs and desires, and their relationship with organisation.

3. **Political frame**, relates to power, competition, and conflict.
4. **Symbolic frame**, relates to beliefs and culture.

Each frame was discussed and the concept of organisations was presented from these frames. Although B1 discusses the concept of organisation in a general context (not specific to CED context), the concept was founded upon human beings and teamwork. This is aligned with the foundation of any collaboration work, including CED (Chapter 1). From this perspective, the concept of organisation presented in the book could be considered relevant to the concept (phenomena) of CED presented in this thesis, and thus, could be used to review the model

7.2.1.2 B2

This book was written for managers as practical guidance for creating an effective team in an organisation. It covers various issues of organisational teamwork such as creating teams, setting the objectives of the team, promoting creativity, providing emotional support, and managing conflict. These are discussed in a general organisational context and in a problem-solving process context, using a product development team for examples. An engineering design process may be considered a problem-solving process (Section 4.3.2), and thus, collaboration in a design process (i.e. CED) may be perceived as teamwork in a problem-solving process. In this sense, the issues on how to create an effective team in an organisation can be considered relevant to those in a CED team, and thus, may be used as a basis to evaluate the model.

7.2.2 Findings

Of interest from the literature were the sentences pertinent to the elements of collaborative work in an organisation that were not presented in the model and/or presented differently in the model. For example, in B1, Bolman & Deal (2013, p.117) mentioned, “People’s skills, attitudes, energy, and commitment are vital resources that can make or break an enterprise,” and as such, this sentence is considered pertinent to the “human being” theme of CED. From the sentence, it could be concluded that people (human beings) have skills, attitudes, energy, and commitments that influence an enterprise (organisation). The skills and attitudes of human beings were discussed and presented in the model (see Chapter 5), and thus, they were not considered as new findings. The commitment of human beings was already presented; however, was identified as an attribute of <u>customers and users</u> only. In the social literature, “commitment” was identified as an attribute of human beings in general. As there was discrepancy concerning the commitment of human beings in the social literature and in the model, the commitment of human beings was considered as a new finding. Lastly, the energy of human beings had not been discussed nor presented in the model. Therefore, it was considered as a finding. In conclusion, there were two findings identified within the aforementioned citation, i.e. human beings have commitment, and human beings have energy. The full list of sentences cited from the social literature and the findings derived from them can be seen in Appendix 14: Findings from B1 and B2.

In all, twenty-two findings were derived from the social literature. Three findings were derived from both, B1 and B2 (highlighted), eight findings were derived from B1 only, and eleven were derived from B2 only. These findings can be categorised into the four themes of CED, i.e. "human being", "organisation", "communication", and "(design) process", as seen in Table 50.

Table 50 List of findings from the social literature

Theme	Findings	Source	
		B1	B2
Human being	Human beings have competency	√	√
	Human beings have commitment	√	√
	Human beings have desire		√
	Human beings have energy		√
	Human beings have natural (informal) role	√	
	Needs are important elements of a human being's psychology	√	√
Communication	There are two forms of communication: verbal and non-verbal		√
	Relationship has quality	√	
Organisation	Organisations have age	√	
	Organisations have organisational goals	√	
	Organisational goals have focus		√
	Organisational goals have quality		√
	Organisations have size	√	
	Policies limit human beings	√	
	Rules consist of informal rules		√
	Rules limit human beings	√	
	Organisational goals are embedded in strategy	√	
Design process	Process consists of activities		√
	Risk has impact		√
	Risk has probability (of occurrence)		√
	Schedule and cost influence each other		√
	Team work requires planning		√

The findings applicability to refine the model was reviewed through further analysis within the CED context. To exemplify this, a finding, "human beings have commitment" was used. From the industrial investigation, commitment was identified as an attribute of customers (Section 5.3.2.1). However, Lu et al. (2007) argued that collaboration involves the highest degree of commitment from its participants when compared to cooperation and coordination. From this perspective, commitment should not be seen as an attribute of customers and users only, instead, it should be viewed as an attribute of all CED participants (i.e. stakeholders). On this basis, commitment was deleted from an attribute of customers and users and added as an attribute of stakeholders. As the finding "human beings have commitment" was used to refine the model, the finding was considered applicable. The detailed review of the findings can be seen in Appendix 15: Review of findings from B1 and B2.

From the review, using the same categories of refinement as described in Section 6.5.2, fourteen findings were considered applicable and eight were considered inapplicable to evolve the model, summarised in Table 51.

Table 51 Summary of findings applicability

Theme	Findings	Applicability
Human being	Human being have competency	Applicable
	Human beings have commitment	Applicable
	Human being have desire	Inapplicable
	Human beings have energy	Inapplicable
	Human beings have natural (informal) role	Applicable
	Needs are an important element of a human being's psychology	Inapplicable
Communication	There are two forms of communication: verbal and non-verbal	Applicable
	Relationship has quality	Applicable
Organisation	Organisations have age	Inapplicable
	Organisations have organisational goals	Applicable
	Organisational goals have focus	Applicable
	Organisational goals have quality	Applicable
	Organisations have size	Inapplicable
	Policies limit human beings	Inapplicable
	Rules consist of informal rules	Applicable
	Rules limit human beings	Inapplicable
	Organisational goals are embedded in strategy	Applicable
Design process	Process consists of activities	Applicable
	Risk has impact	Applicable
	Risk has probability	Applicable
	Schedule and cost influence each other	Inapplicable
	Team work requires planning	Applicable

7.2.3 The refinements of STAM-4

Based on the "applicable" findings, twenty-three refinements were applied to the model. This number consists of 14 refinements from the applicable findings listed in Table 51, and 9 refinements motivated by the refinements of the applicable findings. For example, Table 51 lists "organisations have organisational goals" as an applicable finding under the "organisation" theme. In the current model, the design process theme already has goal as a member, and therefore must be altered to design goal to differentiate from the organisational goal in the organisation theme. The categories of refinements applied to the fourth version of the model were similar with the categories of refinements applied to the second version of the model (Chapter 6), i.e. **addition**, **deletion**, **expansion, category refinement**, and **term refinement** (Section 6.5.2).

Nineteen additions, three deletions, and one term refinement were applied to the model. There was no expansion or category refinement applied to the model at this stage. In Table 52, these refinements are presented.

Table 52 Summary of refinements

Findings	Refinements	Category of refinement
	Human being	
Human being have competency	Add "competency" as an attribute of "stakeholders"	Addition
Human beings have commitment	Add "commitment" as an attribute of "stakeholders"	Addition
	Delete "commitment" from an attribute of "customers and users"	Deletion
	Delete "interest" from the model	Deletion
	Delete "satisfaction" from the model.	Deletion
Human beings have natural (informal) role	Add "natural role" as an attribute of "stakeholders"	Addition
	Communication	
There are two forms of communication: verbal and non-verbal	Add "form" as an attribute of "communication"	Addition
Relationship has quality	Add "quality" as an attribute of "relationship"	Addition
	Organisation	
Organisations have organisational goals	Add "organisational goal" as an entity	Addition
	Add "organisational goal" as an attribute	Addition
	Add "has" to connect "organisation" and "organisational goal"	Addition
	Add "determines" to connect "organisational goal" and "[design process] goal"	Addition
Organisational goals have focus	Add "focus" as an attribute of "organisational goals"	Addition
Organisational goals have quality	Add "quality" as an attribute of "goals"	Addition

Rules consist of informal rules	Add "informal rule" as a sub-entity of "rule" with "disjointed" relationship	Addition
	Add "formal rule" as a sub-entity of "rule" with "disjointed" relationship	Addition
Organisational goals are embedded in strategy	Add "embeds" to connect "strategy" and "organisational goals"	Addition
	Add "creates" to connect "organisation" and "strategy"	Addition
Design process		
Organisations have organisational goals	Refine the term "goal" in the model into "design process goal"	Term refinement
Process consists of activities	Add "activity" as an attribute of "design process"	Addition
Risk has impact	Add "impact" as an attribute of "risk"	Addition
Risk has probability	Add "probability" as an attribute of "risk"	Addition
Team work requires planning	Add "design process planning" as a sub-entity of "design process"	Addition

The refinements were applied to STAM-4 and they are described in the following sections based on their themes: human being (Section 7.2.3.1), communication (Section 7.2.3.2), organisation (Section 7.2.3.3), and design process (Section 7.2.3.4). To present the refinements in the architectural model, the graphical notations used in Section 6.5.2 were applied. Additionally, to aid visualisation, the same colour notations were applied to represent each theme.

7.2.3.1 Human being

Six refinements on the "human being" theme were applied to its attributes. The refinements consisted of three attribute additions and three attribute deletions. These refinements are outlined in Table 53.

Table 53 Summary of refinement on the "human being" theme

Refinements	Category of refinements	Elements of model
Add "competency" as an attribute of "stakeholders"	Addition	Attribute
Add "commitment" as an attribute of "stakeholders"	Addition	Attribute
Delete "commitment" from an attribute of "customers and users"	Deletion	Attribute
Delete "interest" from the model	Deletion	Attribute
Delete "satisfaction" from the model.	Deletion	Attribute
Add "natural role" as an attribute of "stakeholders"	Addition	Attribute

The refinements of the "human being" theme based on Table 53 are depicted by Figure 80.

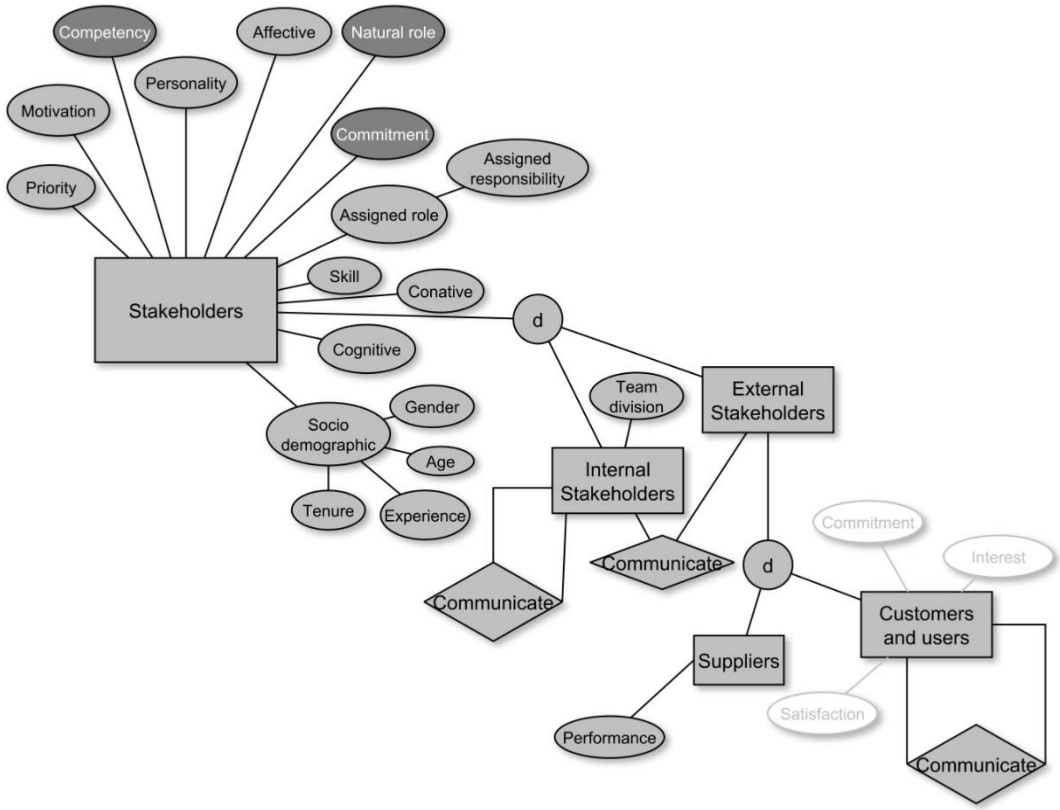


Figure 80 Refined architectural model of "human being"

7.2.3.2 Communication

Within the "communication" theme, two attributes were added, as listed in Table 54 and depicted by Figure 81.

Table 54 Summary of refinements on the "communication" theme

Refinements	Category of refinements	Elements of model
Add "form" as an attribute of "communication"	Addition	Attribute
Add "quality" as an attribute of "relationship"	Addition	Attribute

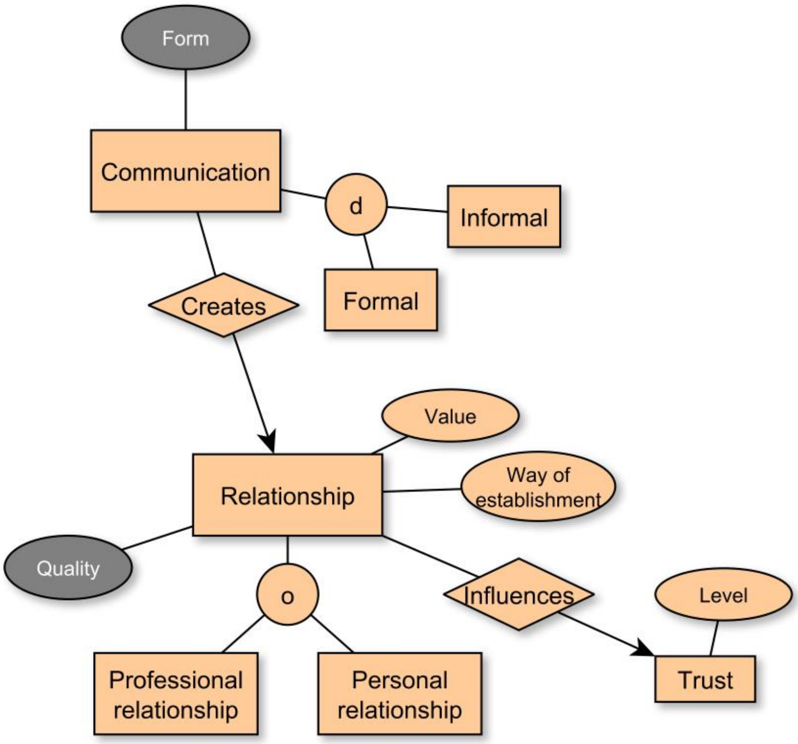


Figure 81 Refined architectural model of "communication"

7.2.3.3 Organisation

Ten refinements were applied to the "organisation" theme. The refinements consisted of one entity addition, two sub-entity additions, three attributes additions, and four relationships additions. Of note is one relationship addition (i.e. determines), which involved a member of two themes (i.e. organisation goal, a member of the organisation theme and [design process] goal, a member of the design process theme). The refinements are listed in Table 55.

Table 55 Summary of the refinements on the "organisation" theme

Refinements	Category of refinements	Elements of model
Add "organisational goal" as an entity and an attribute of "organisation"	Addition	Attribute
	Addition	Entity
Add "has" to connect "organisation" and "organisational goal"	Addition	Relationship
Add "determines" to connect "organisational goal" and "(design process) goal"	Addition	Relationship
Add "focus" as an attribute of "organisational goals"	Addition	Attribute
Add "quality" as an attribute of "goals"	Addition	Attribute
Add "informal rule" as a sub-entity of "rule" with "disjointed" relationship	Addition	Sub-entity
Add "formal rule" as a sub-entity of "rule" with "disjointed" relationship	Addition	Sub-entity

Add "embeds" to connect "strategy" and "organisational goals"	Addition	Relationship
Add "creates" to connect "organisation" and "strategy"	Addition	Relationship

Based on the refinements listed above, the architectural model of *organisation* was refined, as can be seen in Figure 82.

7.2.3.4 Design process

Five refinements were applied to the architectural model of "design process". The refinements consisted of one entity term refinement, three attributes additions, and one sub-entity additions, as presented in Table 56.

Table 56 Summary of refinements on the "design process" theme

Refinements	Category of refinements	Elements of model
Refine the term "goal" in the model into "design process goal"	Term refinement	Entity
Add "activity" as an attribute of "design process"	Addition	Attribute
Add "impact" as an attribute of "risk"	Addition	Attribute
Add "probability" as an attribute of "risk"	Addition	Attribute
Add "design process planning" as a sub-entity of "design process"	Addition	Sub-entity

In Figure 83, the refinements of the architectural model *design process* listed in the above table (Table 56) are depicted.

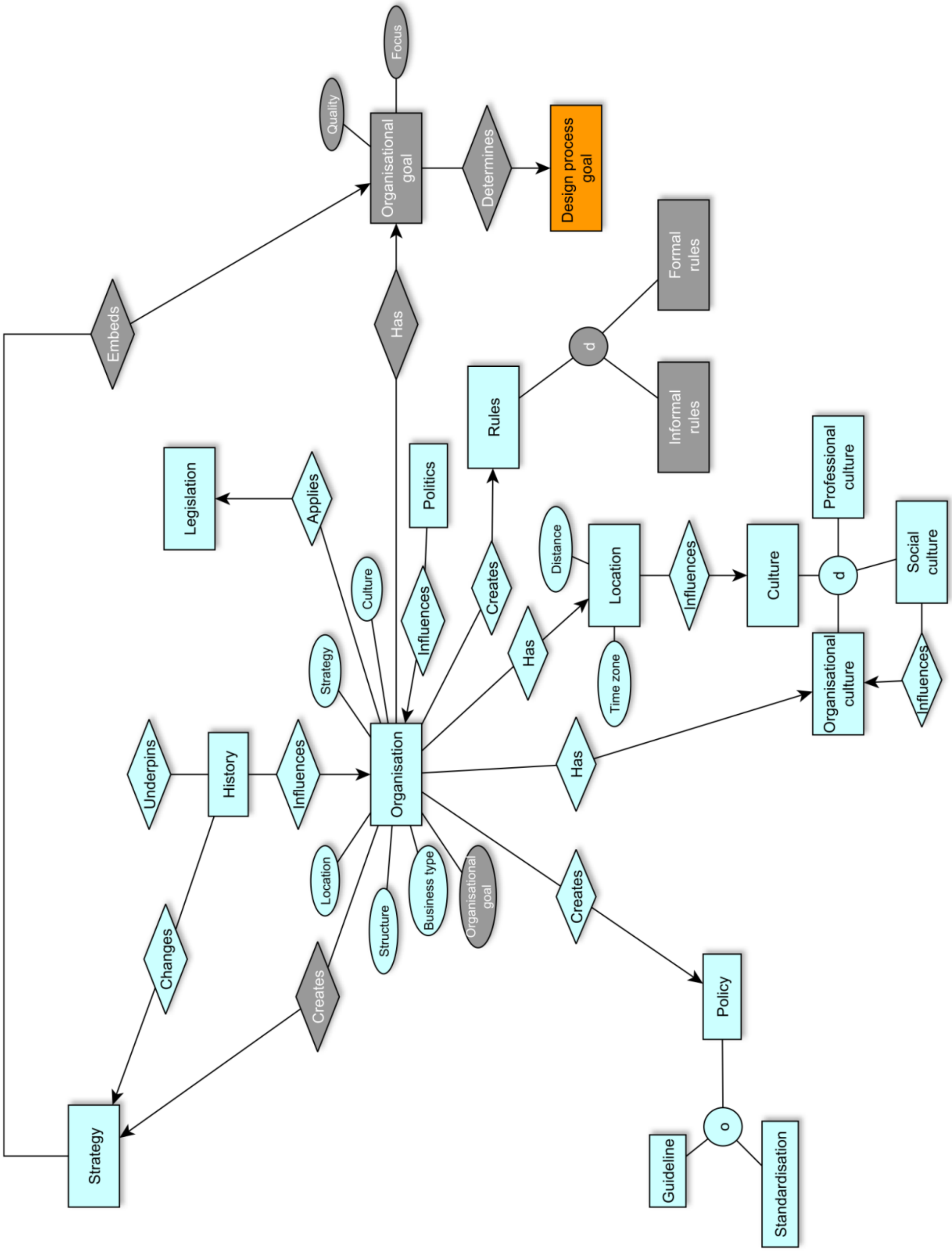


Figure 82 Refined architectural model of "organisation"

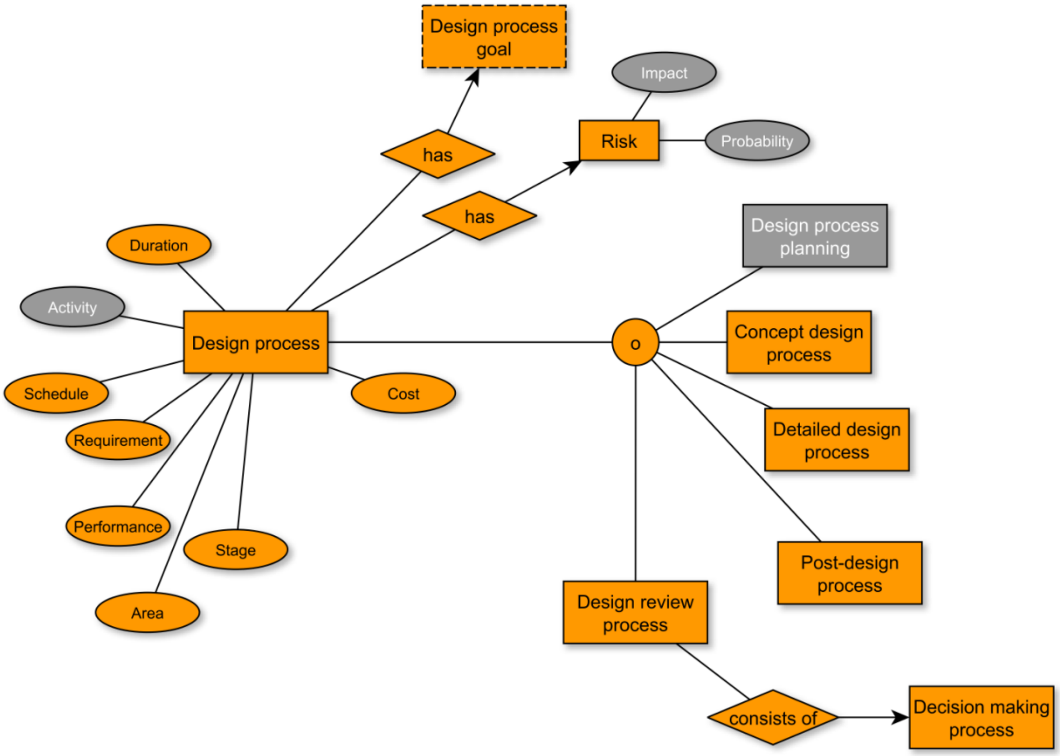


Figure 83 Refined architectural model of "design process"

7.2.4 STAM-5

Having combined the refined architectural models presented in Section 7.2.3, STAM-5 level 2 was resulted, depicted by Figure 84.

From the second level of the architectural model, one relationship (i.e. determines) that connects two members of different themes (i.e. organisation and design process) was identified. In the previous version of the first level of the model (Section 6.6.2), no relationship that links the organisation and design process theme was identified, and thus, the model needs to be refined. As the relationship only involves one member of each theme (i.e. organisational goal, a member of the organisation theme and design process goal, a member of the design process theme), to refine the first level of the model, the relationship was directly obtained from the second level of the model (Figure 84). Based on the second level of the model, the organisation and design process theme was connected in the first level of the model using the term determines. Given this, STAM-5 level 1 can be viewed in Figure 85. Additionally, in STAM -5, no new themes were identified and no refinement was made to the existing themes. This was viewed as a confirmation that the model has reached its saturation point (Section 2.3.2). For this reason, the iteration of model evolution was terminated.

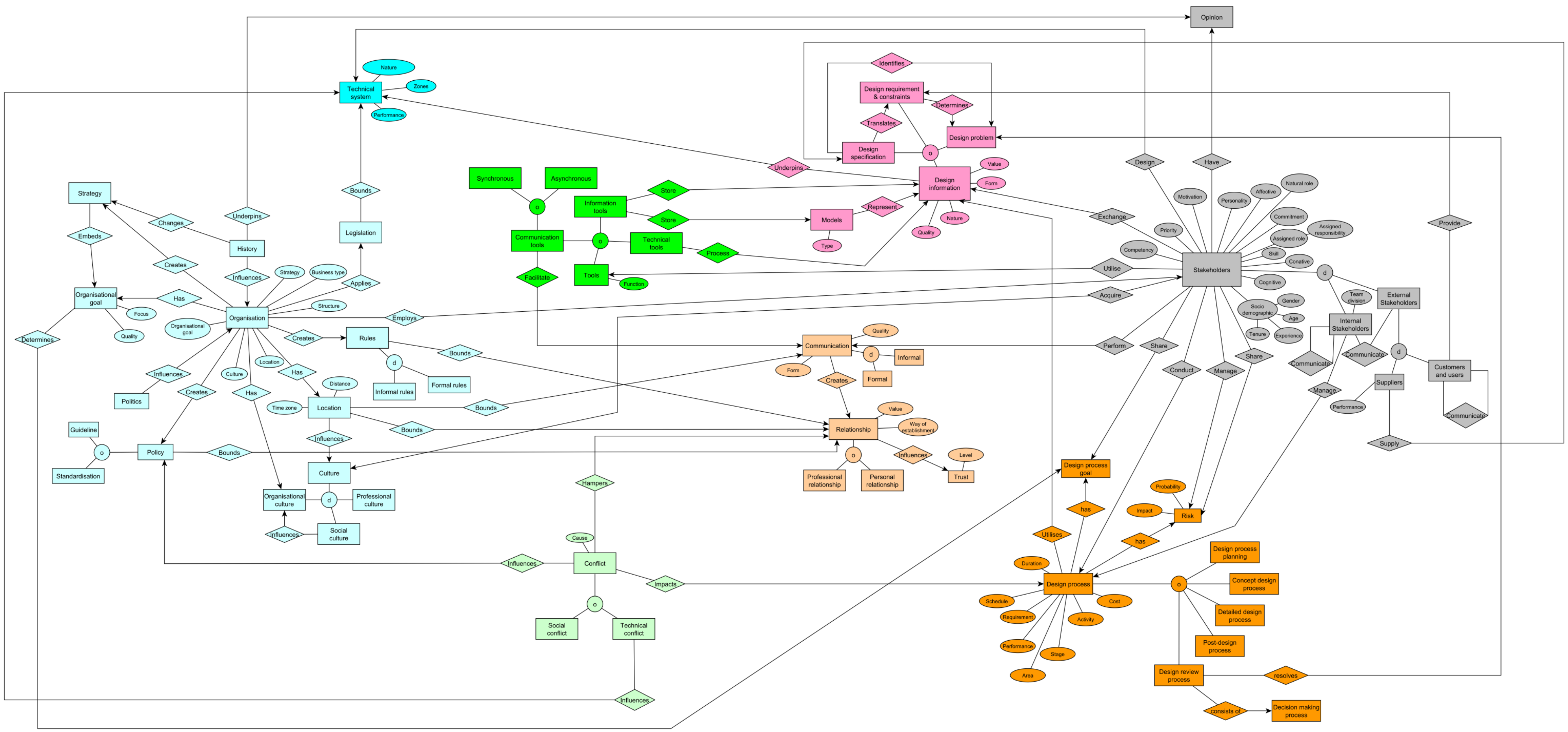


Figure 84 STAM-5 level 2

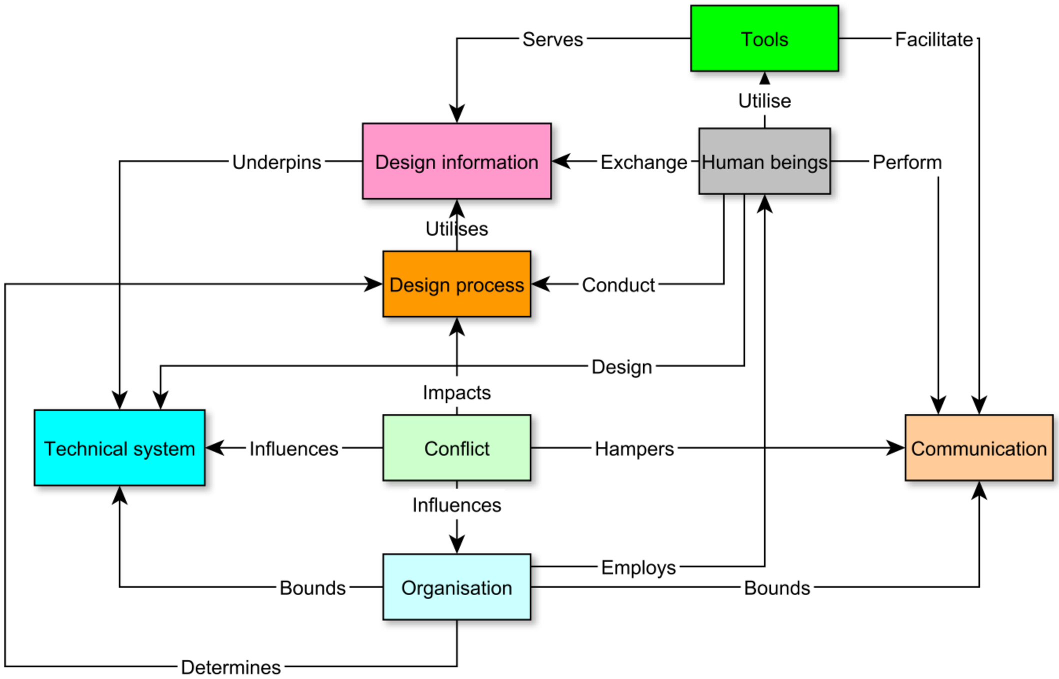


Figure 85 STAM-5 level 1

7.2.5 Summary

In this section, the architectural model was further evolved from the social perspective through an exploration of social literature. Two books were recommended as references by the social science academic. The books are titled "Reframing organizations: artistry, choice, and leadership" by Lee G. Bolman and Terrence E. Deal (regarded as B1), and "The secrets of successful team management: how to lead a team to innovation, creativity and success" by Michael A. West (regarded as B2). In B1, a concept of organisations was presented from different perspectives that Bolman and Deal (2013) regarded as "frames" (Section 7.2.1.1). In B2, practical guidance on how to create an effective team in an organisation was provided (Section 7.2.1.2). Although the two books were not written specifically for CED, they were considered appropriate to evaluate the model due to the following reasons. Firstly, the concept of organisation presented in B1 is centralised in human beings and teamwork and this was considered as aligned with the concept of CED. Secondly, the guidance presented in B2 applies to teamwork in a problem-solving process (e.g. CED).

Twenty-two findings were derived from the social literature (Section 7.2.2). They were analysed for their applicability to refine the model. As a result, fourteen findings were considered applicable and eight were inapplicable to refine the model. From the applicable findings, twenty-three refinements were applied to the four themes of CED (Section 7.2.3). Six refinements were applied to the "human being" theme (Section 7.2.3.1), two were applied to the "communication" theme (Section 7.2.3.2), ten to the "organisation" theme (Section 7.2.3.3), and five to the "design process" theme (Section 7.2.3.4). These refinements can be categorised as addition, deletion, and term refinement. They were applied to the different elements of the model (i.e. entity, sub-entity, attribute, and relationship). The number of refinements broken down by category and element are outlined in Table 57.

Table 57 Number of refinements to the fourth version of the model

	Addition	Deletion	Term refinement	**Total**
Entity	1	0	1	**2**
Sub-entity	3	0	0	**3**
Attribute	11	3	0	**14**
Relationship	4	0	0	**4**
Total	**19**	**3**	**1**	**23**

Having applied the refinements outlined above, the fifth version of the architectural model was developed in its greatest level of detail (Level 2) (Section 7.2.4). Additionally, one relationship between two themes (i.e. organisation and design process) was identified. This relationship was not identified in the previous version of the first level of the model, and thus, it was added. As the relationship only involves one member of each theme, the relationship between said members (i.e. organisational goal and design process goal) was directly added to connect the organisation and design process theme in the level 1 of the model. Finally, as no new themes were identified and no themes were refined, it was concluded that the model has reached saturation point. Thus, the model review and refinement was terminated.

7.3 Overall summary

This chapter had presented the STAM review and refinement from the social perspective through two approaches: 1) semi-structured interview, involving a social science academic from the University of Strathclyde, and 2) literature review, encompassing two organisational collaboration books recommended by the social science academic. Findings from the first approach were used as the basis to refine STAM-3 into STAM-4, while findings from the second approach were used as the basis to refine STAM-4 to STAM-5.

Part 4. Model evaluation

8. Industrial evaluations

The study presented in this thesis aims to develop a socio-technical architectural model of collaborative engineering design. To allow the model to evolve in an incremental manner as well as to address potential misinterpretation and bias, the model was developed in two phases, each with a different focus. The first phase focussed on the development of the model while the second phase focussed on the evolution of the model through review and refinement processes. These phases yielded five versions of the model: STAM-1 to STAM-5, presented from Chapter 4 to Chapter 7. The latest version of the model (i.e. STAM-5) was then evaluated (i.e. third phase) to assess the degree of the model's appropriateness in representing the CED process from the socio-technical perspective through independent case studies. In this chapter, how the model was evaluated, the findings derived from the evaluation, and the conclusions on the model's quality drawn from the findings are presented. Additionally, given the aim of the evaluation phase, i.e. to assess the model, no further changes were made to the model. The findings derived from the evaluation were only used as the basis to assess the model's appropriateness.

The goal of the model development is to better understand the CED process, and thus, can improve it. Therefore, industrial practice was deemed appropriate to form the basis of the model evaluation. As Blessing & Chakrabarti (2009, p.7) stated, "If the aim of the design research is to improve [the] design [process], this research should have some effect on practice, directly or indirectly". Furthermore, as well as the literature (i.e. social and technical) and the academics (i.e. engineering designers and industrial psychologists), the model was developed based on the CED process of one company (i.e. Company 1) which specialises in the design and manufacture of complex technical systems in the shipbuilding industry. Accordingly, assessing the degree of the model's appropriateness in representing the CED process in other industries was perceived important and became the major purpose of the model evaluation.

The industrial evaluation started with preliminary evaluation in an Indonesian company specialised in the design and manufacture of complex technical systems within the shipbuilding industry, similar with Company 1. This company is regarded as Company 2 in this thesis. The evaluation continued with the main model evaluation in two different companies, with a different life phase or product focus. These companies are regarded as Company 3 and Company 4 throughout this thesis. The evaluation approach, and the findings obtained from the preliminary and main industrial evaluations in are presented in

Section 8.1 and Section 8.2, respectively. A summary of work is provided in Section 8.3. The findings are then discussed in Chapter 9.

8.1 Preliminary evaluation

Preliminary evaluation was conducted in an Indonesian, ETO Company specialises in the design and manufacture of complex technical systems within the shipbuilding industry, similar with Company 1. However, Company 2 is located in Indonesia while Company 1 in the United Kingdom. Location is perceived as an influencing factor of culture, and culture is identified as an influencing element of a CED process (Chapter 7). For this reason, the practice of the CED process in Company 2 was deemed appropriate to form the first basis for model evaluation.

One of the main challenges in industrial evaluation identified was to find participating companies. An unexpected opportunity to evaluate the model in Company 2 emerged from network connection when the researcher was in Indonesia. Thus, the evaluation in Company 2 was conducted in an informal manner. Nevertheless, the outcome of the evaluation was considered valuable to the study and for this reason, the evaluation was included in this thesis as preliminary evaluation.

In this section, the model evaluation conducted in Company 2 is presented. The section starts with the explanation of the evaluation approach applied in the company, provided in Section 8.1.1. The findings derived from the model evaluation are presented in Section 8.1.2. Lessons learned from the evaluation approach are discussed in Section 8.1.3.

8.1.1 Evaluation approach

As aforementioned, the main purpose of the model evaluation was to assess the degree of the model's appropriateness in presenting the CED process from a socio-technical perspective in different companies, each with a different set of characteristics. The presentation of the CED process from the socio-technical perspective was represented by the socio-technical elements and their inter-relationships in the model. In Company 2, the distinct characteristic is its national culture. Accordingly, the aim of the model evaluation in Company 2 was to check whether the socio-technical elements and their inter-relationships presented in the model represent the practice of the CED process in a different national culture, which can reflect the generic nature of the model.

To achieve this aim, a semi-structured interview method was adopted based on the consideration of the time limitation and the availability of the participant. The participant (hereafter IP-3) was the head of the company's technology division, with more than 25 years of experience in the design and manufacture of complex technical systems within the shipbuilding industry. As the head of the company's technology division, IP-3 is involved in the CED process as a technical authority, responsible for ensuring that the design of the technical systems complies with the predefined standards and guidelines (e.g. government legislations) (as explained by IP-3).

The interview with IP-3 was conducted for one hour. The conversation was mainly done in Indonesian. To capture the conversation, an audio recorder was used with the participant's consent. The recorded interview was transcribed and translated to English. From the English transcription, the socio-technical elements and their relationships were derived from *coding* and *condensing* the transcription (see Chapter 5). The same qualitative analysis process as the one employed and explained in Chapter 5 was employed. The codes assigned to the transcription were based on the socio-technical elements of CED presented in the latest version of the model (i.e. STAM-5).

8.1.2 Evaluation findings

From applying *coding* to the interview transcription, 30 codes (i.e. socio-technical elements) were identified and outlined in Table 58. As can be seen from the table, no additional socio-technical elements on top of those already in STAM-5 can be identified from the interview transcription. Furthermore, Table 58 shows that the eight socio-technical themes of the CED process, presented in the first level of STAM-5, were all identified from the interview, albeit to a varying extent.

Table 58 Codes identified from the interview transcription

Theme	Codes	Presence in STAM-5
Human being	Internal stakeholders	√
	Customers and users	√
	Suppliers	√
	(Stakeholders) Assigned role	√
	(Stakeholders) Competency	√
	(Stakeholders) Conative	√
	(Stakeholders) Experience	√
	(Stakeholders) Knowledge	√
	(Stakeholders) Responsibility	√
	(Stakeholders) Skill	√
	(Stakeholders) Socio-demography	√
Communication	Communication	√
Conflict	Technical conflict	√
Organisation	History	√
	Legislation	√

	Location	√
	Organisation	√
	Policy	√
Design process	Design process	√
	Concept design process	√
	Detailed design process	√
	Post-design process	√
	(Design process) stage	√
Technical system	Technical systems	√
Design information	Design information	√
	Design requirements and constraints	√
	Model	√
	(Model) type	√
Tools	Information tools	√
	Technical tools	√

From *condensing* the interview transcription, 16 relationships between the elements of CED were identified, as listed in Table 59. As can be seen in the table, three additional relationships can be identified. However, these relationships connect what is recognised as *attributes* in this thesis (See Appendix 8: Information modelling language review). Presenting the relationships between attributes was not within the scope of the model (see Chapter 5). Thus, although their presence was acknowledged, these additional relationships were not considered in relation to the model evaluation.

Table 59 Relationships identified from meaning condensation

Condensation result	Presence in STAM-5
Cognitive determines assigned role	x
Communication tools facilitate communication	√
Customers and users provide design requirement and constraints	√
Design information underpins technical system	√
Experience influences cognitive	x
Experience influences skill	x
History influences organisation	√
Information system stores model	√
Internal stakeholders manage design process	√
Legislation bounds technical system	√
Location bounds communication	√
Model represents design information	√
Organisation applies legislation	√
Organisation creates policy	√
Suppliers supply design specification	√
Technical conflict influences technical systems	√

8.1.3 Lessons learned

Above, the evaluation approach and findings derived from the model evaluation in Company 2 were reported. Although the results can be used to identify the degree of the model's appropriateness in representing the CED process at Company 2, three points can be taken as lessons learned, particularly in relation with the evaluation approach. They were considered to be:

1. The model was evaluated without specific evaluation criteria. Consequently, assessing the degree of the model's appropriateness in representing the CED process from the socio-technical perspective was not possible. Learning from this, the criteria to assess a model was reviewed for its application in the next model evaluation.
2. An interview method was selected for practicality reasons. However, it was learned that this method did not allow the model to be evaluated thoroughly as an interview requires time to build trust between the interviewer and interviewee. Furthermore, an interview opens the possibility of irrelevant conversations. As such, during the one hour allotted time, the information derived was considered limited to form the basis for model evaluation. In light of this, applying a different method (s) for the next model evaluation was considered.
3. As the interview was conducted with only one person, it did not provide the basis for a triangulated view of the model, and thus, there was a potential of bias. Secondly, due to IP-3's position in the Company (i.e. head of technology), their view towards the CED process tended to be general. Lastly, as the interviewee comes from an engineering background, their perspective towards the CED process tended to be technical. Having learned from these aforementioned points, for a multi-perspective view, involving more than one participant, a mixture of profiles (i.e. role domain, position) was required for further model evaluations.

8.2 Main evaluation

As Company 2 have similar company profile with Company 1, two companies practicing CED with a different life phase or product focus were selected for the main model evaluation. However, these companies have one commonality, i.e. they can be categorised as E*ngineering to Order* (ETO) companies. This commonality was chosen deliberately for two reasons. Firstly, it was chosen because the model was developed based on the practice of a CED process in an ETO company (Chapter 5). Secondly, Dasgupta (1991) argued that to make an explanation of a design process (i.e. the model) useful, it needs to address a specific problem. In turn, the explanation "must attend… the practical quest for domain-specificity" (Dasgupta 1991, p.xiv). Thus, for the model to be useful, it was limited to the socio-technical elements of the CED process identified on the practice in ETO companies. Each company involves in the main evaluation (i.e. Company 3 and Company 4) and their distinct life phase and product focus that underpinned their selection are explained below.

Company 3

Similar with company 1 and 2, Company 3 is part of the shipbuilding and ship repairing industry. The distinct characteristic that differentiates Company 3 with Company 1, 2, and 4 is its product phase focus. While the other companies specialise in the design and manufacture of technical systems, Company 3 specialises in the maintenance of technical systems. Within the maintenance life phase of a ship, there is a process regarded as *refitting* (Peri, 2016). *Refitting* involves redesigning and/or remanufacturing a particular part(s) of the ship to adapt with the current requirements (e.g. environments and legislations) and/or prolong the ship's life (Jeremy, 1972). Due to the complexity of the technical systems, this redesigning and remanufacturing process is done collaboratively. Based on this distinct product phase speciality, Company 3's practice of the CED process was selected as the second basis for model evaluation.

Company 4

Different from Company 1, 2, and 3, Company 4 is a part of the optoelectronics industry. Generally speaking, optoelectronics may be defined as "the branch of technology concerned with the combined use of electronics and light"(The Oxford English Dictionary, 2017). The technical systems that Company 4 designs and manufactures, for example, are infra-red cameras and submarine periscopes. As the technical systems being designed are different from Companies 1, 2, and 3, the CED process in Company 4 was used as the third basis for model evaluation.

In Table 60, the two companies involved in the main evaluation are summarised based on their aforementioned characteristics. For comparison, Company 1 and Company 2 are included in the table.

Table 60 Companies involved in the model development and evaluation

		Industry		
		Engineering-To-Order		
		Shipbuilding		**Optoelectronics**
Product life phase	**Design and manufacture**	Company 1 (UK)	Company 2 (Indonesia)	Company 4 (UK)
	Maintenance	Company 3 (UK)		

The model evaluation in Company 3 and Company 4 is presented in this section. Based on the lessons learned from the evaluation approach in Company 2 (Section 8.1.3), the evaluation approach in these two companies was refined, as explained in Section 8.2.1. How this approach was applied is explained in Section 8.2.2. The findings derived from it are presented in Section 8.2.3.

8.2.1 Evaluation approach

The refinements on the evaluation approach were made with respect to evaluation criteria, method, and participants. Similar to the model review and refinement process in Company 1, the check and evaluation process in Company 3 and Company 4 was done through a workshop. To check if the workshop was structured appropriately, and therefore, if the aim of the model evaluation could be achieved, a pilot study was conducted, presented in Section 8.2.2.1. Feedback derived from the pilot study was used as the basis to refine the structure of the workshop. The refined structure of the workshop is provided in Section 8.2.2.2.

8.2.1.1 Evaluation criteria

As mentioned in Section 8.1.3, the evaluation in Company 2 was done without defining any criteria to measure against the model. Consequently, it was not possible to assess the model's appropriateness properly. Furthermore, from the design research perspective, evaluation involves assessing research results against predefined criteria (Duffy and O'Donnell, 1999). It became apparent that to evaluate the model properly, evaluation criteria must be defined.

The model developed and presented in this thesis may be categorised as an information model (Appendix 8). It can also be categorised as a conceptual model based on the general definition given by Krogstie (2012), which states, "[a conceptual model is] a description of the phenomena in a domain at some level of abstraction, which is expressed in a semi-formal or formal visual (diagrammatical) language" (Krogstie 2012, p.1). A number of frameworks to assess the quality (e.g. appropriateness) of a conceptual model can be identified from the literature. For example, the SEQUAL framework developed by Krogstie (2013); the syntax-sematics-pragmatics framework developed by Lindland et al. (1994); the conceptual modelling quality framework developed by Nelson et al. (2012); and a composite framework devloped by Shanks & Darke (1997). However, it was identified that only the framework developed by Lindland et al. (1994) was used to evaluate the appropriateness of information models (see Moody et al. 2003). Thus, the Lindland et al's framework was deemed appropriate to form the basis for defining evaluation criteria in this thesis.

Lindland et al. (1994) defined evaluation criteria with respect to three aspects of modelling, i.e. language, domain, and audience interpretation. The criteria of each aspect, how they were used as the basis to define the evaluation criteria of the model presented in this thesis, and how they can be measured are explained below.

Language

With respect to the language aspect, the evaluation focusses on assessing the degree of the model adherence to the language rules. The criteria was "the more closely the model adheres to the language rules, the higher the syntactic [language] quality" (Lindland et al. 1994, p.44). However, adhering to language rules was not the aim of the model development presented in this thesis. Instead, it aimed to facilitate a better understanding of the CED process, and thus, how the process can be improved. To achieve the aim, the model needs to be understood by its potential users. Hence, the language used in the model was adapted to enhance its clarity (Appendix 11.1: Concept of the model). For this reason, assessing the degree of adherence to language rules was excluded from the model evaluation, and thus, the evaluation criterion pertinent to the language aspect was not applied.

Domain

Concerning the domain aspect, the evaluation focusses on assessing the degree of representativeness of the domain, with the term "domain" being "the part of the world to be modelled" (Moody et al. 2003, p.2). In other words, the evaluation seeks to assess how well the model corresponds to the part of the world being modelled. To measure this, the model needs to be checked if "all the statements about the reality being modelled [i.e. domain] are correct and relevant" (Lindland, Sindre and Sølvberg, 1994). From this perspective, three evaluation criteria can be derived: 1) *completeness,* i.e. the model contains all the statements about the domain, 2) *correctness*, i.e. the model contains the correct statements about the domain, and 3) *relevance*, i.e. the model presents the relevant statements about the domain.

Generally speaking, a statement may be defined as “a definite or clear expression of something” (The Oxford English Dictionary, 2017). From this perspective, in the context of model design, statements can be perceived as any piece of descriptive information about the domain, which can be used to build the model. In the model presented in this thesis, these statements were derived, for example, from the literature and during conversations with the participants (e.g. IP-1 and social science academics). The elements of the STAM of CED process (i.e. entities, sub-entities, attributes, and relationships) were elicited from these statements. Based on this, with respect to the aforementioned evaluation criteria, the following conclusions can be drawn and defined as the criteria of the model evaluation in this thesis.

Firstly, the *completeness* of the model can be related to how comprehensively the elements of the model (i.e. entities, sub-entities, attributes, and relationships) cover the socio-technical CED process (hereafter E1). From this perspective, the model is therefore complete if all the elements of the socio-technical CED process are presented in the model (if no elements are deemed missing). Based on this, the model’s completeness can be measured from the number of element additions suggested.

Secondly, the *correctness* of the elements of the model can be related to how accurately said elements can be perceived (by model users) as the socio-technical elements of the CED process (hereafter E2). In this regard, the elements of the model are correct if they are perceived as the socio-technical elements of the CED process. Given this, the model’s correctness can be measured from two parameters: 1) the number of potential users (e.g. CED participants) who perceive the model consists of the socio-technical elements of the CED process (E2-1), and 2) the number of element refinements suggested (E2-2). The second parameter is as an indication that the participants agreed that the elements are correct However, they may be inappropriately labelled or categorised.

Thirdly, the *relevance* of the elements of the model can be related to how significant they are to the CED process (hereafter E3). In this sense, the elements of the model are relevant if they all need to be presented in the model. In other words, the elements are relevant if none of them need to be deleted from the model. Measuring the model’s relevance can therefore be done via the number of element deletions suggested.

In addition to the above, Landry et al. (1983) argued that a model needs to be scientific as well as to be useful. They (1983, p.208) added that representativeness "…is meaningless unless it is lined to …usefulness." While being scientific can be indicated by the correspondence between the model and the domain (its completeness, correctness, and relevance), being useful can be indicated by the correspondence between the model and its utility in the domain. In other words, *usefulness* relates to how well the model can be put into use. *Usefulness* was defined as the fourth evaluation criteria of the model evaluation (hereafter E4). However, as aforementioned, the model presented in this thesis can be considered as conceptual. A conceptual model requires further development before it can be put into use (Robinson, 2013). Consequently, the utility of the model cannot be assessed. Thus, instead of relating *usefulness* with the model's utility, in the context of the model presented in this thesis, *usefulness* was related to how the potential users perceived the usefulness of the model with regard to the practice of CED. In other words, the model is considered useful if the potential users perceive that they can use it in their practice of CED. From this perspective, the model's usefulness can therefore be measured from the number of potential users who believed that the model can be used in their practice of CED.

Audience

According to Lindland et al. (1994), a model is of little use unless it is understood by its audience. The term "audience" used here refers to those who have interest in the model. In the model presented in this thesis, the audience can be the participants of the CED process. Accordingly, the evaluation seeks to assess how well the model can be easily understood by its audience. In other words, it seeks to assess its degree of *ease of understanding* (hereafter E5) from the audience perspective. Thus, the model's ease of understanding can be measured from the number of audience members who perceived the model was easy to understand.

In addition to the evaluation criteria discussed above, as the model was developed for a specific purpose, i.e. to facilitate a better understanding of the CED process from the socio-technical perspective, the extent to which the model can be considered to *achieve this purpose* (hereafter E6) needs to be assessed. In other words, a measure of how well the model facilitates a better understanding of the CED process for its audience needs to be made (hereafter E6). This is seen from the number of audience members who view that: 1) the model effectively explains the CED process from the socio-technical perspective, 2) the model provides insight into the CED process from the socio-technical perspective, and 3) their understanding towards the CED process increases after using the model.

8.2.1.2 Method

As discussed in Section 8.1.3, an interview was deemed not fully effective to evaluate the model thoroughly. Having learned from, a focus group and a questionnaire method were applied to evaluate the model in Company 3. These methods are conducted during a workshop, where "a group of people engage in intensive discussion and activity" (The Oxford English Dictionary, 2017). The applications of the methods are further explained below.

Focus group

A focus group was employed to assess, firstly, the model's completeness, by identifying the number of element additions suggested (E1), secondly, the model's correctness, by identifying the number of element refinements suggested (E2-2), and thirdly, the model's relevance (E3), in accordance to the practice of CED process in the company (Company 3). To achieve this aim, the focus group session was divided into two phases. The first phase was regarded as a review phase. In this phase, the participants were asked to review the model and check for any missing, unrecognisable, and/or inappropriate elements. The second phase was regarded as a discussion phase. Within this phase, the participants were asked to present their feedback, allowing other participants to clarify, to challenge, and/or to discuss the feedback. The two phases of the focus group were conducted as the first activity of the workshop. The complete structure of the workshop can be seen in Section 8.2.2.2.

Questionnaire

After the two phases, a questionnaire method was used to elicit the opinion of the participants with respect to the model's correctness (E2-1), usefulness (E4), ease of understanding (E5), and achievement of purpose (E6). For this, seven statements that correspond to a specific evaluation criterion were given in the questionnaire form. The statements and their corresponding evaluation criteria are outlined in Table 61 and explained subsequently.

The participants were asked to rate their agreement towards the statements along a *Likert Scale*, ranging from *strongly disagree*, through a *neutral* option for no opinion, to *strongly agree*. The questionnaire used *self-completion*, where the respondents read and answered the questionnaire by themselves (Bryman and Bell, 2003). Questionnaire completion was the second activity conducted in the workshop.

Table 61 List of statements given in the questionnaire and their corresponding criteria

Evaluation criteria	Statement
E2-1	The model covers the socio-technical elements of the general collaborative engineering design process.
	The model covers the socio-technical elements of Company 3's collaborative engineering design process.
E4	The model would be useful for Company 3's collaborative engineering design process.
E5	The model was easy to understand.
E6	The model effectively explains the collaborative engineering design process from the socio-technical perspectives.
	The model provided insights into the collaborative engineering design process.
	My understanding towards engineering design process increased after reviewing the model.

Correctness (E2-1)

As mentioned in Section 8.2.1.1, the degree of the model's c*orrectness* can be measured based on two parameters: 1) the number of CED participants who perceive the model consists of the socio-technical elements of the CED process, and 2) the number of elements that were suggested for refinement. The questionnaire was used to measure the model's correctness based on the first parameter. For this, two statements were given. The first statement checked if the model consisted of the general socio-technical CED process (i.e. "the model covers the socio-technical elements of the general CED process"). The second statement was given to check if the model consisted of the company's CED process, i.e. the model covered the socio-technical elements of the company's CED process.

Usefulness (E4)

The model's *usefulness* can be measured from the number of CED participants who believe that the model can be used in their practice of CED (Section 8.2.1.1). To elicit the participant's views towards the model's usefulness, one statement was provided, i.e. "the model would be useful for Company [3]'s collaborative engineering design process."

Ease of understanding (E5)

The model's *ease of understanding* can be measured from the number of audience members who perceive that the model was easy to understand. Similar with E4, only one statement was given in the questionnaire, i.e. "the model was easy to understand."

Achievement of purpose (E6)

The model's achievement of purpose can be measured from the number of audience members (i.e. CED participants) who believe that the model effectively explains the CED process and provides insight into the CED process from the socio-technical perspective. It could also be measured from how their understanding towards the CED process changed after using the model. To elicit the participant's view, three statements were provided in the questionnaire with respect to the aforementioned criteria. Firstly, "the model effectively explains the collaborative engineering design process from the socio-technical perspective." Secondly, "the model provided insights into the collaborative engineering design process." Lastly, "My understanding towards the engineering design process increased after reviewing the model."

8.2.1.3 Participants profile

As discussed in Chapter 2, involving multiple participants with a mixture of profiles was considered important for multi-perspective purposes, to avoid bias. For this reason, an expected mixture of participant profiles was proposed to Company 3 and Company 4. The participants were requested to consist of CED participants having different positions in the company (i.e. from non-managerial staff to director), coming from both technical (e.g. engineering) and non-technical (e.g. human resource) role domains.

8.2.2 Evaluation process

Based on the evaluation approach explained above, model evaluation in Company 3and Company 4 was conducted. As aforementioned, the model evaluation process was conducted as a workshop. To ensure that the workshop was appropriately structured, a pilot study was conducted, presented in Section 8.2.2.1. Feedback derived from the participants of the pilot was used as the basis to refine the structure of the workshop. The refined structure of the workshop is provided in Section 8.2.2.2.

8.2.2.1 Pilot study

A pilot study was conducted in DMEM, at the University of Strathclyde to review the structure of the workshop. Six researchers specialising in different research fields were involved to provide multi-perspective reasons. Three participants specialised in the design field, one in the management field, and two in the engineering field. The pilot study was aimed at checking the appropriateness of the introductory presentation, emphasising the model explanation, as this was identified as an area for improvement in W1 and W2 (Chapter 6). Additionally, the pilot study was also aimed at checking the appropriateness of the questionnaire form in the sense of how well it could be understood by the participants and how appropriate it was for the intended purpose. That is, to obtain the view of the participants regarding the model's correctness (E2-1), usefulness (E4), ease for understanding (E5), and achievement of purpose (E6).

The feedback points that were applied to refine the structure of the workshop are outlined below:

Introductory presentation

As the workshop participants might not be familiar with the EER diagram, the pilot study participants suggested distributing a printed legend (i.e. wording explaining the graphical notations used in the model), with an example for each notation, prior to the introductory presentation. This was applied in the workshop as an effort to help the participants understand the model in a relatively short period of time.

Questionnaire form

In the questionnaire, seven statements were given with respect to the aforementioned evaluation criteria (Section 8.2.1.1). The pilot study participants suggested adding a comment box for every question to allow the participants to elaborate their response. They also suggested adding a comment box at the end of the questionnaire allowing the participants to provide general comments on the model. Considering that unlike an interview, a questionnaire does not provide an opportunity to probe the participants' response (Bryman and Bell, 2003), giving the participants an opportunity to elaborate their answer was deemed necessary. For this reason, the questionnaire was refined as suggested.

8.2.2.2 Workshops

The workshops consisted of two main activities: 1) model review, and 2) questionnaire completion. In each activity, the model was assessed with respect to particular evaluation criteria (Section 8.2.1.1), using a specific method, in an allocated time. The structure of the workshop with respect to its activity, the time duration, the method used, and the criteria underpinning the model evaluation in each activity is depicted by Figure 86.

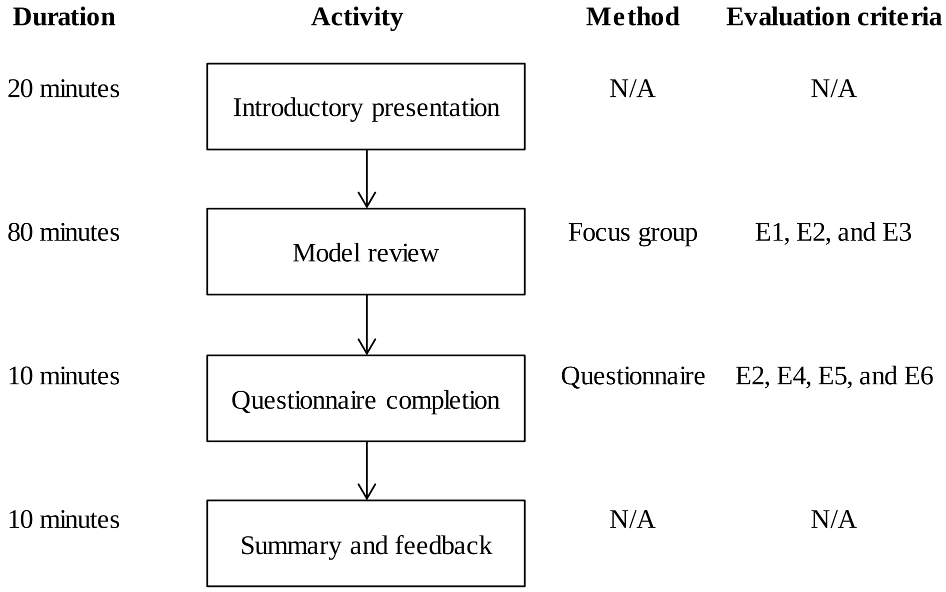


Figure 86 Structure of workshop

The workshop started with a twenty-minute introductory presentation to introduce the research, the model, the purpose of the workshop, and the organisation of the workshop. The participants were then divided into groups for the first activity, i.e. model review.

An A1 printed model was distributed to each group. For the purpose of simplification (see Section 6.1), the model was divided into five zones, where each consists of a theme(s). Each group was assigned to a different zone so that the views of one group were not affected by the views of the other groups. The participants were asked to check for any missing, unrecognisable, and inappropriate elements of the model. Ten minutes were allotted for each zone. Upon the end of each 10-minute block, the groups were requested to move onto the subsequent zone. After all the zones were reviewed (50 minutes in total), each group was asked to present the result of their model review. The total time allocated for the first activity was eighty minutes.

Questionnaire completion was the second activity of the workshop. Ten minutes were allocated for this activity. As aforementioned, in the questionnaire, seven statements were given based on the aforementioned evaluation criteria (Section 8.2.1.1). The participants were asked to rate their agreement towards the statements. A comment box was provided for every statement, allowing the participants to elaborate their response. The list of statements and their related criteria are listed in Table 61. An example of a questionnaire form, already filled in by a participant can be seen in Appendix 17: Questionnaire form. The details in roles and personal information of the participant has been retracted for anonymity purpose.

The workshop concluded with a ten-minute summary of work.

8.2.2.2.1 Participants profile

The workshop in Company 3 was attended by 14 participants (the participant group from Company 3 is regarded as IP-4 in this thesis). To maintain their anonymity, each participant is assigned with a code of identification. Their profiles are listed in Table 62 with respect to the role domain, position in the company, and their experience working in the company.

Table 62 Profile of IP-4

Code	Role domain	Position	Years of experience
W3-1	Engineering	Director	32
W3-2	Commerce	Manager	11
W3-3	Human resource	Non-managerial staff	7
W3-4	Human resource	Non-managerial staff	13
W3-5	Engineering	Manager	20
W3-6	Engineering	Manager	6
W3-7	Engineering	Non-managerial staff	6
W3-8	Engineering	Manager	15
W3-9	Project management	Manager	4
W3-10	Finance	Manager	0.2
W3-11	Engineering	Manager	24
W3-12	Engineering	Manager	25
W3-13	Finance	Director	1.5
W3-14	Engineering	Non-managerial staff	8.5

As can be seen above, eight participants came from an engineering background, two from finance, two from human resource, one from commerce, and one from project management. Each role domain can be related with a specific responsibility. The list of responsibilities for each role can be seen in Appendix 3. However, two new roles emerged from the workshop in Company 3: 1) commerce, i.e. relating to the management of the company's business aspects (e.g. sales, contract management), and 2) finance, i.e. relating to the management of the company's financial aspects (e.g. cash flow). Two participants were identified as directors, eight as managers, and four as non-managerial staff. Collectively, IP-4 held approximately 173 years of experience, with an average of 12 years each.

The workshop in Company 4 was attended by 14 participants (the participant group from Company 4 is regarded as IP-5 in this thesis), with a cross-section of roles, positions, and years of experience represented, as listed in Table 63. One participant (W4-14) did not fill in their years of experience in the company, and thus, it was written as “unknown” in the following table.

Table 63 Profile of IP-5

Code	Role domain	Position	Years of experience
W4-1	Engineering	Manager	30
W4-2	Engineering	Non-managerial staff	8
W4-3	Engineering	Non-managerial staff	1
W4-4	Engineering	Non-managerial staff	7
W4-5	Engineering	Manager	30
W4-6	Engineering	Manager	6
W4-7	Engineering	Non-managerial staff	37
W4-8	Engineering	Director	32
W4-9	Engineering	Director	24
W4-10	Engineering	Manager	40
W4-11	Commerce	Manager	7.5
W4-12	Engineering	Manager	8
W4-13	Engineering	Manager	35
W4-14	HR	Manager	Unknown

As can be seen in Table 63, 12 participants came from the engineering domain, one from commerce, and one from human resource. Two participants were identified as directors, eight as managers, and four as non-managerial staff. Collectively, IP-5 held approximately 265.5 years of experience, with an average of 20 years each.

8.2.3 Evaluation findings

Findings from the workshop conducted in Company 3 and Company 4 are presented in Section 8.2.3.1 and Section 8.2.3.2, respectively.

8.2.3.1 Company 3

The findings from the workshops are grouped based on the workshop’s activities. Findings derived from the model review are provided in Section 8.2.3.1.1 and those obtained from the questionnaire are presented in Section 8.2.3.1.2.

8.2.3.1.1 Model review

From the model review in Company 3, 108 suggestions for change were derived encompassing all the elements of the model (i.e. entity, sub-entity, attribute, and relationship). These suggestions can be categorised as *addition, deletion, category refinement, term refinement,* and *expansion.* The definitions of these categories can be seen in Section 6.3. As discussed in Section 8.2.1.1, with respect to the evaluation criteria, the number of *additions* suggested can be used as the basis to measure the model's completeness, the number of *deletions* can measure the model's relevance and the number of *refinements* (i.e. *category* and *term*) can measure the model's correctness. Additionally, as *expansion* refers to "the category of feedback for any element that was considered inadequately represented", any *expansion* suggestions can be used to measure the model's completeness.

The number of suggestions for each element is summarised in Table 64 and explained subsequently. The detailed list of suggestions can be seen in Appendix 18: Evaluation findings from Company 3.

Table 64 Number of suggestion for each element derived from the model review activity in Company 3

	Entity	Sub-entity	Attribute	Relationship	Total	%
Addition	4	22	27	35	**88**	**81.5%**
Deletion	0	6	0	5	**11**	**10%**
Category refinement	0	1	1	0	**2**	**2%**
Term refinement	0	0	0	1	**1**	**1%**
Expansion	1	0	1	4	**6**	**5.5%**

Addition

As can be seen in the above table, *addition* has the largest number of suggestions compared to the other categories. In a general sense, the element *additions* can be grouped into four categories based on their purpose. These purposes were implied by IP-4 during the discussion. The first purpose was to include the characteristics of the company that IP-4 perceived to influence the CED process. For example, a group of participants mentioned that their company is characterised by having a high hazard level, and therefore, assuring the level of safety, particularly in their design activity, is important. For this reason, IP-4 argued that hazard influences their design process, and accordingly, they suggested adding "hazard" as an attribute of the "design process" in the model.

The second purpose was to include the specific issues relating to the company, allowing the CED participants in Company 3 to recognise the issues. As an example, a group of participants recommended adding three sub-classes of risk, i.e. "technical", "commercial", and "resource issue" to allow the CED participants to recognise the current lack of technical risk management.

The third purpose was to connect different entities that IP-4 believed influence each other. For example, a group of participants suggested adding "drives" to connect "design information" and "design process", while for the "conflict" theme, a group of participants suggested adding "influences" to connect "conflict" and "technical system".

The fourth and final purpose related with a particular case in the "human being" theme – several *additions* were suggested to differentiate between "stakeholders" and "employees". A participant stated that, "some of the points you [i.e. relationships between entities] make [in the model] are very valid but they only apply to employees while not to the other stakeholders". As such, they suggested, for example adding "employee" as an entity, separate to stakeholders, leading to a relationship addition (i.e. "acquire") between "employees" and "culture".

Deletion

The deletions consist of the elements that IP-4 viewed unnecessary as they do not reflect the practice in Company 3. For example, IP-4 argued that the suppliers and customers in Company 3 can come from the same company (internal) as well as from a different company (external). As a participant mentioned, "Design occurs within the external and internal organisation. We use other people's information (suppliers) in our design, which then feeds to other people's product (customers)". From this perspective, the term "suppliers" and "customers" were discussed within the context of the providers and users of (design) information. In light of this, IP-4 argued that the differentiation between "internal stakeholders" and "external stakeholders" in the "human being" theme was not needed, and therefore, they suggested deleting the "internal stakeholders" and "external stakeholder"; sub-entities of "stakeholders".

In addition to the above suggestions, IP-4 also suggested deleting sub-entities that have no relationship with the other elements in the model. For example, two sub-entities of "communication tools", i.e. "synchronous" and "asynchronous" have no relationship with the other elements of the model, and thus, they were suggested to be deleted.

Category refinement

Two suggestions can be considered as *category refinement*, one concerning a member of the "communication" theme and one a member of the "design process" theme. In the "communication" theme, the refinement was identified in the relationship between entity and its sub-classes. IP-4 conveyed that informal and formal communication can occur at the same time. "Informal" and "formal" communications are sub-classes of "communication". Accordingly, IP-4 suggested refining the relationship between "communication" and its sub-classes from "disjointed" to "overlap".

In the "design process" theme, the refinement was identified as an attribute of "design process", i.e. "requirement", as, according to IP-4, it determines the overall design process and thus should be presented as an entity instead of an attribute.

Term refinement

One suggestion derived from the workshop can be categorised as *term refinement*, i.e. refining the term "underpins" that connects "history" and "opinion" into "influences". IP-4 believed that the influence of history to Company 3 is not limited to underpinning the opinion of stakeholders only. Based on this, IP-4 argued that the term used to represent the relationship between history and opinion (i.e. "underpins") is too specific, and suggested refining it into a more generic term (i.e. influences).

Expansion

Six suggestions of change can be categorised as *expansion*. Most of the element expansions within the aforementioned themes were identified based on a similar argument that the elements can be considered as key influencing factors of the CED process. However, IP-4 felt that the connection of these elements to the other elements in the model was fairly limited. For example, IP-4 argued that the opinion of the stakeholders influences almost everything during the CED process. In the model, "opinion" was shown as owned by "stakeholders" and influenced by "history", with no relationship showing its influence to the other elements of the model. For this reason, IP-4 suggested to expand the relationship between "opinion" and the other elements of the model.

8.2.3.1.2 Questionnaire completion

As shown in Table 61, each statement provided in the questionnaire corresponds to a specific evaluation criterion. The findings from the questionnaire are reported based on their corresponding criteria. This breakdown is presented in this section. The detailed findings are summarised in Table 87 and can be found in Appendix 18: Evaluation findings from Company 3.

Correctness (E2-1)

As mentioned in Section 8.2.1.1, two statements were given to assess the correctness of the model. With respect to the first statement, 93% of the participants agreed that the model covers the socio-technical elements of the CED process in general, while 7% selected for neutral (i.e. no opinion) as they felt unqualified to judge the model from a general perspective.

Regarding the second statement, (i.e. "the model covers the socio-technical elements of the company's CED process"), 7% disagreed, 43 % opted for neutral, and 50 % of the participants agreed. Albeit these different responses, the participants similarly commented that the model generally represents the company's CED process from the socio-technical perspective. However, they believe that the model can be improved, for example, by adding specific elements relating to the company's general policy such as "safety in high hazard environment" if the company intends to use the model (as mentioned by W3-1).

Usefulness (E4)

A total of 79% of the participants inclined towards agreeing with the statement regarding the usefulness to the participants (i.e. 50 % agreed and 29% strongly agreed). Several participants elaborated on how the model can be applied. For example, W3-2 believed that the model can help to diagnose the root cause of the problems occurring in the CED process. Additionally, W3-4, (from a human resource background) believed that the model helps technical people understand the significance of the social elements (i.e. human beings) to the design process. They stated, "recognition of the human influence I see as a fundamental point that can be often missed by very technical leaders/people". Although 21% opted for neutral towards the aforementioned statement, they similarly implied that the model has potential to be useful with some adaptations. For example, W3-13 wrote, "With further development of the model and the addition of supporting information/ process, I believe it could be useful".

Ease of understanding (E5)

For the statement on ease of understanding, 28.5% participants agreed that the model was easy to understand while 43% participants disagreed. These participants found that the model was complex at its first appearance and argued that the model introduction and learning time was insufficient. However, they mentioned that at the end of the model review activity, the model became more apparent and easier to understand. Similar comments were given by the 28.5% participants that have no opinion on the model's ease of understanding (i.e. opted for neutral). To increase understanding, W3-13 suggested a longer time allocation to explain the model. From a different perspective, to simplify the model, and thus making it easier to understand, W3-2 and W3-14 suggested to change the structure of the model from only one level into several levels.

Achievement of purpose (E6)

With respect to the first statement, i.e. "the model effectively explains the CED process from the socio-technical perspective", 50% agreed, although they acknowledged the model's complexity and the model's need for further improvement. As W3-9 stated, for example, "I feel that all (or most) of the entities and attributes are present, however the architecture [structure] of the model could be rearranged to help understand better". 36% of the participants were identified to be neutral. Lastly, 14% participants disagreed with the aforementioned statement. These participants remarked that the model does not explain a process. Instead, it explains the elements of the CED process and how these elements influence one another.

Unlike the split in opinion over the first statement, 86% of participants agreed and 14% strongly agreed with the second statement, i.e. "the model provided insights into the CED process". They implied that the model affected their way of thinking towards the CED process. W3-9, for example, remarked that the model "made me think about the social impact on technical solutions" while W4-7 stated that it is "interesting to see how culture and relationship [social] are so central to the way we operate".

Aligned with the response of the second statement; no participants disagreed with the third statement, i.e. "my understanding towards the CED increased after reviewing the model". Contrarily, 57.5% participants agreed while 14% strongly agreed. They believed that the model provided a new perspective towards the company's CED process, and thus, gave them a new understanding over the company's CED process. W3-1 for example, mentioned, "…the novel way of integrating [i.e. the socio-technical elements] into the design process is new to us!" Similarly, W3-2 stated, "after testing the respective zones of the model, I had a better understanding of its function and potential issue in the business environment." Although 28.5% participants opted for neutral, their comments indicated that their neutrality was not related to their understanding towards the CED process. Instead, it was due to their uncertainty on how the model could be implemented into the company's CED process. W3-7, for example wrote, "It is not clear how we would use the model to increase our understanding on how to implement a CED process", which was echoed by W3-11.

8.2.3.2 Company 4

In this section, findings derived from the workshop in Company 4 are presented with respect to the workshop activities. The model review is provided in Section 8.2.3.2.1, and the questionnaire in Section 8.2.3.2.2.

8.2.3.2.1 Model review

From the model review, 89 suggestions for change were derived, encompassing all elements of the model. Similar with the suggestions identified in Company 3, they can be categorised as *addition, deletion, category refinement, term refinement, and expansion*. The definitions of these categories can be seen in Section 6.3. The number of suggestions for each element is summarised in Table 65 and explained subsequently. The detailed list of suggestions can be seen in Appendix 19: Evaluation findings from Company 4.

Table 65 Number of suggestions for each element derived from the model review activity in Company 4

	Entity	Sub-entity	Attribute	Relationship	Total	%
Addition	3	3	30	33	**69**	**77%**
Deletion	0	0	1	3	**4**	**4.5%**
Category refinement	1	3	0	0	**4**	**4.5%**
Term refinement	2	0	1	4	**7**	**8%**
Expansion	0	0	1	4	**5**	**6%**

Addition

Similar to the suggestions derived from IP-4, *addition* dominates the suggestions derived from IP-5. As can be seen from the table above, 77% of total suggestions were *additions*.

The element additions were mainly identified in two elements of the model. The first area of identification for additions was the relationship between entities, to link the elements of a theme with the elements of other themes. The prominent argument from IP-5 was that many elements in the model have significant influence over the other elements. For example, in Company 4, the company's policy underpins all the decisions taken by their employees, including the decisions pertinent to the CED process such as the decision on the type of tools use during design. Policy also governs the behaviour of the stakeholders, and thus, influences the design process. Considering this, IP-5 suggested adding "influences" to connect "policy" and "tools", as well as "policy" and "stakeholders". The second area of identification for additions was the attributes of the entities used to explain the characteristics of an entity in accordance with Company 4's current practice. For example, a group of participants remarked that the history in Company 4 can be differentiated whether it is based on a real event, i.e. fact-based history, or whether it is based on an invented event, i.e. fake-based history. Based on this, they suggested adding, "fact" and "fake" as attributes of "history".

Further to the points above, a suggestion was identified as a common feeling given by IP-5. All groups of participants suggested adding the same element, i.e. "teams" as an entity in the "human being" theme. They argued that teams are crucial to the CED process in the sense that they are the foundation that determines the success and failure of a CED process. Thus, according to IP-5, "teams" should be presented in the model.

Deletion

Most element *deletions* were identified within the relationships of the model. IP-5 remarked that all the relationships presented in the model were valid. However, three relationships were perceived inappropriate as IP-5 did not recognise them within their CED process. For example, they argued that in Company 4, policy is not always triggered by conflict. Although possible, they mentioned that the number of policies triggered by conflict were relatively few compared to those triggered by other factors such as changes in legislation or changes in business strategy. On this basis, they suggested deleting "influences" that connects "conflict" and "policy". Another deletion was identified within one attribute of the model due to the fact said attribute was presented as an entity as well. IP-5 suggested that an element should be presented as one category only, which in this case should be an entity only, to avoid confusion. IP-5 went on to state that, all elements that have dual categories (i.e. entity and attribute) needed to be changed.

Category refinement

The suggestions that could be categorised as category refinements mainly entailed the refinement on the type of relationship between an entity and its subclass(s). As an example, IP-5 suggested refining the category of relationship between "culture" and its sub-classes from "disjoint" to "overlap". Their argument was that culture is a complex element, consisting of overlapping subsets as presented in the model (i.e. organisational, professional, and social) that influence each other.

Term refinement

With respect to the terms used in the model, IP-5 found that several terms used to represent entities were unfamiliar; in particular those used in the "design information" and "technical system" themes. For this reason, IP-5 suggested refining the terms used in the aforementioned themes. Additionally, IP-5 also argued that several terms used to represent relationships were inappropriate. For example, the term "acquire" used to represent the relationship between "stakeholders" and "culture".

Expansion

Similar to the expansion suggestions derived from the participants in Company 3, the participants from Company 4 mentioned that several elements could be considered key influencing factors on the CED process in the sense that they influence many elements of the CED process. Examples of such elements are the "opinion" of "stakeholders" and the "policy" of "organisation". For this reason, the participants suggested that further investigation needs to be done to expand the aforementioned elements.

8.2.3.2.2 Questionnaire completion

Findings from the questionnaire are reported based on their corresponding criteria (see Table 61) as can be seen below:

Correctness (E2-1)

100% of the participants agreed that the model covers the socio-technical elements of the CED process in general (i.e. the first statement – see Table 61). However, with respect to the company's CED process (i.e. the second statement), apart from the 61.5% who agreed, 8% of the participants disagreed that the model covers the socio-technical elements of the company's CED process. The participants highlighted the importance of "team" to Company 5's CED process. According to them, "how the team formed and perform is a key" (W4-1). This was not presented in the model.

30.5% of participants took a neutral stance. These participants indicated that the model included most of the socio-technical elements of Company 5's CED process. Nonetheless, they pointed out the following concerns: 1) several detailed elements were missing from the model as discussed in the model review (Section 8.2.3.2.1), and 2) the model used terminology different to that used in Company 4.

Usefulness (E4)

With respect to the model's usefulness, 46% of the participants agreed and 8% participant strongly agreed that the model would be useful for Company 5's CED process. One participant specified that the model can be used to diagnose the root cause of any problem occurring in the company's CED process (W4-11) and another showed the intention to use the model in the company once it was finalised (W4-9).

No participants disagreed that the model would be useful for the company, while 46% selected to be neutral. These participants believed that the model could potentially be useful to the company, however, they emphasised the need for further refinement.

Ease of understanding (E5)

23% of the participants agreed that the model was easy to understand, although they mentioned that understanding the model requires time due to its complexity. As W4-5 stated, "Once you get used to the format, it is good [easy to understand]". Similarly concerned over the high complexity of the model, 69% participants opted for neutral. They also highlighted the differences between the terminology used in the model and that used in Company 5's CED process. According to IP-5, although a glossary was available, the differences in terminology created confusion, and thus, made it difficult to understand the model. This terminology issue was also mentioned by the 8% who disagreed that the model was easy to understand.

Achievement of purpose (E6)

For the first statement, i.e. "the model effectively explains the collaborative engineering design process from the socio-technical perspective", 46% agreed. They indicated that the majority of the information presented was "correct" (as mentioned by W4-7), with "subtle differences based on organisational practice" (W4-11). The same percentage of participants (46%) opted for neutral. IP-5 argued that some links are missing as the model seems to only explain the key elements of the CED process (as stated by W4-1; W4-9; W4-8; W4-10). They also highlighted the high complexity of the model, which made the model rather ineffective (as mentioned by W4-4; W4-8). Disagreement was given by 8% because they believed that they are incapable of judging the model's completeness or validity.

Regarding the second statement, i.e. "the model provided insights into collaborative engineering design process", 77% of participants agreed. They remarked that the presentation of social elements and their inter-relationships with the technical elements had changed the way they view the CED process. For example, W4-4 mentioned, "the model made me think more about collaborative engineering more in relation to how the company works, particularly the social elements which often get overlooked". Furthermore, they believed that the model provided a "holistic" view of the process, allowing them to see the bigger picture, and thus, gave them a deeper understanding of the company workings (as mentioned by W4-5; W4-8; W4-9; W4-11). However, 15% of participants disagreed that the model provided insight into the CED process. 50% of these participants argued that the model only presented constituent parts, instead of elements of the CED process. The remaining 50% highlighted the absence of "team" that made the model less insightful. Additionally, 8% of the participants took a neutral stance without providing further comment.

For the third statement, i.e. "my understanding towards the collaborative engineering design process increased after reviewing the model", 46% of the participants agreed. These participants credited the model for changing the way they perceive the CED process (e.g. W4-3; W4-4; W4-5; W4-6). 46% participants opted for neutral. These participants emphasised that they had an understanding of the socio-technical CED process before reviewing the model. W4-11, for example, mentioned "I would say that I understand the process", and thus, they argued that the model did not or only slightly increased their understanding towards the CED process. Finally, 8% of participants disagreed with the aforementioned statement. However, they believed that once the model was refined, it would help to understand the process more (W4-10).

8.3 Summary

As part of the evaluation, the model was assessed in the companies were the CED process is practiced. This chapter has reported how the model was evaluated and findings derived from the industrial evaluations.

A preliminary model evaluation was conducted in Company 2. The company is an Indonesian ETO company, specialising in the design and manufacture of complex technical systems within the shipbuilding industry. For practicality reasons, an interview was conducted with the company's Head of Technology (Section 8.1.1). The aim of the interview was to check the completeness of the model, i.e. if there were any socio-technical elements of the company's CED process that had not been represented by the elements of the model. From the interview, thirty socio-technical elements were derived through *meaning coding* (Section 8.1.2). These identified elements were represented in the model. Additionally, sixteen relationships between the socio-technical elements were derived through *meaning condensation*. Three new relationships were identified. However, these relationships connect what are regarded as *attributes* in the model, which is beyond the scope of the model, and therefore not included in the model.

The main model evaluation was conducted in Company 3 and Company 4. Company 3 is a UK ETO company, specialising in the maintenance of complex technical systems within the shipbuilding and ship repairing industry. Company 4 is a UK ETO company, specialising in the design and manufacture of complex technical systems within the optoelectronics industry. Having learned from the evaluation approach conducted in Company 2 (Section 8.2.1), the approach applied to evaluate the model in Company 3 and Company 4 was changed. The changes included the following: firstly, six evaluation criteria were defined:

completeness (E1), correctness (E2), relevance (E3), usefulness (E4), ease of understanding (E5), and achievement of purpose (E6) (Section 8.2.1.1). Secondly, instead of an interview, the model was evaluated using a focus group and questionnaire, conducted as a two-activity based workshop (Section 8.2.1.2). The workshop was done with 14 participants in Company 3 and 14 participants in Company 4 from a cross section of roles and disciplines (Section 8.2.1.3), following a pilot study with six researchers from DMEM, the University of Strathclyde (Section 8.2.2.1). The workshop was divided into two main activities: model review and questionnaire completion (Section 8.2.2.2). During the model review, the participants were asked to check the model for any missing, unrecognisable, and inappropriate elements. This was done to assess E1, E2-2, and E3.

From the workshop in Company 3, 108 suggestions of changes were derived. 81.5% of the suggestions were categorised as addition, 10% as deletion, 2% as category refinement, 1% as term refinement, and 5.5% as expansion (Section 8.2.3.1.1). For the questionnaire, the participants were asked to rate the five statements given with respect to E2-1, E4, E5, and E6. From the questionnaire, 9% disagreed, 23.5% opted for neutral, 59.5% agreed, and 8% strongly agreed with the seven statements given in the questionnaire form (Section 8.2.3.1.2).

From the workshop in Company 4, 89 suggestions for change were derived, consisting of 77% addition, 4.5% deletion, 4.5% category refinement, 8% term refinement, and 6% expansion (Section 8.2.3.2.1). From the questionnaire, 7% of participants disagreed, 35% opted for neutral, 57% agreed, and 1% strongly agreed with the overall seven statements given in the questionnaire form (Section 8.2.3.2.2).

In general, findings from the evaluation support the model’s correctness, relevance, usefulness and achievement for understanding. However, the findings suggest that the model may not be completed and easy to understand due to its structural complexity and terminology differences. The detailed discussion on the findings derived from the model evaluation is reported in Chapter 9.

Part 5. Reflection

9. Discussion

The study presented in this thesis aims to develop a socio-technical architectural model of the collaborative engineering design process from a holistic perspective. To achieve this aim, the model was developed through two phases: 1) development (Chapter 5), 2) review and refinement (Chapter 6 and 7). The developed model was then evaluated for its completeness, correctness, relevance, usefulness, ease of understanding, and achievement for purpose (Chapter 8). This chapter aims to discuss the overall study, specifically, on the main findings from the evaluation (Section 9.1), the methods adopted (Section 9.2), and the overall methodology applied (Section 9.3), reflecting upon the advantages and disadvantages of each. Based on the advantages and disadvantages discussed, areas for future work are highlighted and elaborated in Section 9.4 . A summary of the chapter is provided in Section 9.5.

9.1 Research findings

The model was developed and refined based on the practice of CED in a UK company, which specialises in the design and manufacture of complex technical systems within the shipbuilding industry. This company was regarded as Company 1. To assess its appropriateness in representing the CED process in different life phase and product focus, the model was independently evaluated at three other companies, divided into preliminary and main evaluation. The preliminary evaluation was conducted in Company 2, an Indonesian company, specialising in the design and manufacture of complex technical systems at shipbuilding industry. The main evaluation was conducted in Company 3, a UK company, specialising in the maintenance of complex technical systems in the shipbuilding industry and Company 4, a UK company, specialising in the design and manufacture of complex technical systems in the optoelectronic industry.

Findings derived from the model evaluation in the aforementioned companies were presented in Chapter 8. In this section, the findings from these companies are discussed, leading to the identification of avenues for future research. The discussions encompass the six aspects of the model that were used as the basis of evaluation (i.e. evaluation criteria): *completeness, correctness, relevance, usefulness, ease of understanding, and achievement of purpose* (Section 8.2.1.1). The discussions of each aforementioned aspect are presented from Section 9.1.1 to Section 9.1.6, respectively. Based on these discussions, conclusions on the model's representativeness are derived, presented in Section 9.1.7.

9.1.1 Completeness

As mentioned in Section 8.2.1.1, the evaluation criteria were defined after the preliminary evaluation in Company 2. Although there was no specific set of evaluation criteria chosen, a general aim of the model evaluation was defined. The aim of the preliminary evaluation was to check if all elements of the model (i.e. entities, sub-entities, attributes, and relationship) could be identified in an Indonesian shipbuilding company's CED practice (Section 8.1). In other words, the evaluation sought to identify if any new elements needed to be added to the model. From this perspective, the model evaluation in Company 2 was to assess the model's *completeness*.

The preliminary evaluation was conducted informally through an interview. The completeness of the model was therefore measured from the number of new elements of the CED process that emerged during the interview. Alternatively stated, the model was believed complete if no new elements and new relationships emerged. For this, the interview was transcribed and interpreted through *coding* and *condensing* the transcription (Section 8.1.1).

The result from the meaning coding showed no new elements emerged from the interview. Accordingly, the conclusion is that the model can be considered complete. The result from the meaning condensation showed three additional relationships: between <u>cognitive</u> and <u>assigned role</u>; <u>experience</u> and <u>cognitive</u>, and <u>experience</u> and <u>skill</u> (Section 8.1.2). <u>Cognitive</u>, <u>assigned role</u>, <u>experience</u>, and <u>skill</u> are attributes of <u>stakeholders</u>. Presenting the relationships between attributes was beyond the scope of the model, as discussed in Chapter 6. As such, these additional relationships were not used as the basis to measure the model's completeness, and the model can therefore be considered complete. Nonetheless, adding the relationships between attributes can be further investigated as an area for future research. Additionally, as the model was evaluated using an interview method with only one participant (Section 8.1.3), evaluating the model in the same type of company using a different evaluation method with more than one participant is suggested to investigate if similar conclusions could still be drawn.

The main evaluations were conducted using focus groups and its completeness was measured from the number of element additions and expansions suggested during the focus groups (Section 8.2.1.1). The findings showed that the number of additions suggested dominated the total number of suggestions from the participants (i.e. 81.5% in Company 3 and 78% in Company 4 – Chapter 8). Given these figures, it is possible that the model is not complete. However, there are also four other possibilities.

Firstly, it is possible that the concept of the model was not clearly understood by the participants. For example, as can be seen in Table 64 and Table 65, the highest number of element *additions* and *expansions* in both companies were relationship additions and expansions. The participants argued that certain entities affect almost all the other entities in the model and therefore they can be considered key influencing factors within the CED process. According to the participants, the significance of these entities was not visible in the model, and thus, addition and/or expansion of the relationships that involve said entities were deemed necessary. Examples of such entities were "opinion" and "relationship".

It should be noted that all entities included in the model were considered as influencing factors of the CED process (Chapter 5). Because these entities influence the overall CED process, they influence most or all of the other entities in the model. Adding all the relationships between every entity would increase the model's complexity, and thus, they were not represented in the model. The emergence of these addition suggestions can be seen as an indication that the concept of the model was not clearly understood by the participants.

Secondly, it is possible that the participants were not familiar with the modelling language used. For example, many of the attribute additions suggested were what are regarded as *value attributes* in an EER diagram. That is, they are *attribute* descriptions. For example, the participants suggested adding "cost" and "technical" as sub-classes of "impact". However, value attributes are not presented in EER diagram and therefore should not be in the model (Chapter 6). For those who are not familiar with EER, the concept of *value attribute* may not be understood.

Thirdly, it is likely that the terminology used was not recognised by the participants. Several attribute additions were suggested although they were already present in the model. For example, "intelligent" was suggested to be added as an attribute of "stakeholders". However, "intelligent" is related with a human being's cognition, and "cognitive" was already included in the model as an attribute of "stakeholders". Nonetheless, the participants did not recognise "intelligent" and "cognitive" as having similar meanings.

Fourthly, it seems that the additional elements suggested by the participants tend to be specific to the company's CED practice. For example, in Company 3's CED practice, safety hazard is one of the company's main concerns that influence their design process. Thus, the participants suggested adding "hazard" in the model. This was not identified in the feedback derived from Company 4.

Based on the above points, it is therefore cannot be concluded whether the model is complete or not. Instead, the model may form the basis for customisation to suite a specific company's requirement. To apply the model in CED practice within different type (i.e. industrial and product life phase) of companies, the model may need adaptation. Additionally, further evaluation may be necessary, using different approach that allows the participants to understand and experience the model prior to evaluating the model. This is suggested for future work (Section 9.4).

9.1.2 Correctness

Correctness refers to how accurately the elements of the model are perceived (by the participants) as socio-technical elements of CED process. To assess *correctness*, both a focus group, and a questionnaire were employed. Through a focus group, the model's correctness can be measured from the number of element refinements (i.e. category and term) suggested. In both companies, the numbers of category and term refinements are relatively low compared to the overall number of overall suggestions. In Company 3, only 2% of the total suggestions (i.e. 2 from 108) were category refinements, and only 1% (i.e. 1) was term refinements. In Company 4, 4.5% of the total suggestions (i.e. 4 from 89) were category refinement, and 8% of the total suggestions (i.e. 7) were term refinement.

The number of term refinements in Company 4 is almost twice as high as the number of category refinements and almost four times higher than the total number of refinements suggested in Company 3. The participants in Company 4 argued that a number of terms used in the model are not used in their company. However, they did not reject the correctness of the terms. Thus, it was perceived as an indication that the model needs further adaptation before being applied to different industrial practices.

Based on the above findings, it can therefore be concluded that the model accurately represents the CED process from the socio-technical perspective. This conclusion was also supported by the response of the participants given in the questionnaire (see Section 8.2.3.1.2 and Section 8.2.3.2.2). The majority of the participants from Company 3 and Company 4 agreed that the model covers the general socio-technical elements of the CED process (i.e. 93% from Company 3, 100% from Company 4). The majority of the participants from Company 3 and 4 also agreed that the model covers the specific socio-technical elements of the company's CED process (i.e. 50% from Company 3, and 65% from Company 4). In Company 3, the majority of comments conveyed by the participants who opted for neutral (i.e. 43%) highlighted subtle differences between the model and the practice of CED in their company. They believe that with small adaptations, the model can better represent the company's CED process from the socio-technical perspective. In this sense, it was concluded that the participants did not reject the accuracy of the model's elements in representing the company's CED process. Instead, they suggested that model can be further improved by adapting it slightly.

9.1.3 Relevance

As discussed in Section 8.2.1.1, the model's relevance can be measured from the number of element *deletions* suggested by the focus groups. In Company 3, 11 element deletions were suggested, consisting of six sub-entity deletions and five relationship deletions. The sub-entity deletions were suggested, as the participants believed it was unnecessary to include sub-entities that have no relationship with any other elements of the model. As mentioned in Section 9.1.1, all the elements included in the model were considered to influence the overall CED process. Thus, although they are not all related with one another on the model, they are all considered influencing factors of the CED process. Furthermore, as explained in Chapter 8, based on the concept of an EER diagram, sub-entities are involved in all relationships that their parents are involved in. In other words, although relationships between sub-entities with other elements of the model were not visible, it does not mean that said relationships do not exist. As such, instead of perceiving these suggestions as an indication that the elements of the model were not relevant, they were seen as an implication that the introduction to the concept of the model and as well as the modelling language itself needed improvement.

With respect to the relationship deletions, the comments from the participants indicated that the deleted relationships did not reflect the practice of Company 3. Similar arguments were given by the participants in Company 4 on their suggestions to delete three relationships. It is possible that these relationships were not relevant to the CED process, as they were not identified in the company's CED practice. Nonetheless, it is also possible that these relationships exist under different terminology and/or a different form of relationship, and thus, were not recognised. Further investigation is needed to confirm these possibilities.

Lastly, one attribute deletion was suggested by the participants in Company 4 as they argued that, to avoid confusion, an element should not be in more than one category (i.e. be both entity and an attribute). This particular suggestion related with the ease of understanding. As such, it was not perceived as an indication of the model elements' relevance.

Based upon the aforementioned findings, which saw no rejections stemming from the relevance of the model elements at representing the socio-technical elements of the CED process, it can therefore be concluded that the elements presented in the model are relevant.

9.1.4 Usefulness

The usefulness of the model was assessed using the following statement in the questionnaire: "the model would be useful for the company's CED". The majority of the questionnaire respondents (i.e. the participants) from both companies inclined towards agreeing with the aforementioned statement, i.e. 50 % agreed and 29% strongly agreed in Company 3; 46% agreed and 8% strongly agreed in Company 4. From these findings, it may be concluded that the STAM (Socio-technical Architectural Model) can be useful to industrial practice. Nonetheless, certain comments provided by the participants suggested that the model needs to be adapted if it is to be applied in the company. Further research on the applicability of the model in different companies may be needed (Section 9.4).

9.1.5 Ease of understanding

Similar with the usefulness, the model's ease of understanding was assessed using the questionnaire. This time around, the following statement was used: "the model was easy to understand". In Company 3, 43% of the participants disagreed with the statement, while 28.5% had no opinion. These participants argued that the model was difficult to understand because of its structural complexity. However, the majority of the comments given by the participants indicated that although the model was complex, with sufficient time to learn, the model would have been better understood.

In Company 4, although the majority of the participants have no opinion (i.e. 64%) on the aforementioned statement, their comments suggested that the model was not easy to understand. The majority of these participants commented on the terminology used and the fact they were unfamiliar with it. According to them, changing the terminologies into the common terminologies used in the company would increase the model's ease of understanding. For example, changing "technical system" into "design solution".

On the basis of the aforementioned findings, two prominent conclusions can be derived from the questionnaire responses. Firstly, both companies suggest that the model is not easy to understand. Secondly, each company is concerned over different aspects on the model, i.e. IP-4 are concerned over the structure of the model, while IP-5 are concerned over the terminology used. In this sense, it seems reasonable to conclude that to apply the model in different industrial practices; the model needs to be adapted accordingly. Identifying how the model can be adapted for different industrial practices was suggested as an area for future work (Section 9.4).

9.1.6 Achievement of purpose

Three statements were given in the questionnaire to assess the extent to which the model achieved its intended purpose (i.e. to provide insight into the CED process from the socio-technical perspectives to allow for a better understanding of the phenomena). The responses for each statement from Company 3 and Company 4 are summarised in Table 66.

Table 66 Summary of questionnaire responds from Company 3 and Company 4

Statement	Company 3	Company 4
The model effectively explains the collaborative engineering design process from the socio-technical perspectives	Agree: 50% Neutral: 36% Disagree: 14%	Agree: 46% Neutral: 46% Disagree: 8%
The model provided insights into the collaborative engineering design process	Strongly agree: 14% Agree: 86%	Strongly agree: - Agree: 77% Neutral: 8% Disagree: 15%
My understanding towards the collaborative engineering design process increased after reviewing the model	Strongly agree: 14% Agree: 57.5% Neutral: 28.5%	Strongly agree: - Agree: 46% Neutral: 46% Disagree: 8%

As can be seen above, 50% of the participants from Company 3 and 46% from Company 4 agreed that the model effectively explains the CED process from the socio technical perspective. The majority of the overall comments, including those who are neutral indicated that the model has the potential to explain the CED process from the socio-technical perspective effectively. Nonetheless, further adaptation based on a specific company's practice may be needed.

The participants from both companies inclined towards agreeing that the model provides insights into the CED process.

Lastly, the majority of the participants from Company 3 agreed that their understanding towards the CED process increased after reviewing the model. However, different findings were derived from the participants from Company 4. 46 % participants agreed, while 46% had no opinion towards the statement. As mentioned in Section 8.2.3.1.2, the majority of the comments given by the participants who have no opinion indicated that they have understood the CED process, based on prior experience with CED. Thus, they argued that the model does not give new information, and does not change their understanding of the CED process. From this perspective, two conclusions may be derived. The first is that it is possible the participants understand the CED process from a general perspective. A different response may have been given if the statement instead read "my understanding towards the CED process increased after reviewing the model from socio-technical perspective". Further investigation may be needed to confirm this argument. The second suggestion is that, given the participants gave a neutral response; their prior knowledge of CED is aligned with the information presented in the model. With this in mind, it suggests that the model can be considered an accurate depiction of CED.

Based on the above findings, it can be concluded that the purpose of the model development has been achieved. The need for further adaptation is noted as an area for future work (Section 9.4).

9.1.7 Conclusion

In conclusion, the model can be considered to represent the socio-technical elements of the CED process and their inter-relationships for an ETO company that specialises in the design and manufacture of complex technical systems within the shipbuilding industry (i.e. Company 2). However, the model may not be considered a complete representation of CED elements in companies with distinct life phase and product focus. The elements of the model may be considered to accurately represent the socio-technical elements of the CED process and they may be considered relevant to the CED process for an ETO company that specialises in the maintenance of complex technical systems within the shipbuilding industry (i.e. Company 3), as well an ETO company specialises in the design and manufacture of complex technical systems within the optoelectronic industry (i.e. Company 4). In these companies, the intended purpose of the model is considered to be achieved. Nonetheless, the model may not be completed due to the way the model was introduced and mostly, due to the different nature of CED practice in companies with different life phase or product focus. Furthermore, the model may not be easy to understand due to its structural complexity and differences in terminology. Based on these points, to be applied in different industrial practices, the model may need further adaptation.

A summary of the conclusions based on the research findings discussed above is outlined in Table 67.

Table 67 Summary of conclusion drawn from the discussed evaluation findings

Evaluation criteria	Company 2	Company 3	Company 4
Completeness	√	x	x
Correctness	N/A	√	√
Relevance	N/A	√	√
Usefulness	N/A	√	√
Ease of understanding	N/A	x	x
Achievement of purpose	N/A	√	√

9.2 Research methods

As presented in Section 2.2, the research methods adopted in this thesis can be categorised as either data collection or data interpretation methods, depending on their application. In this section, the discussion on the research methods is presented with respect to these categories.

9.2.1 Data collection

Four data collection methods were adopted in this thesis (Section 2.2.1). The advantages and disadvantages of these methods with respect to their use in this thesis are discussed from Section 9.2.1.1 to Section 9.2.1.4, respectively.

9.2.1.1 Literature review

Literature reviews were used in the research focus definition (Chapter 3 and Chapter 4), and model review and refinement (Chapter 7, Section 7.2), using traditional approach. Such approach was deemed beneficial, particularly, when forming a broad basis of the research focus definition and of the model development. However, the absence of a formal methodology in the traditional approach also created challenges during the study.

Firstly, a massive number of papers can be resulted in every search. For example, using the term "collaborative design" in google scholar yielded around 3 million papers. Without any formal methodology, it was difficult to filter the literature and selected literature sources to include in the study.

Secondly, the selection criteria were based solely on the researcher's (i.e. the author) knowledge and personal beliefs. As such, the findings and conclusions derived from the literature review were likely to be subjective.

To accommodate the above traditional review challenges, a variety of data collection methods had been employed throughout the study. However, the use of systematic literature review might have minimised the level of author subjectivity more rigorously.

In contrast to the traditional approach, a systematic approach involves the use of a formal methodology. There is a study protocol that needs to be followed in a systematic approach, including the criteria to select the literature. Furthermore, a systematic approach typically involves more than one researcher (for multi-perspective purposes), and thus, can minimise individual bias and misinterpretation.

In addition to the above, with a specific note on the social literature review (Chapter 7), the fourth version of the model (STAM-4) was reviewed and refined based on findings from the social literature recommended by the social science academic. Although the recommended literature was useful in providing a social-perspective, from both, the academics (i.e. B1) and practitioner (i.e. B2) point of view, they were suggested by one social science academic only. Despite the expert’s knowledge and experience in the field of organisational psychology, other relevant social literature that can provide additional insight might exist. Furthermore, as the social literature was selected by a social science academic, who was suggested by peer-recommendation, the author considered the literature valuable without cross checking it with other social science academics. To compare and contrast multiple insights, asking for social literature recommendations from multiple social science academics could be beneficial for future work.

9.2.1.2 Interview

Interviews were used to obtain insights from: 1) IP-1 (i.e. 28 interviewees) during the model development phase, 2) a social science academic during the model review and refinement phase, and 3) IP-3 (i.e. one interviewee) during the model check and evaluation phase. A total of 30 participants were interviewed using semi-structured approach. In semi-structured interview, a set of questions were prepared for guideline, allowing the questions to evolve based on the response of the participants.

A prominent advantage from conducting semi-structured interviews in the study presented in this thesis was that it allowed in-depth conversations towards a topic with the people who directly experience the problem being studied. Detailed information about CED process can be derived and can be used to form a basis for the model development. Nevertheless, interview was considered a time-costly approach (e.g. approximately one-year duration covered for 28 interviews) and dependent on the availability of the participants. Due to this, to plan the timeline for the data collection process was found to be challenging. As the time availability for PhD research was limited, contingency plans were needed.

Another point noted as a disadvantage of an interview method was that the information elicited depended on several factors such as the level of knowledge and experience of the interviewees, their interpretation towards the problem, their feeling towards the company and towards the interviewers. Consequently, their answers can be biased. This disadvantage was mitigated to some extent by involving multiple participants and by using multiple methods of data collection. However, apart from the literature review, the other methods used were conceptually similar with interview (i.e. eliciting information from conversations). Regarding this, incorporating different methods such as participant observation may be considered for future work to provide different perspective towards the problem (i.e. CED process). Additionally, one avenue that can be further investigated is the use of multiple interviewers (i.e. investigators) for future work.

With a specific case on the interview with IP-3, the Indonesian culture seemed to affect the participant's openness towards a specific type of question, i.e. the questions that have negative connotations such as the challenges in the company's CED process. This could have been addressed by re-wording the questions in a more positive tone. However, as the effect of culture to the participant's behaviour was not taken into account, it was not anticipated during the interview. Finally, as the interview was conducted in the Indonesian language, the interview needed to be translated into English. For time and cost reasons, the translation process was done by the researcher - a non-native and non-professional English speaker/translator. As such, there is a potential for miss-translation that might affect the findings. For this reason, involving a professional translator is suggested for other studies in a foreign language.

9.2.1.3 Focus group

Focus groups were applied in the two phases of the solution generation: 1) model review and refinement, and 2) model check and evaluation. In each phase, the focus group involved different groups of participants. The focus groups were applied in the form of workshops, were the participants were engaged in several activities and discussions regarding the STAM of CED process.

As discussed in Chapter 2, one of the main advantages of a focus group method that became the main reason of its adoption in the study was its effectiveness to elicit insights from multiple perspectives at relatively short time (i.e. approximately 2.5 hours). However, during its applications, it became apparent that the responds of the participants were determined by their understanding towards the model. To explain the model to the participants, a 10 to 15-minute presentation was delivered in the beginning of the workshop. However, the allocated time was perceived insufficient by the participants. The result of the questionnaire showed that the participants believe the model can be better understood if a longer time was allocated to explain the model (Section 8.2.3.1.2 and Section 8.2.3.2.2). However, considering the time availability of the participants, extending the time may not be possible. As such, it might be worth to consider improving the way the model is introduced, for example by adding exercise to provide more experience with the model.

9.2.1.4 Questionnaire

A questionnaire method was used to elicit opinions from industrial practitioners regarding the model's appropriateness in representing the CED process from the socio-technical perspective. The method was employed within the model check and evaluation phase, as part of the workshops in Company 3 and Company 4. As explained in Section 8.2.1.1, in the questionnaire, seven statements were given, which correspond to the four evaluation criteria defined (i.e. *correctness*, *usefulness*, *ease of understanding*, and *achievement of purpose*). The participants were asked to rate their agreement, using *Likert Scale* ranging from *strongly disagree* to *strongly* agree around *neutral* selection for no opinion, towards each statement.

Two advantages from using questionnaire were identified during the study. Firstly, questionnaire provides clear response on the questions given. The participants were given options that they have to select and their response cannot deviate from these options. Secondly, the method was considered efficient to elicit opinion from a large number of participants. Compare to the focus group that took 2.5 hours, the questionnaire only took 10 minutes to elicit opinion from 14 participants.

In contrast to the advantages mentioned above, questionnaire was found to have two disadvantages from its application in the study documented in this thesis. The first disadvantage noted was that the result of the questionnaire tends to be subjective, influenced by for example, their experience with the model during the workshop, and their experience on the practice of CED process in the company. The model evaluation process may be benefitted from identifying the reason behind the participants' response. However, as the questionnaire was *self-completion*, it was not possible to probe on the response, and therefore, the reasoning behind the response of the participants cannot be identified. Although a box of comment was provided for every statement, their comment was only limited to the length of the box. This was identified as the second disadvantage of a questionnaire method. Combining questionnaire with interview may facilitate obtaining in-depth opinions from the participants towards the model.

A final note relating to the disadvantage of questionnaire was the use of boxes to present the *Likert Scale* (See Appendix 17: Questionnaire form). The participants were instructed to select one of the options given. However, because of the way the scale was presented, two participants opt for "in-between" response. For example, instead of selecting neutral or agree, they circle the blank space between these aforementioned selections. This type of response required further verification to the participants. This could have been avoided by presenting the options as a set of multiple choices using alphabets or numbers. Additionally, a clearer instruction on how to fill in the questionnaire may have also helped.

9.2.2 Data interpretation

Two data interpretation approaches were applied in the study: inductive approach for the model development phase, and deductive approach for the review and refinement as well as the check and evaluation phase.

With respect to the inductive approach, two methods of data interpretations were employed, namely *coding* and *condensing* (Chapter 5). Through *coding*, the large body of data collected from the interviews was filtered for its key features (i.e. socio-technical elements) by assigning a specific keyword developed from the literature. While through *condensing,* relationship between socio-technical elements can be identified by condensing statements that contains socio-technical keywords from meaning coding. These methods were considered useful to summarise the 28 interview transcriptions in a structured way in the sense that there are steps to follow that are transparent and repeatable.

A salient disadvantage from meaning coding and meaning condensation identified was the degree of subjectivity involved in it. These methods are mainly based on interpretation. Thus, the result can be subject to bias. Efforts have been done to minimise bias by triangulating, for example, research methods and data sources. However, it could have been more rigorously improved by involving more than one coder to analyse the interview transcriptions, or regarded as inter-coding (Campbell *et al.*, 2013). Due to confidentiality issue as well as the time and resource constraint, this was not possible to be applied. Furthermore, as the process was conducted manually, there was a possibility for human error. The use of analysis software such as NVivo to facilitate particularly the coding process might have helped mitigating such error.

As discussed in Section 2.2.2, deductive approach was adopted in the sense that the interpretation was based on the pre-defined theories and assumptions obtained from the model development phase. The adoption can be viewed general and no specific data interpretation method was adopted. Deductive approach started with predefined assumptions derived from the model development phase. As such, it required less time to interpret and provided, arguably, more direct result. Deductive approach is typically related with hypothesis formulation. However, as the adoption of deductive approach in this thesis was considerably general, no hypothesis was formulated. Consequently, the objective of the study was not clearly articulated, and thus, it became challenging to draw the conclusion.

Formulating hypothesis prior to the data collection might have facilitated articulating the aim of the study.

9.3 Research methodology

The philosophical assumption that underpins the study is *interpretivism* (Chapter 2). *Interpretivism* was adopted in the study, as its ontological and epistemological views were perceived compatible with the aim of the study, as discussed in Chapter 2. The philosophical assumption led to the adoption of qualitative approach to the study as it was deemed appropriate to elicit interpretations from human beings. Qualitative approach allows the phenomena of CED process to be studied in a great level of detail, for example by understanding the reason behind the phenomena. Nonetheless, the results tend to be subjectivity as it mainly based on interpretations. Consequently, the result cannot be generalised, or can only be generalised to a certain extent.

Triangulating the methods, data sources, and theory was aimed to reduce the degree of subjectivity and minimise potential bias in the results of qualitative approach. However, mixing qualitative approach with quantitative approach, e.g. by adopting quantitative method such as survey to elicit interpretations from the participants, and involving more than one investigator (i.e. investigator triangulation) might have reduced the subjectivity and bias more significantly. These were not considered during the study due to the time and resources constraints on PhD study, and thus, can be considered for future work.

The study documented in this thesis consisted of four main phases: research problem definition, solution generation, evaluation, and documentation. Throughout the solution (i.e. the model) generation phase, Scrum framework was adapted. Through the adoption of this framework, the model can be evolved following the level of understanding on the phenomena being modelled. As such, instead of creating one final model at the end that can be rather overwhelming, the model can be created in an incremental manner. This was considered an advantage to the study. Another advantage noted was that because of the iterative nature of the framework (Chapter 2), issues identified from the previous iteration can be learned. The lessons learned can be used as the basis to plan for the next iteration. In this sense, it can be viewed that Scrum framework facilitates continuous learning.

The iterative nature of Scrum was also identified as the main disadvantage of the framework. As the plan (e.g. methods adopted, data sources targeted) for the next iteration was determined by the lessons learned from the previous iteration, it cannot be prepared in advance. Consequently, there was a degree of uncertainty involved in the study. For this particular reason, having contingency plans were deemed important and proven to be useful. Another disadvantage from not being able to plan ahead was the plans selected for the next iteration was often driven by practicality reasons (i.e. time and data sources constraint). Thus, methods that were considered to be time-consuming such as participant observation were not selected, although they might be able to add insights from different perspectives towards the CED process.

The developed model was evaluated independently in three different companies (Company 2, Company 3, and Company 4), two of which focussed on different products or life phases. These evaluations provided a broad basis to assess the model's representativeness. Thus, the results were considered comprehensive. However, the participants involved were mainly those holding managerial roles, there were very few representing the lower tiers of employment in each company. Due to this, the views generated from the evaluation sessions in each company did not go into a great level of detail in terms of the CED practice.

In addition to the above, the workshop approach was selected as appropriate to obtain insights from a number of participants in a relatively short time. Reflecting upon the way the workshop was organised, one point can be highlighted as the main lessons learned. The highlighted point related to the fifteen-minute introductory presentation of the model that was conducted at the beginning of the workshops. It was presumed that this time would be sufficient to introduce the model to the participants. However, during both workshops, the participants require a longer time to understand the model. One reason identified was that the participants have no and/or limited knowledge and/or experience on the information modelling language used (EER). To overcome this, two suggestions can be made: 1) extending the presentation time, allowing more time to get participants familiarised with the model; and 2) refining the way the model is introduced to the participants, and tailoring it depending on the background of the participants.

In connection with the second suggestion above, in W1, the participants understood the model faster when the terms used in the model were framed within the company's collaborative design practice context. For example, to explain the term "policy" used in the model, a policy in the company, named "design maturity" was used as an example. To provide such example, the facilitator(s) of the workshop needs to conduct a preliminary investigation to understand the company's collaborative design practice. Framing the model in the context of the company will be used to introduce the model in the future workshops.

9.4 Future work

Above, the advantages and disadvantages of research findings, research methods, and research methodology of the study were discussed, leading to suggestions for future work. In this section, these suggestions are elaborated from Section 9.4.1 to Section 9.4.3

9.4.1 Further investigation on developing the third level of the model

The relationships between attributes was emerged not only during the model evaluation in Company 2, it was also identified from the literature exploration during the model development phase. The literature suggests that, for example, the behaviour (i.e. “conative” attribute) of a human being can be influenced by their “personality” (Chapter 4). Furthermore, the relationship was also found on the list of feedback points derived from W1 and W2 during the model review and refinement phase (Chapter 6). Given these evident, modelling relationships between attributes can potentially facilitate a better understanding on the phenomena of the CED process. For this, future research focussing on modelling the relationships between attributes (STAM Level 3) was recommended as an avenue for future work.

9.4.2 Further investigation on the model’s representativeness

With respect to the model’s evaluation, three areas for future work may be suggested. They are considered to be:

1. Changing the introductory approach

One of the challenges that the participants face during the model evaluation was the model’s complexity and the limited time given to understand the model (Section 9.2.1.3). Furthermore, as discussed in Section 9.1.1, there was a possibility that the model’s concept was not properly explained to the participants, and thus, it was not clearly understood. However, extending the time to understand the model during the focus group may not be possible considering the participants level of activity. For this reason, for future work, it might be worth to change the way the model is introduced, for example by adding exercise to provide more experience with the model.

2. Evaluating the model with academics

During the review and refinement phase, in addition to involving a group of industrial practitioners, a group of engineering design academics was also involved. Their involvement yielded a broader perspective towards the model evolution. However, due to the time constraint, in the check and evaluation phase, only industrial practitioners could be involved.

Involving engineering academics may have provided a broader view towards the model evaluation, and thus, was identified as an area for future work.

3. Evaluating the model in different industrial practices

Although the industrial practitioners had been selected from three different industries, the model evaluations were limited in ETO companies specialising in the engineering design of complex technical systems. To gain further insights into the extent of the model's appropriateness, evaluating the model in other types of company such as Make to Order (MTO) or Make to Stock (MTS) companies specialising in less-complex technical systems such as car to assess its appropriateness is recommended for future research.

4. Evaluating STAM level 1

Lastly, further evaluation could also include the evaluation of STAM level 1. An aggregated version of STAM, i.e. STAM level 1, has been generated to present the CED process in a more general sense. However, this model was not included in the model evaluation. To gain insight on the extent of the model's appropriateness in representing the CED process in a general sense, evaluating STAM level 1 is suggested.

9.4.3 Further investigation on the model's adaptation

On the basis of the evaluation findings discussed in Section 9.1, it was found that different type of industry focusses on different elements of the model. For example, Company 3, a company that specialises in shipbuilding industry, focusses on the structure of the model, while Company 4, a company that specialises in optoelectronic industry, focusses on the terminologies used. Although the evaluation was limited in one company for each industry, it can be seen as indication that to be applied in different practices of CED process, the model needs further adaptation based on the specific company's need(s) and preference(s). This provides an avenue for future works. How the model can be adapted in different type of industries can be further investigated for future research.

9.5 Summary

In this chapter, the study documented in this thesis is discussed with respect to its findings, methods employed, and the overall methodology adopted. The discussions are presented in Section 9.1, Section 9.2, and Section 9.3 respectively. From these discussions, advantages and disadvantages were identified, leading to the suggestions for future research, presented in Section 9.4. In Table 68, these advantages, disadvantages, and suggestions are summarised.

Table 68 Summary of discussion

Strengths	Weaknesses	Suggestions
Research Findings		
✓ The model comprehensively represents CED process from a holistic socio-technical perspective for the practice of CED process in ETO company that focusses on the design and manufacture of complex technical systems, at shipbuilding industry. ✓ The elements of the model accurately represent the socio-technical elements of CED process. ✓ The elements of the model are significant to the CED process, and thus, needed to be presented in the model. ✓ The model provides insights on the CED process from socio-technical perspectives ✓ The model facilitates a better understanding on the CED process.	✗ The model does not include how attributes inter-relate with each other ✗ The model is considered not comprehensive for the practice of CED process in the company that focusses on the maintenance of complex technical system, at shipbuilding industry. ✗ The model is considered not comprehensive for the practice of CED process in the company that focusses on optoelectronic industry. ✗ The model is complex, and thus, ✗ The model needs slight adaptation for different industry types.	➢ Model relationships between attributes (STAM Level 3). ➢ Investigate how to further adapt the model based on the industry type. ➢ Further evaluate the model's representativeness in different industry types. ➢ Evaluate STAM level 1
Research methods		
Traditional literature review		
✓ Allow literature exploration in a wider domain. ✓ Facilitate to provide a broad basis for research foundation.	✗ Can yield in a large number of literatures. ✗ Difficult to filter the literature. ✗ The literature selection criteria tend to be subjective.	➢ Adopt systematic literature review.
Interview		
✓ Allow in-depth conversations on a topic, and thus, ✓ Facilitate an in-depth understanding on the topic being discussed. ✓ The findings derived come from people who directly experience the topic being discussed.	✗ Time-costly approach. ✗ Depends on the availability of the participants. ✗ The findings tend to be subjective and bias. ✗ The culture of the interviewee can influence their behaviour towards certain questions ✗ There is a potential for miss-translation for the interview in a foreign language	➢ Prepare contingency plans. ➢ Employ other type of data collection such as participant observation. ➢ Use multiple interviewers. ➢ Adapt the question based on the cultural background of the interviewees ➢ Use professional translator if the interview is conducted in a foreign language.

Focus group		
✓ Effective to collect insights from multiple perspectives at the same time.	× The findings derived depend on the participants' level of understanding towards the model being discussed.	➢ Improve the way the model is introduced. ➢ Provide longer time to introduce the model.
Questionnaire		
✓ Provides clear response towards the questions asked. ✓ Efficient to elicit opinion from a large number of participants.	× Findings tend to be subjective. × Not possible to probe on the questionnaire respondents' response. × The instruction can be misunderstood by the respondents.	➢ Combine questionnaire with interview to probe and verify the response. ➢ Use multiple choices instead of bars to present the *Likert scale.* ➢ Provide clear instruction on questionnaire completion
Data interpretation		
Inductive approach ✓ Facilitate to summarise a large body of data in a structured way.	× Conclusions derived tend to be subjective × Individual coder and manual coding can potentially lead to mistakes from misinterpretation and human error	➢ Adopt inter-coding to reduce subjectivity ➢ Employ coding software such as Nvivo.
Deductive approach ✓ Requires less time. ✓ Provides more direct conclusion than inductive approach.	× The objective of study can be vague without hypothesis.	➢ Formulate hypothesis to articulate the objective of study.
Research methodology		
✓ The *interpretivism* philosophy suits the research aim and objectives. ✓ Qualitative approach facilitates in-depth study on the topic. ✓ Scrum framework allows the model to be developed incrementally. ✓ Scrum framework facilitates continuous learning throughout the study. ✓ Triangulation of the data sources, methods, and theories mitigated subjectivity. ✓ Evaluation in three different companies provides a comprehensive view towards the model's representativeness.	× Qualitative approach tends to be subjective × Scrum framework involves a degree of uncertainty where plans cannot be detailed in advance in Scrum Framework × The industrial practitioners involve in model evaluation mostly consist of those holding manager roles and their views tend to be general	➢ Investigator triangulation. ➢ Incorporate quantitative approach (i.e. survey) to elicit human beings' interpretation. ➢ Prepare contingency plans.

10. Conclusion

The study reported in this thesis was aimed at developing a socio-technical architectural model of CED. The study was conducted to address both the lack of socio-technical research from a holistic perspective and the lack of social awareness in the practice of CED (Chapter 4). These lacking were addressed through the main knowledge contributions, as explained below.

The main knowledge contribution of the study documented in this thesis is a socio-technical architectural model (STAM) of CED, a generic model describing a phenomenon of the CED process from a holistic socio-technical perspective. The model was developed through a review of CED literature (Chapter 4) and interviews with industrial practitioners from an ETO company (Company 1 - Chapter 5); reviewed and refined through focus groups with academics and industrial practitioners (Chapter 6), a social science academic’s judgement and a review of organisational teamwork research (Chapter 7); and evaluated through independent case studies in three companies (Chapter 8) using an interview in Company 2, and focus groups and questionnaires in Company 3 and 4.

The above contribution was built upon a number of inter-related elements. The aim of this chapter is to conclude this thesis by providing a summary of these elements, which can be grouped as research methodology (Section 10.1), review of CED research (Section 10.2), investigation of CED practice (Section 10.3), STAM of CED (Section 10.4), evaluation (Section 10.5), and strengths-weaknesses-future work (Section 10.6).

A summary of work is depicted by Figure 87, highlighting the contribution of the study and their interdependencies.

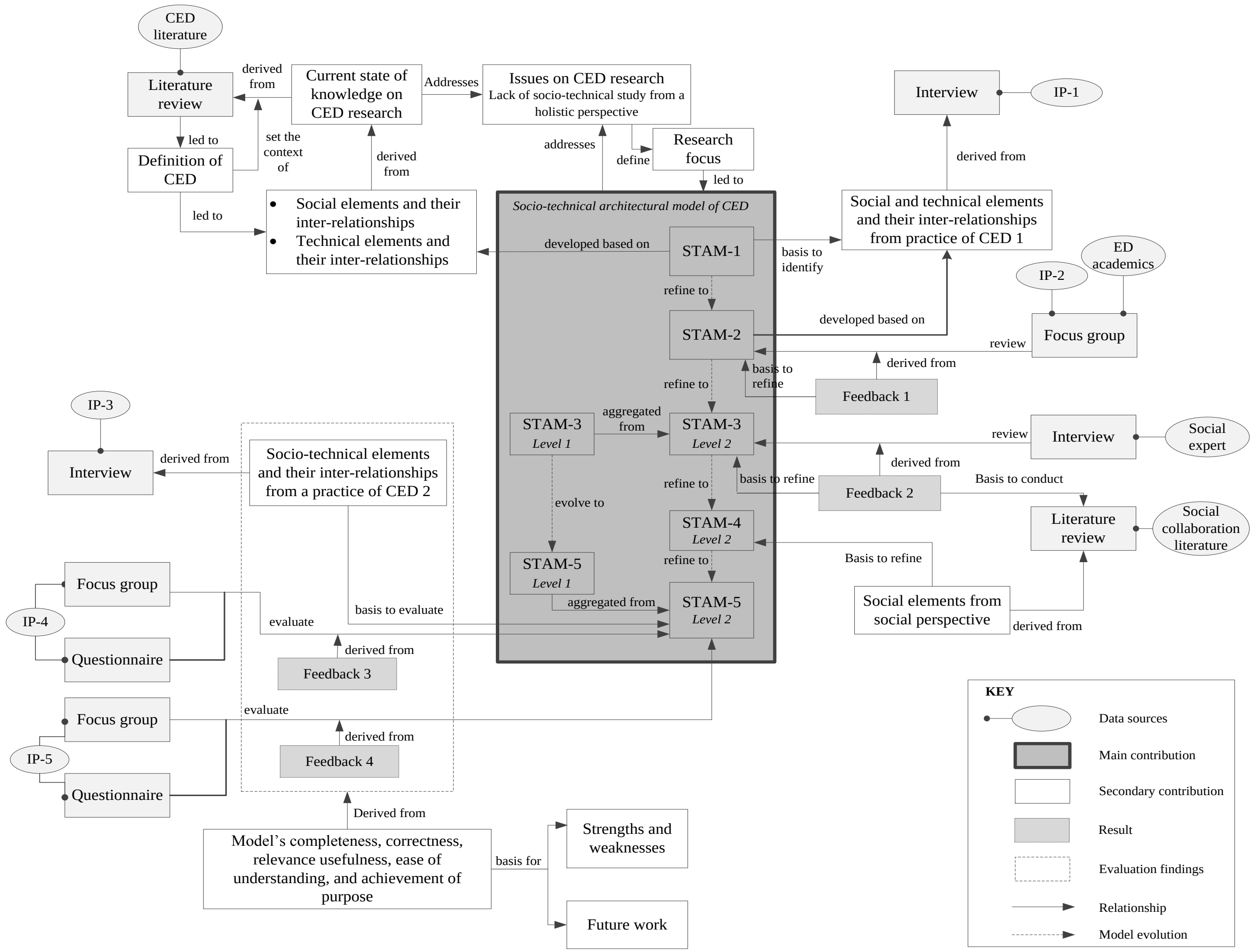


Figure 87 Summary of work

10.1 Research methodology

The study documented in this thesis adopted an *interpretivism* philosophical assumption with the basic belief that reality can be accessed through the subjective interpretation of individuals. This assumption underpinned the overall methodology of the research that consisted of three main phases: 1) research focus definition, 2) solution generation, and 3) evaluation. Each phase adopted a number of methods to collect and interpret information.

Within the research focus definition phase, two methods were used: 1) a traditional literature review, to identify issues faced in the CED research derived from the current state of knowledge on CED research, and 2) semi-structured interviews with 28 industrial practitioners (IP-1) to identify issues faced within current CED practice. The issues identified from both the literature review and interviews with practitioners were used to form the basis of defining the focus of the study, the main aim of the phase.

A scrum approach was adopted in the solution generation phase, which allowed the model to be developed iteratively, fusing two steps: 1) model development, and 2) model review and refinement. The findings from the literature review conducted in the research focus definition phase were used as the basis to develop the first version of the model (i.e. STAM-1) during model development phase. The social and technical elements presented in this model were used to form the basis of *coding* and *condensing*, i.e. methods to interpret the transcriptions of the interviews with the 28 engineering design practitioners (IP-1). The results were used as the basis to refine STAM-1 into STAM-2. In the model review and refinement phase, three methods were used. The first method used independent focus groups involving industrial practitioners (IP-2), and engineering design academics (ED academics). During these focus groups, the participants were asked to review STAM-2. The feedback derived from this was used to refine STAM-2 into STAM-3. The second method involved an interview with a social science academic to elicit their view towards the model from the social perspective. The feedback derived from the social science academic was used to refine STAM-3 into STAM-4. A further literature review focussing on social literature was the third method used, which came from a suggestion from the social science academic who recommended two highly relevant social collaboration reference books. Findings from this literature review were used as the basis to refine STAM-4 into STAM-5.

STAM-5, the final version of the model, was evaluated for its representativeness in three different companies. In the first company (Company 2), an interview with an industrial practitioner (IP-3) was conducted. The result from the interview was used to assess the model's completeness. In the second and third company (Company 3 and Company 4), independent focus groups and questionnaires were carried out to elicit opinions from industrial practitioners (IP-4 and IP-5) towards the model.

As may be seen from the aforementioned points, the study adopted the triangulation of: 1) data sources (i.e. CED literature and social collaboration literature, industrial practitioners from four different companies, engineering design academics, and a social science academic), 2) methods (i.e. literature reviews, interviews, focus groups, and questionnaires), and theories (i.e. social and technical). These triangulations were used to mitigate bias and misinterpretation that can potentially occur from an *interpretivism*-based study.

10.2 Review of CED research

A literature review was conducted to identify the current state of knowledge on CED research. A clear definition of CED was not identified, and thus, CED was firstly defined to frame the context of the literature review. The following definition of CED resulted and used throughout the thesis:

The act of working together between multidisciplinary human beings, all of which require communication for shared understanding and support from various tools in order to design a technologically-related solution to an ill-defined problem throughout an iterative process.

From this definition, six elements of CED were derived: human beings, interaction, tools, design solution, design problem, and design process. Together, these lead to the notion of CED as a socio-technical process. Accordingly, the literature was categorised into social, technical, and socio-technical literature.

Sixty-eight studies on CED were identified. From these studies, 23 were categorised as social, 35 as technical, and 10 as socio-technical. Two prominent issues facing CED research emerged from the literature review: 1) there is a lack of socio-technical studies, 2) a lack of a socio-technical study from a holistic perspective, and 3) a consensus on the fundamental constitution of socio-technical CED and their inter-relationships.

10.3 Investigation of CED practice

An investigation into CED practice was conducted in Company 1 by employing interviews with 28 collaborative engineering design practitioners. Company 1 is a UK company, specialising in the design and manufacturing of complex technical systems within the shipbuilding industry. Through the interviews, the challenges faced by the company's CED practice, the company's strategies to address the challenges, and improvement suggestions were derived from the participants. The investigation suggested that most challenges were related to the social elements of CED. However, the company's improvement strategies currently applied were only addressing the technical-related challenges. Additionally, although the suggestions given by the interviewees were mainly to address social-related challenges, the suggestions themselves were still related with the technical elements of CED. Thus, it was concluded that the company lacked awareness on the social elements of CED. This issue alongside the issues identified from the review of CED research was used as the basis to define the focus of the study (Chapter 4). That is, to develop a socio-technical architectural model of CED.

10.4 The STAM of CED

Five versions of the STAM of CED were created as a result from the study reported in this thesis. Each version was developed using a number of methods, based on data collected from various sources, in order to obtain multiple-perspectives (as explained in Section 10.1).

The STAM consists of eight themes, comprised of four social themes: human beings, communication, conflict, and organisation, and four technical themes: design information, tools, technical systems, and design process. Each theme encompasses a number of socio-technical elements, sub-elements, the properties that characterise an element, and the inter-relationships between the elements. These were presented by adapting an EER information modelling language. Through an EER, the socio-technical elements, sub-elements, descriptive properties, and their inter-relationships are presented by different graphical notations, namely: *entities* (elements), *sub-entities* (sub-elements), *attributes* (descriptive properties), and *relationships*. In Table 69, the numbers of each elements type in STAM-5 is summarised with respect to the theme of the model.

Table 69 Summary of STAM elements

	Theme	Entity	Sub-entity	Attribute	Relationship
Social	**Human beings**	2	4	19	16
	Communication	3	4	5	2
	Conflict	1	2	1	4
	Organisation	10	7	10	19
Technical	**Design information**	2	3	5	4
	Tools	1	5	1	4
	Technical systems	1	0	3	0
	Design process	3	5	10	5

To reduce the complexity of the model, the STAM is presented in two levels of detail. The model with the greatest level of detail (i.e. level 2 – Figure 84) consists of the aforementioned elements (i.e. entities, sub-entities, attributes, and relationships). This model was aggregated to create a model with less level of detail (level 1- Figure 85), consisting of entities and their inter-relationships. A list of glossaries explaining the terminology used in the model is provided in Appendix 20.

10.5 Evaluation

As STAM-5 was developed based on CED practice in one company only (Company 1, a UK Company specialising in the design and manufacture of complex technical systems within the shipbuilding industry), its representativeness was independently evaluated in three companies (i.e. Company 2, Company 3, and Company 4), two of which focussing on different life phase or product adopting different approaches (i.e. Company 3 and Company 4). In Company 2, (i.e. an Indonesian company specialising in the design and manufacture of complex technical systems within the shipbuilding industry), an interview was conducted with an industrial practitioner (IP-3). Findings from the interview were used as the basis to assess the model completeness, i.e. how comprehensively the elements of the model cover the socio-technical CED process. The result from the evaluation in Company 2 supports the completeness of the model.

In Company 3 (i.e. a UK company specialising in the maintenance of complex technical systems within the shipbuilding industry) and Company 4 (i.e. a UK company specialising in the design and manufacture of complex technical systems within the optoelectronic industry), focus groups and questionnaires were conducted to elicit opinions towards the model. Feedback derived from the focus groups and questionnaires were used as the basis to evaluate with respect to the following criteria: 1) completeness, i.e. as explained above, 2) correctness, i.e. how accurately the elements of the model can be perceived as the socio-technical elements of CED, 3) relevance, i.e. how significant the elements are to the CED process, 4) usefulness, i.e. how the potential users perceived the usefulness of the model, 5) ease of understanding, and 6) achievement of purpose, i.e. the extent to which the model can facilitate a better understanding of the CED process from the socio-technical perspective. These criteria were defined based on the syntax-sematics-pragmatics framework developed by Lindland et al. (1994) for assessing the quality of conceptual information model.

The evaluation results generally support the model’s correctness, relevance, usefulness, and achievement of purpose. However, the model may not be completed and difficult to understand due to its complexity and differences in terminology between that used in the model and that used in each company.

10.6 Strengths, weaknesses, and future work

The model was developed adopting a scrum approach that allows the model to be developed incrementally, facilitated through continuous learning, and resulted in a model with a significant level of detail. The triangulation approach adopted in this research enabled the model to be developed based on a comprehensive perspective, i.e. literature, academic, industrial practice, social, and technical. The aim was to minimise the subjectivity and potential bias. The model evaluation in three other companies with different product or life phase focus generally supports the model's representativeness. Thus, the model can be considered generic for ETO CED process of complex technical systems. Furthermore, the evaluation findings generally showed that the model has presented the CED process from a holistic socio-technical point of view and that it provides a better understanding on the socio-technical CED process. Based on this, it can be concluded that the issues aimed to be addressed by the model (Chapter 4) has been achieved.

One of the main weaknesses of the model development lies in the subjectivity that may exist in the qualitative studies. Although this had been mitigated through a triangulation approach, there is a degree of subjectivity that may have influenced the development of the model. Additionally, the evaluation findings showed that the model was readily understood due to its complexity. Consequently, feedback related with relationships between attributes was not applied to avoid increasing the model's complexity even though this feedback might be beneficial to provide a more comprehensive understanding towards the CED process. The model was also complex due to terminology differences in different companies. Thus, it needs to be tailored based on the specific company needs.

In light of the aforementioned weaknesses and considering the future direction of the study, the following areas for future work were identified:

- Further investigation on developing a third level of the model, consisting of inter-relationships between attributes.
- Further investigation on the model's representativeness in different industrial practices
- Further investigation on how the model can be adapted to companies with different life phase and product focus, and types of industry.

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Appendices

Appendix 1: Industrial challenges

To further form the basis of the study, an investigation on CED practice was conducted in Company 1 (see Chapter 1). The investigation focussed on identifying the challenges therein and improvement strategies to address the challenges. The aim of this chapter is to present the findings from this investigation. The chapter starts with the method used for the investigation, followed by a brief background of the company's CED process. Findings from the investigation and a summary of findings are presented subsequently.

Method

The investigation was conducted through semi-structured interviews with 28 multidisciplinary CED practitioners. The questions given covered the current CED practice in the company, the challenges faced, the efforts that the company had done to address the challenges, and improvement suggestions towards the current CED practice.

The interviews were conducted in three phases, dispersed over one year. The detailed structure of the interview can be seen in Appendix 2: Interview structure. The interviewee profiles are outlined in Appendix 3: Profile of IP-1. Each interviewee is assigned with a code for identification, used throughout the thesis, for anonymity reasons, as required by the interviewee. This identification code for each interviewee can also be found in Appendix 3: Profile of IP-1.

Company background

As mentioned in Chapter 1, Company 1 is a UK-based company, specialising in the design and manufacture of complex technical systems within the shipbuilding industry. The company can be categorised as an ETO company (see Section 1.1) whereby the customer has a relatively high influence towards the design process and outcome.

Due to the complexity of the technical systems in Company 1, the design projects typically last for more than five years and involve more than 500 multidisciplinary participants located in three different cities around the UK.

Company CED practice

The challenges, improvement strategy, and suggestions for improvement are presented respectively.

Challenges

As mentioned by several interviewees (e.g. INT-2, INT-4, INT-5, INT-12, and INT-26), the design process in Company 1 is structured into two main stages, where each stage has deliverables that influence subsequent stages. The first stage focusses on concept design, while the second focusses on detailed design. The design teams are divided based upon these stages. While this is considered effective for task distribution, it has been acknowledged as a trigger for a number of challenges in the company's CED practice.

Firstly, it triggers the *working-in-silos* behaviour (as discussed by INT-12, INT-18, INT-27, and INT-28). That is, the mentality of focusing on achieving the individual's task only, ignoring the tasks of others and how their own task inter-relates with the tasks of others. As CED participants are only concerned about their own task and not aware of the tasks of others, they become segregated and the communication with other participants, particularly those from different teams, is lacking, leading to disintegrated design (INT-3; INT-8). *Working-in-silos* behaviour was perceived as the major contribution towards the high percentage of redesign, the main concern of the company (INT-5; INT-15; INT-26).

It is believed that, among other factors, the behaviour of people is one of the key factors that determine the success of a CED process (INT-7). Without the improvement of this behaviour, other improvement strategy might not work. As INT-7 stated, "You can put tools in place, but at the end, it's really about people's behaviours". INT-3 and INT-17 pointed out how behaviour is often underestimated as an influencing factor by the participants and this lack of behaviour awareness can be seen from how the participants interact with one another during the design process (INT-3).

Secondly, the way the design team is divided at different stages also leads to differences in priorities (INT-1; INT-3; INT-4; INT-25; INT-26). For example, the design teams in Stage 1 prioritise their work on the functional design, while the design teams in Stage 2 prioritise their work on the spatial design (INT-3). When these priorities are not aligned, there is a potential for conflict (INT-10; INT-27). Conflict often negatively influences the relationship between the CED participants (INT-2; INT-26).

The dispersed location of the participants was also indicated as a challenge in the company's CED process (as implied by INT-3; INT-8; INT-14). As the participants are physically separated, it affects their communication behaviour. INT-18 remarked, "You need to actually, physically make the effort to go there and they [other team members] need to make effort to come up here" and consequently, people favour indirect communication through email (INT-2; INT-27; INT-28). However, the participants suggested that with email, misunderstandings and lost information could potentially arise (INT-7; INT-13; INT-14). When these issues occur, the relationships between the participants are often affected (INT-5). Furthermore, the dispersed location of the participants also leads to segregated relationships. As INT-6 remarked, "if you are split across many sites it is easy for teams to be segregated rather than integrated".

The segregated teams also lead to dis-integrated tools in the sense that different teams use different tools that do not integrate with one another (INT-6; INT-11). Consequently, different formats of information are often produced, causing confusion amongst team members. This is exacerbated with the *work-in-silos* behaviour (INT-8; INT-12). For example, Team A needs information in electronic format from team B as an input for their calculation. However, Team B produced the information in a handwritten format. Because Team B is not aware of Team A's needs, the information that Team B provided cannot be directly used by Team A. Further effort is therefore needed. This can eventually lead to frustration and affect the relationship between the teams (INT-16)

As mentioned in the Company Background, the company's customers highly influence the design process and the technical system being designed. However, the information exchange between the company and the customers was considered ineffective, i.e. mainly done through email. Due to this, information loss and misunderstanding often occurred, again, leading to redesign (INT-1).

In the company, new processes for undertaking work emerged overtime. INT-9 remarked that such changes created frustration for "people [design participants] who are doing it" (INT-9). Process changes often resulted from problems and difficulties identified in the past. However, instead of improving the process, the company tended to change the process entirely, often without withdrawing the former process (INT-11). Consequently, different team members create their own processes for practicality reasons (INT-10).

Improvement strategy

Four improvement strategies to address the challenges in the company's CED practice were derived from the interviews.

The first strategy was the development of an integrated system to enhance information sharing and disintegrated tools, challenges aforementioned.

The second strategy was to apply a policy called "information maturity" to: 1) ensure that CED participants have a shared understanding towards the level of information maturity

(INT-15; INT-26), and 2) to ensure that the information exchanged is mature, with minimum potential changes having to take place (INT-1’ INT-19; INT-22; INT-27). This strategy is done to mitigate the potential of redesign.

One of the causes of redesign as aforementioned is the ineffective information exchange between the designers and their customers (who are very influential in the design process) (see Company Background). To address this, the third strategy was suggested – to place the customers in the company’s premises for the duration of the design project (INT-9; INT-25). This allows customers and designers to interact on a daily basis and resolve any issues more effectively. INT-9 remarked, “Having customers interacting closely with the designers reduces the design change and rework.”

The fourth strategy to address the challenges in the company’s CED practice was the development of a state-of-the-art virtual reality based application to facilitate the interaction between distributed participants (INT-22). The platform generates realistic images of the technical systems being designed, allowing the distributed participants to interact with the same technical systems, and manipulate them in a synchronous manner (INT-22; INT-25). The platform is primarily used during the second stage of the design process (i.e. detailed design stage).

Improvement suggestions

Three improvement suggestions were garnered from the interviews.

The first suggestion identified was to balance soft skills (e.g. communication, negotiation, working in team) with hard skills (e.g. engineering skill). This can be achieved through several possibilities, such as increasing soft-skill development training (INT-3; INT-6) and using this training as a key performance indicator (INT-12; INT-18). According to INT-7, soft skill development training was only given to CED participants at the managerial level. Consequently, they appeared to be more aware of the importance of behavioural aspects compared to the participants sitting at the non-managerial level.

The investigation revealed two factors that can influence the behaviour of the participants. The first is the personality of the individual (INT-6; INT-9; INT-10; INT-11; INT-13; INT-18; INT-20). For example, an individual with an introverted personality tends to communicate only when required. The second factor is the structure of the design process, as discussed in the Challenges section. While it may be difficult to alter personality, altering external factors such as the structure of the design process may be easier. Changing the structure of the design process emerged as the second suggestion for behavioural improvement (e.g. INT-12).

Several interviewees remarked that the design process in the company is complex (INT-5) and frequently changes (INT-9). These conditions have created confusion among the design participants, particularly because an updated clear guideline is unavailable (INT-3; INT-18). The third suggestion was therefore to create a clear guideline that covers the design process from start to finish (INT-4; INT-5; INT-9; INT-10).

Summary

This appendix has provided findings from an investigation into CED practice. The investigation was conducted in Company 1, where 28 CED participants were interviewed. Findings were presented with respect to the company's CED challenges, improvement strategy to address the challenges, and improvement suggestions derived from the interviews. In Table 70, the challenges, improvement strategy, and improvement suggestions are outlined.

The following points summarise the findings:

- Nine inter-related challenges were identified, six of them can be categorised as social (highlighted in grey) and, three as technical.
- Four improvement strategies were found. One of them was aimed at addressing social challenges, and three at addressing technical challenges. In addition, one strategy can be viewed as being social (highlighted in grey).
- Three improvement suggestions were derived from the investigation. Two of these suggestions were aimed at addressing social challenges, and one at addressing the technical challenge. Additionally, one suggestion can be perceived as being social (highlighted in grey)

Table 70 Summary of findings from the industrial investigation

Challenges	Improvement strategy	Improvement suggestions
Work-in-silos behaviour	-	Change the stage-based structure of the design process
Priority differences	-	
Segregated relationship	-	-
Lack of face-to-face interaction	Virtual reality	-
Location differences		-
Lack of awareness on the importance of behavioural aspect	-	Balance soft skill and hard skill development

Disintegrated tools	Integrated systems	-
High percentage of redesign	Information maturity	-
	Embedding customers in the company's design process	
Continuous process change	-	Clear design process guideline

As can be seen from Table 70, while most of the challenges identified in Company 1's CED practice can be considered as social challenge, most of the improvement strategy was done to address the technical challenge. Only one strategy was applied to address social challenge. This strategy, however, can be considered as technical (e.g. development of tools). In this sense, it can be viewed that there is a lack of awareness on the social elements of CED in Company 1. The improvement suggestions given by the interviewees echoed this argument. Three suggestions were identified. Only one of the three suggestions can be related to the social elements of CED (highlighted in grey). However, the interviewees believed that to improve the company's CED practice, the social challenges need to be addressed, and thus, two of their suggestions were for addressing social challenges. Based on these points, it can therefore be concluded that there is a need to increase the company's awareness towards the social elements of CED.

Appendix 2: Interview structure

The interview stages and the aim of each stage are outlined in Table 71 and explained subsequently.

Table 71 Stages of interview

	Participants number	Aim
Stage 1	1	Engage with the company; Understand the company's design process and challenges in their collaborative design practice.
Stage 2	3	Test the structure of interview, type of questions, and timing (Pilot study); Identify collaborative design practice in the company, pros and cons, and improvement suggestions; Identify socio-technical elements of CED and their inter-relationships.
Stage 3	24	Identify collaborative design practice in the company, pros and cons, and improvement suggestions; Identify socio-technical elements of CED and their inter-relationships.

Stage 1

The first stage of interview was considered a preliminary study, with the main intention to engage with the company and gain a better understanding on the company’s CED process. For this, the interviewer (i.e. the researcher) asked the interviewee to explain the profile of the company such as the company’s organisational structure, how the CED process is conducted, and the challenges therein. An interviewee was selected by the industrial supervisor. The interviewee was an engineering designer who had worked in the company for more than 25 years, and had been involved in CED practice for more than 15 years. Thus, the interviewee was considered competent to provide reliable information on the company’s profile and CED process.

Stage 2

The second interview stage was intended as a pilot study to test the structure of the interview, the type of questions, and the timing. This stage was also conducted to gain insights on the company’s collaborative design practice in a more detailed sense. The interview was planned for a maximum duration of 60 minutes per person. This duration was set considering the participants workload, based on the discussion with the interviewee in Stage 1.

The interviewees consisted of one customer and two engineering designers, have managerial role, and directly involved in the company's CED practice for more than 20 years. They were selected by the industrial supervisor as they were considered having enough experience to provide insights on the company's CED practice. Additionally, they were selected to provide multiple perspectives, i.e. a customer was selected to provide external perspective, while engineering designers internal, to mitigate subjectivity.

The structure of the interview and duration is shown in Table 72.

Table 72 Interview structure

Duration (minutes)	Activity
5	Ice breaking
5	Briefing
45	Collaborative design-related questions
5	Closing

1. Ice breaking
   According to Silverman (2011), ice breaking establishes rapport and builds trust between the interviewer and interviewee. Thus, it is considered important to be conducted. For this, non-work-related conversations were initiated by the interviewer.
2. Briefing
   As suggested by Kvale (2007), briefing is important to introduce the interview and set the "nuance". In here, the interviewer briefly explained the overall study, the purpose of the interview, and the role of the participants. Additionally, the interviewer asked for the interviewee's permission on the use of an audio recorder. A consent form was given to the interviewees to sign that stated they are willing to participate and to be recorded.
3. Collaborative design-related questions
   The purpose of the interview was to gain a deeper understanding on the company's collaborative design activity, its pros and cons, and the participants' improvement suggestions, from socio-technical viewpoints. These became the main themes of the interview. A set of general open-ended questions based on these themes were prepared as a guideline only (see Figure 88). Since the study was exploratory

(Chapter 2), it was deemed essential to allow the interviewees exploring their insights on the subject with minimum intervention. Giving open-ended questions can facilitate this. As Kvale (2007, p.12) remarked, "Through open question, the interview focuses on the topic of the research [i.e. socio-technical CED]. It is then up to the subjects [i.e. the interviewees] to bring forth the dimensions they find important by the theme of inquiry."

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DEPARTMENT OF DESIGN, MANUFACTURE & ENGINEERING MANAGEMENT

LIST of QUESTIONS for Company 1

Collaborative engineering design process - elements

1. Who are the participants in collaborative engineering design process?

Social aspects

2. What are the social aspects of collaborative engineering design process?
3. How is the interaction between the participants?
4. How does roles and boundaries (policies) in the company? Does it affect the collaboration process?

Technical aspects

5. What are the technical aspects of collaborative engineering design process (tools, process management)
6. What have been done to manage the process?
7. Is there any tool to facilitate the collaboration design process? Does it work? What can be done better?

Collaborative engineering design process - performance

8. How do you measure the company's collaborative engineering design process performance? Is it good or not? why?
9. What works?
10. What have been the main challenges when collaborating? What does not work? What have been done to address these challenges?
11. What can be done to make the collaborative process better and in which area?

Figure 88 List of questions version 1

4. Closing

Kvale (2007) regarded closing as debriefing. At the end of the interview, the interviewer summarised the interview, and asked if the interviewee had any questions or concerns. In addition, the interviewer requested the interviewee to nominate other people to be interviewed.

Stage 3

The structure and type of questions of the semi-structured interviews were evaluated and refined based on the result of the pilot with the three participants. The following points summarise lessons learned from the pilot and the way they were addressed:

1. Ice breaking session

   Lesson: Ice breaking session tended to take longer than the allocated time and was not effective in building a rapport.

   How addressed: Eliminated the three-minute ice breaking session.

2. Personal information

   Lesson: Personal information of the participants (e.g. their current role in the company) was not asked. However, it was considered necessary for two main reasons: 1) to build rapport and trust (Kvale 2007; Silverman 2011), and 2) to identify the interviewees' background. From the pilot, it was seen that the interviewee's background influences their responses, and thus, can influence the result of the study. For example, the interviewees with management background could provide detailed information on the interaction between CED participants while the interviewees with only engineering background could not.

   How addressed: Allocated a five-minute session to inquire personal information, i.e. the interviewees' position; tenure (in the company and in the current project); roles and responsibilities; educational background; experience (i.e. past roles and responsibilities); and contact details (for verification and follow-up purposes).

Based on the above lessons learned, the structure of the interview was refined, shown in the following table (Table 73).

Table 73 Refined interview structure

Duration (minutes)	Activity
5	Briefing
5	Personal information questions
45	Collaborative design-related questions
5	Closing

3. Type of questions

   Lesson: Several questions were considered too direct (e.g. what are the social aspects of CED process). Such questions created confusion and required further elaboration from the interviewer. This could have potentially led to two outcomes: 1) the interviewer influences the interviewee's response; 2) the interviewee's answers are not aligned with the questions.

   How addressed: Refined the method of questioning. Instead of asking specific and direct questions, the interviewer started with general questions and built specific questions based on the interviewees' response. The refined set of questions can be seen in Figure 89.

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University of Strathclyde Engineering

LIST of QUESTIONS for Company 1

Version 2.1

Basic questions:

1. Position
2. Tenure (how long have you worked in the company)
3. How long have you worked on this project
4. Roles & responsibilities in this project
5. Education background – major, latest education (bachelor, master, PhD)
6. Past experience and position

General questions:

1. Can you explain how people working together to design the warship (especially type 26)?
2. What are the main challenges in working together?
3. What has been done to address the challenges?
   Does it work?
   What do you think needs to be done to address the challenges?
4. Is there any guideline or SOP to organise how you work together?
   Does it work?
5. What do you think can be improved?
6. Can you suggest people that I could talk to? I am aiming to have equal distribution of people from different areas.

Figure 89 List of questions version 2

4. Interviewees profile

   Lesson: The result from the pilot study indicated that the interviewees have only a general insight of the company's collaborative design activity. This might be influenced by their managerial position, and as such, their involvement in the collaborative design practice can be considered semi-direct (i.e. their role is on the decision-making level). As a result, for a multi-perspective point of view, interviews with collaborative design participants from non-managerial level were needed.

   How addressed: Requested to the company for interviewees from non-managerial level, who directly conduct collaborative design activity daily.

At this stage, the first five new interviewees were nominated by the pilot study interviewees. The remainder of the interviewees were obtained using the same peer-nomination approach. Twenty-four interviewees participated at this stage.

Appendix 3: Profile of IP-1

Table 74 outlines the role and number of years' experience in collaborative design practice, of each interviewee.

Table 74 List of interviewees

Code	Role domain	Years of experience
INT-1	Customer	20 years
INT-2	Project management	5 years
INT-3	Engineering	17 years
INT-4	Engineering	5 years
INT-5	Engineering	20 years
INT-6	Engineering	4.5 years
INT-7	Systems engineering	17 years
INT-8	Ship building	25 years
INT-9	Engineering	15 years
INT-10	Engineering	10 years
INT-11	Function management	1.5 years
INT-12	Engineering	17 years
INT-13	Function management	21 years
INT-14	Systems engineering	33 years
INT-15	Function management	6 years
INT-16	Supply chain	16 years
INT-17	Human Resource	11 years
INT-18	Engineering	11 years
INT-19	Engineering	20 years
INT-20	Engineering	25 years
INT-21	Function management	26 years
INT-22	Systems engineering	25 years
INT-23	Engineering	25 years
INT-24	Function management	20 years
INT-25	Project management	5.5 years
INT-26	Engineering	25 years
INT-27	Engineering	32 years
INT-28	Engineering	6 years

Collectively, the interviewees held approximately 464.5 years of experience, with an average of 17 years of experience. The detailed collective years of experience and average years of experience for each role are summarised in Table 75.

Table 75 Summary of total and average years of experience of the industrial investigation participants

Role domain	Total years of experience	Average years of experience
Customer	20 years	20 years
Engineering	232.5 years	17 years
Function management	74.5 years	15 years
Human resource	11 years	11 years
Project management	10.5 years	5 years
Ship building	25 years	25 years
Supply chain	16 years	16 years
Systems engineering	75 years	25 years
Total	464.5 years	17 years

In the following table, the responsibilities of each role outlined above are described.

Table 76 Description of the interviewees' responsibility based on their role

Role domain	Responsibility
Customer	Convey design requirements and constraints, approve or reject the design.
Engineering	Conduct design project and design according to design requirements and constraints.
Function management	Lead functional department (i.e. outside the design project) and assign their resources to project if require.
Human resource	Support project manager to manage the people of the project
Project management	Lead project (of designing) and ensure that the project (of design) runs according to plan (e.g. schedule and cost).
Ship building	Realise the design into product.
Supply chain	Mediate communication between supplier(s) and engineering designer(s).
Systems engineering	Resolve technical challenges in design process (e.g. design integration).

Appendix 4: Coding and condensing example

Transcription	Code	Condensation
I: How would you describe how people are working together in terms of designing type xx?		
INT-18: Is this a, are you looking for an understanding of process or, I'm just wondering is it my opinion or an overview of process you're after?		
I: Well, both.		
INT-18: Okay. So, in terms of working together, pretty much all disciplines. There are, it's so big, it is a big question, I'm trying to think where's the best place to start umm.. We are responsible[1] for ensuring… this is the engineering's role[2], we're supposed to ensure that the supplier[3] can deliver something that is of quality[1], for example.	1 – Responsible 2 – Role	Engineering's responsibility attached to engineering's role
There's a lot of process instructions[3] in this business exist to provide guidance on a design process. But it doesn't give you guidance on how to behave or how to work, so it gives you guidance on steps to follow.	3 – Guideline 4 – Behaviour	No guidelines to behave
So, there are some steps to follow there with regards to processes and interfacing, creation of certain documents etc. But type xx once again, we go through reinventing the wheel on a lot of processes[5] or we take lessons learned from previous projects[6] and try and improve the process.	5 – Design process 6 – History	Learning from history leads to improved design process
I: Ok		
INT-18: But that's with regards to actually doing the work. Interactions, so I'm engineering[7], so we interact[8] with the supply chain[7], we interact with other engineering disciplines.	7 – Role 8 – Interaction	Human beings with role (i.e. engineering and supply chain) interact
I: Yes. Which team are you interacting the closest, the most?		
INT-18: It depends on the phase of the program. Up until detailed modelling[9] started, most of our interactions[8] were with supply chain[7] and other stage 1 engineering teams and the customer[10].	9 – Design process stage 10 – Customer	In a design process stage, human beings interact
Because we are working from a set of requirements[11], that say, the technical systems at high level, the technical system[12] needs to do this, and then from systems, the system needs to be able to deliver the following.	11 – Design requirements 12 – Technical system	Technical system is designed based on design requirements
So we13 work with[8] the customer[10] to ensure that they understand what the system looks like to deliver what they're asking for[11],	13 – Engineers	Engineers (from company 1) interact with

and then we have to work[8] with other engineering disciplines[13], to ensure that when I put a piece of kit in a compartment, nearly always it needs power[14], so do the electrical team know that I've put that in that compartment[15], have I told them[8] I need to put a piece of kit in there that requires a certain amount of power and can they provide that power[15]? If it's a big piece of equipment then it needs a seat or a mount to sit on[14], have I liaised with the structures team? So I need to liaise with them[8] to tell them that this large item needs a fixing arrangement to the deck[15].	14 – Interrelated 15 – Awareness	customer to deliver design requirements Engineers interact with other engineers Technical systems are interrelated Interaction creates awareness
I: Ok.		
INT-18: We take that and then we go to stage 2[9] with it, which are the modelling guys, which is what we call stage 2 here. The detailed modelling team and we say well here's the drawing of the items, and we've calculated we need these systems connected to it etc. can you fit it in? [16] Can you fit it into the 3D model17 and make it work for us?	16- Detailed modelling 17 – 3D model	Desain process stage consists of detailed modelling
I: Ok.		
INT-18: But now we add to that, the CAD modelling guys, because we're creating the 3D model[17] of the technical system[12], so that's another big interface that's added in.		Technical system is represented to a 3D model
That with regards to interaction with them, again it's not, there's not a defined process and a lot of the behaviours[4] involved in that have, are intended to be best practice, I mean good engineering behaviour with regards to if we need to change something we notify them[8], because we're not on a firm change control at this stage. That relationship is more difficult when formal change control isn't part of the process. When that comes into the process, then you know there is an official notification. Up until that point the interaction, the dialogue right now between us and the modelling guys, is key.		Good behaviour is communicating changes
I: Okay.		
INT-18: That we're having that go look see what's in the model[18]. Say for example combat systems need to rearrange a certain area of the technical system, therefore we need to rearrange the vent for that area, which means that what we've already given the modelling guys, is going to change. Therefore, we need to tell them, and they can make the judgement call, do they want to proceed with what they are doing, or do they stop?[19]	18 – Design review 19 – Design decision	Design review leads to design decision
I think a lot of this communication is informal[20], although there's processes captured.	20 – Informal communication	
I: Is there any other way to communicate?		

INT-18: A lot of it, i mean, we have regular meetings[21] with them, and the e-mail and phone[22]. The regular meetings are intended to give advanced notice, advanced warning, make them aware of what we're dealing with. The e-mail tends to be, we run this kind of register at the minute, which captures the following needs to change feeding back from the modelling guys, they're saying we can't fit in what you've given us, can we change it to the following? And we take a look at that, and we go, okay great, fine, yes, no problem, we can do that, sign in that line, on the spreadsheet, and say that's an agreement that we'll capture in the next update. And then we build up the spreadsheet which is a record of agreements, you know, when communication and stuff about their problem, what was the resolution it's captured on the spreadsheet.	21 – Meeting 22 – Communication tools	Communication can be done through meetings and through communication tools
I: Okay.		
INT-18: There's regular meetings[21], everybody is aware of what's going on[15], we capture the agreements, but it's the time to step back and look at it from an overall point of view that we don't have, regardless of others sometimes, you know it's worth, you need to take the hint to step back to look at it from a bigger perspective.		Meetings create awareness
I: I see. What about the relationship, how would you define your relationship with the four different teams that you mentioned? with stage 2, supplier, customer, and other stage 1 engineering team?		
INT-18: Those are the main ones, there are others, it could go out, it could be endless, the support team that's actually producing the big interfaces at the minute.		
I: Okay, and how would you describe the interaction difference, the dynamic?		
INT-18: It's very different between other stage 1 teams and stage 2 which are the modelling guys. It's very different there because, well I think that's because engineering is effectively split, and we split those teams[23] and define them as stage 1 and stage 2[9]. And because they're split and defined, there's almost, there is a handover and it becomes, it's not quite contractual but it becomes very contract, heading that direction, so it is seen as an official handover. They take it, they work it, any changes need following through a correct change process. I think it's quite a difficult relationship[24], because we're not all one. Stage 1 to stage 1[9]. If you manage to effectively interact a bit more casually[25] you	23 – Design team 24 – Relationship 25 – Informal interaction	Design teams are split based on the design process stage Design process stage hampers relationship Informal interaction affects relationship

might call it. And it's a more formal interaction[26] with stage 2.	26 – Formal interaction	
I: Okay.		
INT-18: And I think because we are physically split on site[27], it doesn't help. I think that relationship[24] is more difficult because this is seen as the stage 1 building, and down the yard, in the fitting out complex, it's where all the stage 2 guys are.	27 - Location	Location influences relationship
I: Ok.		
INT-18: So it's split. You need to actually, physically make the effort to go down there, they need to make the effort to come up here. It works, you know people do, do it, but if everybody was in the one location[27], I feel there would probably be, it helps, it makes for a better working relationship[24], because we've been there, my team was the only stage 1 team that was down in that building down the yard where stage 2 are now. We were down there for six months.		Location influences relationship
I: Ah, okay.		
INT-18: Maybe more than six months, and it's very difficult when you are physically isolated from the other teams.		

Appendix 5: Codes

Code	Definition	Theme
2D	Two dimensional type of model	Design information
3D	Three dimensional type of model	Design information
Affective	Emotion, feeling towards something	Human being
Age	A length of time a person has lived	Human being
Amount (of information)	Quantity of information	Design information
Assigned responsibility	Task required to fulfil that attached to the assigned role	Human being
Assigned role	Function in collaborative design practice or in the company as appointed by the company, often relates with hierarchical position	Human being
Asynchronous	Tools utilise for communication that occurs at a different time (e.g. email)	Tools
Awareness	Knowledge on something, the state of knowing of what other people is doing	Design process
Boundary	Acts/objects that regulate or restrict relationship and the design of technical system	Boundary
Business type	The type of business that the company focusses into	Organisation
Calculation	Determination of amount	Tools
Cognitive	Relates to intelligence, knowledge, and way of thinking	Human being
Commercial minded	Concerned with commercial side of the design (such as profit, market)	Human being
Commitment	The state of being dedicated to collaborative design activities	Human being
Communication	Exchanging information between two stakeholders or more	Interaction Design process
Communication tool	A type of tools to exchange information between stakeholders	Tools
Complex	Having many elements with intricate dependencies among them	Technical system
Computer-based	Computer as the basis of operating technical tools	Tools
Conative	Behaviour, action or way of doing	Human being
Concept design process	The earliest stage of design process that focusses on identifying the basic conceptual design of technical system	Design process
Conflict	Disagreement, incompatibility	Conflict
Consistency	The state of being consistent (e.g. not containing contradictory information, each design team has the same information)	Design information Design process
Culture	Customs or habits embedded in human being	Organisation
Culture difference	Differences in customs and habits embedded in human being	Boundary
Customers	Buyers or potential buyers of the product	Human being
Decision making process	The process of making decision regarding the design of technical system	Design process
Delivery time	The time needed to deliver the product ordered	Human being
Design information	Information utilised as a basis to design technical system	Design information
Design problem	Issues related to the design of technical system	Design information
Design process	Process to design technical system	Design process
Design requirements and constraint	What needs to be included and/or excluded in the design of technical system	Design information
Design review process	The process to review the design of technical system by comparing the design against design information, and resolve design problem	Design process
Design specification	Translation of design requirements and constraints into technical specifications (e.g. speed, level of noise)	Design process

Detailed design process	The stage of design process where the focus is to specified concept design into physical integration of the design	Design process
Disintegrated design	The design of technical system where its components are not connected	Conflict
Distance	Length between two places	Boundary
Duration	Length of time	Design process
Engineers	Stakeholders who designs, deals with technical issues of the design	Human being
Employer	An organisation that employs someone	Human being
Experience	Being contact with something or have done something in the past	Human being
External stakeholder	Stakeholders who are involved in the collaborative design process, but employed by other companies	Human being
Form	A particular way in which design information exists	Design information
Formal	Interaction between stakeholders through official forms, that can be more structured, following specific rules, such as meeting	Human being
Function	The utilisation of tools	Technical tool
Gender	State of being male or female	Human being
Goals	Aim or objective of the collaborative design process	Human being
Guest	Not the owner of collaborative design practice, but participate and have influence in it	Human being
Guidelines	General rules of conducting something	Organisation
Hard-skilled	Engineering related skill	Human being
History	Past-events	Organisation
Host	Own the collaborative design practice, act as the main coordinator	Human being
Human being	The main actor who conducts collaborative design practice	Human being
Importance	The state of being significant	Design information
Influence	An ability to have an effect on something (i.e. design of technical system)	Human being
Informal	Interaction between stakeholders through unofficial forms, often in a relaxed environment, such as discussion during lunch time	Human being
Information system	System to organise, store, and communicate information	Design information
Integrated	Combined	Technical system
Interest	Wanting to know or learn about something (i.e. the design)	Human being
Internal stakeholder	Stakeholders who are involved in the collaborative design process, employed by Company 1	Human being
Interrelated	Connected with each other	Design information Technical system
Involvement	Participating in something (i.e. collaborative design activity)	Human being
Legislation	Law related with the whole life cycle of technical system (e.g. design, manufacture)	Organisation
Level of trust	The level of believe in someone else's reliability	Interaction
Location	Physical placement of an organisation	Human being Organisation Boundary
Measurement	A unit or system for measuring	Design process
Model	Representation	Design information
Nature	Basic features or character	Design information
New policy	A policy that is not existing before, triggered by different events such as conflict	Organisation
Non-engineers	Stakeholders who deal with commercial issue of the design	Human being
Non-work related (relationship)	Not relating with task assigned to stakeholders	Human being
Objective	Goal	Human being
Organisation	A group of people with purpose	Human being

Organisational culture	Customs or habits embedded in an organisation	Boundary
Parameter	Defines the scope of a particular process or	Design process
Performance	Level of success compare to predetermined objective	Human being Design process Technical system
Personal relationship	Relationship that is established through non-work related interaction	Interaction
Personality	A set of characteristics of an individual	Human being
Personality clash	Incompatibility of personalities between two human beings or more that potentially cause a conflict	Conflict
Policy	Principle of action adopted or proposed by the company	Organisation
Politics	All activities that relate to the acquisition of power	Organisation
Post-design process	Stage of design process where the design has been approved for production	Design process
Price	Amount of money required to pay the product	Human being
Priority	Things that perceived by human beings to be more important than other things	Human being
Product quality	Quality of product that can be measured by different factors such as compliance with specifications, reliability	Human being
Professional relationship	Relationship that is established through work-related interaction	Interaction
Relationship	The state of being connected	Interaction
Requirement	Something needed or wanted	Human being Design process
Risk	Possibility of unwanted event and/or outcome	Human being
Rules	Regulations that must be followed	Organisation
Satisfaction	Fulfilment of requirements	Human being
Social culture	Customs or habits embedded in the society	Boundary
Social conflict	Conflict related with the actors of collaborative design	Conflict
Socio-demographic	The profile of human being related to their demographic and sociological characteristics	Human being
Soft-skilled	Non-engineering related skill	Human being
Stage	Step in a process	Design process
Stakeholders	All human beings who are involved in collaborative design practice and affected any decision taken during the practice	Human being
Standardisation	A framework to which all relevant parties in the company requires to follow	Organisation
Strategy	Company's plan of action to achieve long-term aim	Organisation
Structure	The arrangement of authority, roles and responsibility	Organisation
Suppliers	The source from which the company order the part of the end product during post-design process	Human being
Synchronous	Tools utilise for communication that occurs at the same time	Tools
Team division	Division of team members into different groups	Human being
Technical conflict	Conflict related with the design of technical system such as disintegrated design	Conflict
Technical minded	Concerned with technical side of the design (such as function, behaviour, structure)	Human being
Technical system	Artefact, result of CED process, utilise as a basis of product realisation	Technical system
Technical tool	A type of tools to design technical system	Tools
Tenure	Duration of holding a position and/or role and/or responsibility in a company	Human being
Tool	Instruments and/or application that execute a particular function(s)	Tools
Trust	Belief in someone else's reliability	Human being
Type	Category of something with common characteristics	Interaction Tools Boundary Design information
Users	The ones who use the end product being design	Human being

Visualisation and representation	Depiction of design in different forms such as model	Tools
Work related (relationship)	Relating with the tasks assigned to stakeholders	Interaction
Zones	A physical area of the ship	Design process Technical system

Appendix 6: Relationships between codes

Condensation	Relationship type
Internal stakeholder interacts with external stakeholder	Interacts
Engineers interacts with non-engineers	Interact
Customers interact with users	Interact
Internal stakeholders manage risk	Manage
Internal stakeholders shares risk and goals	Shares
Personal relationship influences level of trust	Influences
Relationship hampered by conflict	Hampered by
Conflict motivates new policy	Motivates
Stakeholders belong to	Belong to
History changes strategy	Changes
Organisation creates policy, rules, and legislation	Creates
Organisation learns from history	Learns from
Relationship bounded by location	Bounded by
Technical system bounded by legislation	Bounded by
Culture difference cause conflict	Cause
Location leads to culture difference	Leads to
Design specification aid to identify design problem	Aid to identify
Design information exchanged by stakeholders	Exchanged by
Design information represented as model	Represented as
Design information stores in information system	Stores in
Design requirements and constraints translated into design specification	Translated into
Model utilised in design review process	Utilised in
Design information communicated through communication tool	Communicated through
Model created through technical tool	Created through
Communication tool facilitate communication between different location	Facilitate communication between
Design information processed through technical tool	Processed through
Technical system complies to design requirements and constraints	Complies to
Stakeholders design technical system	Design
Technical system influenced by technical conflict	Influenced by
Design review process consists of decision making process	Consist of
Design process influenced by new policy	Influenced by
Design process influenced by conflict	Influenced by
Concept design process reviewed in design review process	Reviewed in
Detailed design process reviewed in design review process	Reviewed in

Appendix 7: Categorisation of results from meaning coding

Element	Category		
	Main element	Sub-element	Property
2D			√
3D			√
Affective			√
Age			√
Amount (of information)			√
Assigned responsibility			√
Assigned role			√
Asynchronous			√
Awareness			√
Business type			√
Calculation			√
Cognitive			√
Commercial minded			√
Commitment			√
Communication			√
Communication tool		√	
Complex			√
Computer-based			√
Conative			√
Concept design process		√	
Conflict	√		
Consistency			√
Culture			√
Culture difference	√		
Customers		√	
Decision making process	√		
Delivery time			√
Design information	√		
Design problem		√	
Design process	√		
Design requirements and constraint		√	
Design review process	√		
Design specification		√	
Detailed design process		√	
Disintegrated design			√
Distance			√
Duration			√
Engineers		√	
Experience			√
External stakeholder		√	
Form			√
Formal			√
Function			√
Gender			√
Goals		√	

Guest			√
Guidelines		√	
Hard-skilled			√
History	√		√
Host			√
Human being	√		
Importance			√
Informal			√
Information system	√		
Integrated			√
Interest			√
Internal stakeholder		√	
Interrelated			√
Legislation	√		
Level of trust	√		
Location			√
Measurement			√
Model	√		
Nature			√
New policy	√		
Non-engineers		√	
Non-work related (relationship)			√
Objective			√
Organisation	√		
Organisational culture			√
Parameter			√
Performance			√
Personal relationship		√	
Personality			√
Personality clash			√
Policy	√		
Politics			√
Post-design process		√	
Price			√
Priority			√
Product quality			√
Professional relationship		√	
Relationship	√		
Requirement			√
Risk		√	
Rules	√		
Satisfaction			√
Social culture			√
Social conflict		√	
Socio-demographic			√
Soft-skilled			√
Stage			√
Stakeholders		√	
Standardisation		√	
Strategy	√		√

Structure			√
Suppliers		√	
Synchronous			√
Team division			√
Technical conflict		√	
Technical minded			√
Technical system	√		
Technical tool		√	
Tenure			√
Tool	√		
Trust			√
Type			√
Users		√	
Visualisation and representation			√
Work related (relationship)			√
Zones			√

Appendix 8: Information modelling language review

The socio-technical architectural model of collaborative design was aimed at presenting the socio-technical elements of collaborative design and their relationships to understand its phenomena (as discussed in Chapter 5). A model that presents elements and relationships of a domain (i.e. collaborative design) to gain a better understanding of the domain may be generally categorised as an information model (Kahn *et al.*, 2001). To develop an information model, a modelling methodology is considered necessary (Lee, 1999). According to Lee (1999), modelling methodologies generally consist of three approaches with different focus. The approaches are: 1) entity-relationship (ER) approach, 2) functional modelling approach, and 3) object-oriented (OO) approach. The differences between these approaches are summarised in Table 77.

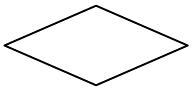
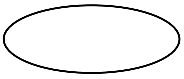
Table 77 Comparison of information modelling approaches

Approach	Focus
ER	Describing information requirement (i.e. the information considered important in the system being represented) (Lee, 1999) Structure (i.e. elements and their relationship) of information (Shoval, 1997)
Functional	Describing flow of information from one process to another (Lee, 1999)
OO	Describing both, information requirement and flow of information (Lee, 1999) Behaviour of the system being represented (Shoval, 1997)

The focus of the model is to present socio-technical elements and their relationships, as they were considered important in collaborative design process (see Chapter 3). Based on the definition given by Lee (1999), socio-technical elements and their relationships may be regarded as an information requirement. That is the information that needs to be presented in the model. From the aforementioned focus of the model, it can be seen that the architectural model is focussed on describing an information requirement. As such, ER was considered the most appropriate to develop the architectural model of collaborative design compared to the other approaches listed in Table 77.

The language utilised in the ER approach may be identified as Entity Relationship Diagram (ERD) language. According to Song et al. (1995, p.2), “The ERD views that the real world consists of a collection of…entities, the relationships between them, and the attributes used to describe them”. As such, the basic structure of ERD consists of entities, relationships, and attributes. ERD uses graphical notations to represent its basic structure, initially developed by Chen (1975), as shown below:

Table 78 Graphical notation of basic ERD

Graphical notation	Name	Definition	Examples
	Entity	A thing with independent existence	a car, a person
	Relationship	Connection between two entities	A person owns a car. "Own" is a relationship that connects a person and a car
	Attribute	A property of entity or relationship that characterises them	Colour of a car, name of a person

An entity may be defined as a thing with independent existence (Elmasri and Navathe 2011), or more simply, as an object (Song, Evans and Park, 1995). Examples of an entity are a car, a house and a person. In ERD, an entity is represented as a rectangle with a given name, usually a noun (Pol and Ahuja 2007).

A relationship may be viewed as a link between entities (Song et al. 1995; Elmasri and Navathe 2011; Ou 1998). Relationship is represented as a diamond with a given name, usually a verb (Pol and Ahuja 2007). Relationship in ERD is bi-directional (Elmasri and Navathe 2011).

An attribute may be defined as a property of an entity (or a relationship) that characterises or describes said entity (Song et al. 1995; Elmasri and Navathe 2011). An attribute is represented by an ellipse in ERD. An attribute may become an entity if their existence and relationship with other elements of the model affect the description of the system. An attribute can be composed of smaller parts, regarded as sub-attributes.

In the context of the study documented in this thesis, the elements of CED practice may be regarded as entities, while the properties of elements may be regarded as attributes.

An example of ERD structure is depicted by Figure 90.

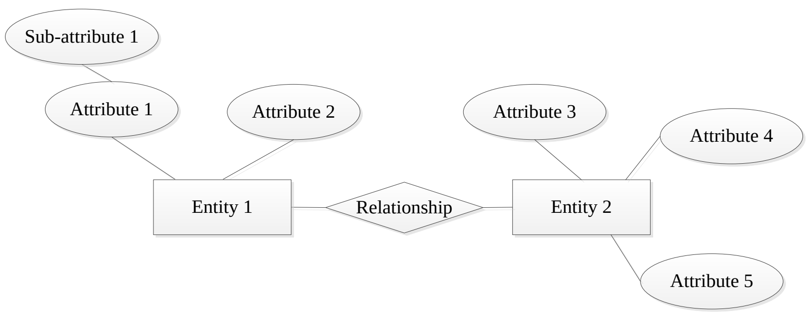


Figure 90 Entity Relationship Diagram

As can be seen above, the basic structure of ERD only represents elements (i.e. entities). It does not differentiate between main elements and sub-elements. For this reason, the enhanced concept of the entity-relationship (EER) approach was explored.

In EER, the relationship between an entity and its sub-entities may be regarded as a superclass/subclass relationship. This is also recognised as an "ISA" relationship (Silberschatz, Korth and Sudarshan, 2011) or generalisation/ specialisation relationship (Song, Evans and Park, 1995). Three versions of graphical notations that represent the superclass/subclass relationship were identified from literature. In several notations, the way the superclass/ subclass relationship is represented "…depends on whether an entity may belong to multiple specialised [i.e. sub-] entity sets [i.e. overlapping] or to at most one specialised [i.e. sub-] entity set [i.e. disjointed]" (Silberschatz et al. 2011, p.296). In this thesis, overlapping and disjointed are regarded as the type of superclass/ subclass relationship. Because of this difference in superclass/subclass representation, the three identified versions of notations were compared based on two things: 1) the way they represent the superclass/ subclass relationship, and 2) the way they represent the type of superclass/ subclass relationship. The notations are summarised in Table 79.

Table 79 Graphical notations representing generalisation/ specialisation hierarchy

Authors	Notations	
	Superclass/subclass	**Type of relationship**
Batini (1992)	Directed arrow	N/A
Elmasri and Navathe (2011)	A circle labelled with the initial of the type of relationship	• "d" label showing disjointed • "o" label showing overlapping
McFadden et al. (2001)	A round box labelled with "IsA"	Arch showing disjointed
Silberschatz et al. (2011)	Directed arrow(s)	• A single arrow showing disjointed • Two separate arrows showing overlapping

From the above table, it can be seen that two authors (i.e. Batini 1992 and Silberschatz et al. 2011) represent the superclass/subclass relationship with directed arrow. This was considered inappropriate, as an arrow may not be clearly visible in the model and thus, can potentially create confusion. McFadden et al. (2001) utilised two separated notations to show the superclass/subclass relationship, and its type of relationship (i.e. arch to show disjointed relationship). This was considered ineffective, can potentially create a cluttered model with too many notations, and thus, can be difficult to understand. On this basis, the notations developed by Elmasri and Navathe (2011) were selected to develop the model.

As described in Table 79, Elmasri and Navathe (2011) used a circle notation labelled with the initial of the type of relationship between an entity and its sub-entities. In Table 80 these notations are listed, defined, and their utilisations exemplified.

Table 80 Additional graphical notations of EER Diagram

Graphical notation	Type of relationship	Definition	Examples
d	Disjoint	An entity can only be a member of one subclass	A person can only be a member of one gender (i.e. a man or a woman)
o	Overlap	An entity can be a member of more than one subclasses	A person can be a member of more than one roles in a family (i.e. a parent and a child)

Additionally if an entity consists of a single sub-entity, circle notation is not utilised and the relationship between them is represented by a single line (Elmasri and Navathe 2011).

One thing needs to be noted concerning the utilisations of EER in developing the model. The application of EER in the study was to provide a formal language in the development of the architectural model solely. For this reason, the notations of EER were selected and adapted as needed. For example, representing different types of attribute (e.g. key attribute, multivalued attribute, and derive attribute), different types of entity (e.g. strong and weak), and different types of relationship between entities (e.g. partial or total) was considered unnecessary to model collaborative design practice. Thus, these notations were not applied.

Appendix 9: Example of printed model for W1 and W2

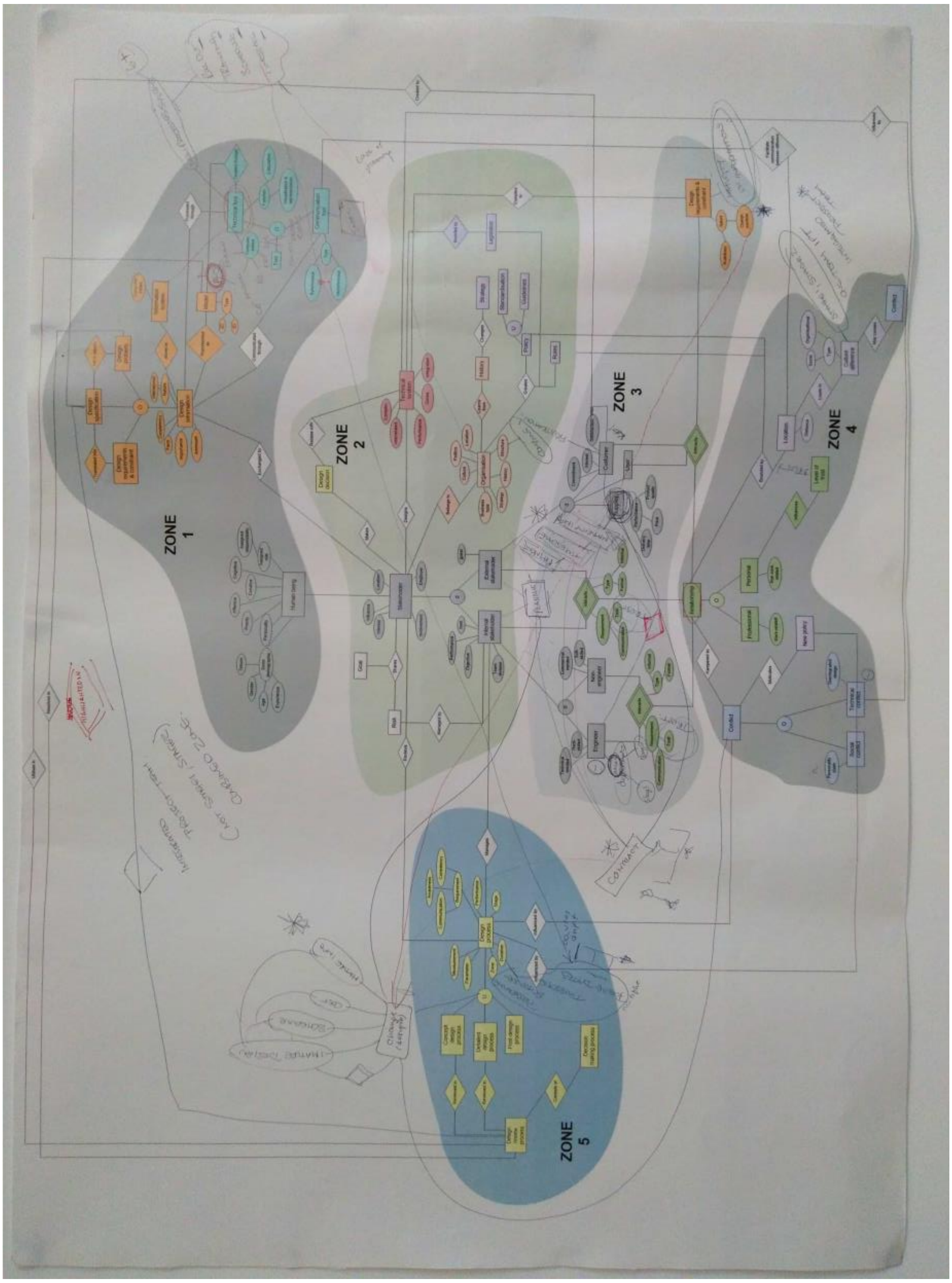


Figure 91Example of printed model

Appendix 10: Profile of workshops participants

Appendix 10.1: Profile of W1 participants (IP-2)

Table 81 Position of the participants in the company

Position	Number of participants
Manager	3
Non-manager	4
Unknown	1

Table 82 Participants experience in the company

Years of experience in the company	Number of participants
0 - 10 years	3
> 10 years	4
Unknown	1

Table 83 Participants experience in the current position

Years of experience in the current position	Number of participants
0 - 10 years	5
> 10 years	2
Unknown	1

Appendix 10.2: Profile of W2 participants (ED Academics)

Table 84 Profession of the participants

Profession	Number of attendees
PhD Student	8
Others (researchers, lecturers)	6
Unknown	6

Table 85 Research field of the participants

Research field	Number of attendees
Engineering design process	3
Design theory	2
Collaborative design	3
Product development	2
Innovation	3
Management	1
Unknown	6

Table 86 Duration in the field

Duration in the field	Number of attendees
0 - 2 years	6
2 - 4 years	2
4 - 6 years	3
above 6 years	3
Unknown	6

Appendix 11: Review on the applicability of the feedback

Appendix 11.1: Concept of the model

#	Feedback	Review	Premise		Conclusion
CO1	The purpose of the model needs to be clearly articulated.	The participants explained the importance of knowing the purpose of the model to determine the type of model needs to be constructed. This is considered the justification of the feedback. According to them, the purpose of the model was not clearly articulated and thus, it created confusion when reviewing the model. As discussed in Chapter 1 and Chapter 5, the main purpose behind the model development was to understand a phenomenon of CED activity from socio-technical perspective. This aim had been identified since the preliminary investigation to develop the model (Chapter 6) as the importance of having an aim in model development has been recognised. This makes the feedback aligned with the research approach. However, during the workshops, the purpose was not clearly articulated in the opening presentation, which was pointed out by the participants in W2. A better verbal articulation of the model development's purpose was deemed necessary when presenting the model.	Feedback is justified and aligned to research approach	P1	Applicable
CO2	The model concentrates on the social side. The technical side needs to be investigated more.	The participants in W2 argued that the model concentrates on the social side as there are more social elements than the technical ones. However, the model was developed with no intention to focus on one side solely. It was developed based on the result of preliminary investigation (i.e. literature) and industrial investigation (i.e. practitioners). The result reveals more social than technical elements of collaborative design activity. This can be perceived as findings that can contribute to the knowledge of CED, rather than room for improvement of the model. For example, CED activity seems to consist of more social than technical elements yet studies tend to focus more on the	Feedback is not aligned to research findings	P3	Inapplicable

		technical side. Applying the feedback can potentially lead to bias as they are not aligned with the research findings			
CO3	The model concentrates on the fragmented social and technical elements. The connection between social and technical elements needs to be investigated more.	The participants argued that the social and technical parts appeared to be fragmented. They believed that the inter-relationships between social and technical elements were lacking. Thus, they suggested to investigate the inter-relationships in a more detail sense. However, the inter-relationships between different elements (i.e. social-social, social-technical, and technical-technical) have been shown in the model based on the result of the industrial findings. For example, design information (i.e. technical element) is inter-related with stakeholders (i.e. social elements). On this basis, it was argued that the model already concentrate on the interrelationships between socio-technical elements.	Feedback already applied in the model	P4	Inapplicable
CO4	Apply different approaches to develop the model (e.g. direct observation)	The participants commented that using different approaches to develop the model will increase the model's quality and mitigate potential bias. A variety of approaches and sources of information have been investigated and planned to enhance the model's representativeness. Conducting the workshop is an example of one approach as an addition to interview.	Feedback already applied in the model	P4	Inapplicable
CO5	Reduce the model's complexity to make it easily understood	The complexity of the model has been mentioned as one of the biggest concern of the participants from both workshops. They mentioned that the model took more than 10 minutes to be understood due to its complexity. As the model is developed to provide a better understanding on a phenomenon of CED activity (Chapter 1), it needs to be constructed in a way that can be	Feedback is justified and aligned to research approach	P1	Applicable

		easily understood. This makes the feedback aligned with the research approach. For this reason, presenting the model in a different level of details was considered.			
CO6	Organise the model based on its purpose.	The participants argued that the model immediately appears to aim at representing human being as it is located at the centre of the model. Thus, they suggested to re-organise the model based on its purpose. The model was a result from applying ERD, a formal information modelling language, and arranging the elements based on the nature of the relationships between the elements. For example, "human being" was naturally placed in the centre as it has relationships with almost all other elements of CED. The main purpose of the model was to present socio-technical elements and their interrelationships. As the model was organised based on the relationships between the elements, it can be viewed that the model has been organised based on its purpose.	Feedback already applied in the model	P4	Inapplicable
CO7	Ensure the consistencies of attributes	The participants brought up the inconsistencies of attributes. They mentioned that it is unclear how an element was considered as an attribute. They believed that this unclarity was the main reason why the attributes seemed inconsistently chosen. Having briefly evaluated the attributes of the model based on the feedback from the participants, inconsistency in the concept of attributes was acknowledged. For example, several attributes were perceived not describing an entity (e.g. host), instead, it describes the value of an attribute (i.e. function). This makes the feedback aligned with the findings from evaluation. For this reason, the concept of attributes in ERD was revisited and the new understanding was used as the basis to review overall attributes presented in the second version of the model.	Feedback is justified and aligned to research findings	R1	Applicable

CO8	Add arrows as bi-directional relationships are not intuitively understood	In the concept of ERD, the directions of relationship between entities are bi-directional, and thus, there is no need to show the direction in the model. This was also applied to the model as it used ERD as its formal modelling language. However, the participants from the workshops commented on the unclear direction of relationship between entities. It becomes apparent that arrows need to be added to enhance the clarity of the model. As mentioned in Section 7.1.4, the concept of ERD is utilised for a formal information modelling language solely. It needs to be adapted in accordance to the purpose of the model development, i.e. to facilitate a better understanding on CED activity. On this basis, if adding arrow can enhance the clarity of the model, which aligns with the approach of the research, then the model needs to be refined accordingly.	Feedback is justified and aligned to research approach	P1	Applicable

Appendix 11.2: Content of the model

Human being

#	Feedback	Review	Premise	Conclusion	Action
		Sub-entity			
HS1	Delete "engineer" sub-entity	Participants in W1 and W2 similarly agree that it is unnecessary to differentiate the role of engineers and non-engineers as the differences of role between them in CED is almost non-existence (i.e. only in technical matter). Thus, they suggested to delete "engineer" and "non-engineer" and only use "human being" to represent the participants of CED process. In the model, the main reason of distinguishing "engineers" and "non-engineers" was to show the influences of different roles in collaborative design activities. For example, it influences way of thinking (i.e. cognitive), way of doing (i.e. conative), and priority. However, the influence of role has been represented by the attributes	P1	Applicable	Delete "engineer" sub-entity

		of human beings. Thus, it was considered unnecessary to distinguish engineers and non-engineers in the model, aligned with the feedback given by the participants. Basing on this, the feedback was deemed applicable.			
HS2	Delete "non-engineer" sub-entity	Similar with the above argument (HS1), it was considered unnecessary to distinguish engineers and non-engineers in the model. For this reason, "non-engineer" is removed.	P1	Applicable	Delete "non-engineer" sub-entity
HS3	Refine subclass of stakeholder from "disjoint" to "overlap"	The disjointed relationship between stakeholders and its subclasses (i.e. internal and external stakeholders) meaning that a stakeholder can be an internal or external stakeholder, not both. This relationship was derived from the industrial investigation. The participants from W2 argued that a stakeholder can be both, internal and external stakeholder. However, this argument was considered weak, as an evident cannot be identified when asked to the participants. As such, the relationship between stakeholders and its subclasses remains unchanged.	P3	Inapplicable	Not refining subclass of stakeholders from disjoint to overlap
HS4	Refine subclass of external stakeholder from "disjoint" to "overlap"	The participants from both workshops similarly argued that there is a thin line differentiating "customer" and "user" in engineering design. They mentioned that customers and users are often represented as one entity and an external stakeholder can be a member of both, users and customers. Based on this, the relationship between external stakeholder and its sub-classes (i.e. customer and user) can be regarded as "overlapping". In the model, the relationship between external stakeholder and its subclasses was defined as "disjoint" based on the industrial investigation. As such,	P2	Partly applicable	Delete "users" Merge "customers" and "users" into one by refining the term "customers" into "customers and users"

		the participants suggested refining it.			
		As indicated from the industrial investigation, in most cases, the voice of user was represented by the customer (INT-2). Thus, they are often viewed as a single entity. This finding is aligned with the feedback from the participants. However, the industrial investigation indicated that user and customer are two separate organisations. As such, an external stakeholder cannot be a member of both, user and customer.			
		To show in the model that customers and users are two separate organisations, however, having one voice, they are merged into one entity, labelled as “customers and users”. This change is however different with the suggestions from the participants. For this reason, the feedback was deemed partly applicable			
HS5	Refine subclass of internal stakeholder from "disjoint" to "overlap"	This feedback is related with other feedback points (i.e. HS1 and HS2). In which, the subclasses of internal stakeholders, i.e. engineer and non-engineer, were deleted (see HS1 and HS2). Hence, this feedback was no longer relevant, and thus, and inapplicable.	P5	Inapplicable	Not refining subclass of internal stakeholders from disjointed to overlap
Attribute					

HA1	Add "technical background" as a sub-attribute of "experience"	The participants from W1 identified “technical background” such as past-experience as engineers, as an essential attribute of human being in CED activity. They suggested adding “technical background” as a sub-attribute of “experience”. However, this was indicated as a specific attribute required for recruiting engineers in Company 1. The influence of “technical background” in general CED activity was not evident. Furthermore, the influence of human being’s general background, not just technical background, has been represented by the attribute of “experience”. For these reasons, the feedback was deemed inapplicable	P3 P4	Inapplicable	Not adding “technical background”
HA2	Add "sub-contractor" as a sub-attribute of "employer"	Participants in W1 mentioned that in Company 1, CED participants consist of employees from Company 1 and also from other companies, recognised as sub-contractor. Thus, they suggested adding “sub-contractor” in the model. However, this may be specific to Company 1 CED practice merely. Whether sub-contractor exists in other CED practice or not was not identified. Participants from W2 for example, did not mention “sub-contractor” as a participant of CED process. Furthermore, sub-contractor describes a type of “employer”. In this sense, sub-contractor can be categorised as a value attribute, and thus, cannot be categorised as a sub-attribute (division) of “employer”. As mentioned in Section 8.5.1.2, value was not represented in ERD, and thus was not added in the model.	P3	Inapplicable	Not adding "sub-contractor" under "employer"
HA3	Add "feedback" as a sub-attribute of “involvement”	The participants from W1 mentioned the importance of customers feedback in their CED process and suggested to include them in the model. The industrial investigation suggested that stakeholders’ involvements can vary broadly, and giving feedback is identified as one of them. In this sense, feedback has been represented in the model, and thus, the feedback was considered inapplicable.	P4	Inapplicable	Not adding "feedback" as a sub-attribute of “involvement”

HA4	Add "mind" as an attribute of stakeholder, with the value of "commercial" and "technical"	The participants from W1 and W2 similarly suggested deleting “engineer” and “non-engineer” entity (as can be seen in HS1 and HS2). However, they agreed that stakeholders have different way of thinking. This, according to them, influences the CED activity. To show the differences on the way of thinking in the model, the participants suggested adding “mind” as an attribute of stakeholders with commercial and technical as its value. Lexically, the term “mind” may be defined as the ability to think and reason (The Oxford English Dictionary, 2013). “The ability of thinking” and “The way of thinking” are perceived different, as the first one represents skill and the second one represents activity. Furthermore, “way of thinking” was already represented by the term “cognition” in the model (as explained in Chapter 7). As such, it was not added.	P3 P4	Inapplicable	Not adding “mind” as an attribute of “stakeholder”, with the value of “commercial” and “technical”
HA5	Add "skill" as an attribute of stakeholder, with the value of "soft" and "hard"	The participants from both workshops similarly believe that stakeholders own different skills, which influence their behaviour, and thus, influence the CED activity. For this reason, they suggested adding “skill” as an attribute of “stakeholder” entity. In STAM-2, “Skill” was shown as an attribute of “engineer” and “non-engineer” entity in a specific manner, i.e. “hard skill” as an attribute of “engineer”, and “soft-skill” as an attribute of “non-engineer” (see Section 7.4.2.1). Both entities were eliminated based on the feedback from the participants (see HS1 and HS2). However, as indicated from the industrial investigation (Chapter 7) and the two workshops (Chapter 8), “skill” influences CED activity, and thus needs to be included in the model. Initially, “engineer” and “non-engineer” were defined as sub-classes of “stakeholders”. As they were eliminated, to include “skill” in the model, it was attached as an attribute of “stakeholder”, aligned with the feedback from the participants		Applicable	Add “skill” as an attribute of “stakeholder” entity

HA6	Add "stage" as a sub-attribute of "team division"	The participants in W1 indicated that in Company 1, the collaborative design teams are characterised based on two categories: the stage of the design process (e.g. concept design, detail design), and the area of the complex system, regarded as "zone". For this reason, the participants believe that "area (or zone)" and "stage" needs to be added as sub-attributes of "team division". However, based on the definition of attribute and value attribute, "area" and "stage" can be considered as value attributes as they describe the attribute, rather than the constituent of the attribute (sub-attribute). Based on the ERD concept, value is not shown in ERD model, which makes the feedback not aligned with the information modelling language used in the model (i.e. research approach). Based on this, the feedback was deemed inapplicable.	P3	Inapplicable	Not adding "stage" to "team division" attribute of "internal stakeholder" entity
HA7	Add "trust" as an attribute of "customer"	According to the participants of W1, the customer's trust to its supplier (i.e. Company 1) plays an important role in the CED activity. They remarked that trust can help to resolve disagreements between customer and supplier. As such, trust needs to be possessed by the customer of CED activity. Thus, the participants suggested adding "trust" as an attribute of "customer" in the model. From this perspective, adding "trust" is viewed as a prescription (to eliminate disagreement in) to CED. However, the purpose of developing the model is to describe the elements of CED activity rather than to prescribe the elements required for a better collaborative design activity. Based on tis, the feedback given was considered not aligned with the research purpose, and thus, inapplicable.	P3	Inapplicable	Not adding "trust" as an attribute of "customer" entity

HA8	Add "confidence" as an attribute of "customer"	Similar with the above (HA7), "confidence" was viewed by the participants in W1 as an attribute that required to be possessed by the customer in CED activity. The customer's level of confidence towards their supplier (i.e. Company 1) determines their relationship, and thus, can influence CED activity. For this reason, the participants believe that "confidence" needs to be added as a required attribute of "customer". However, as aforementioned (HA7), the purpose of developing the model was to describe rather than to prescribe, and therefore, "confidence" was not added as an attribute of "customer" entity.	P3	Inapplicable	Not adding "confidence" as an attribute of "customer" entity
HA9	Add "acceptance" as an attribute "customer"	Customer's acceptance towards the work of supplier (i.e. Company 1) is considered important by participants in Workshop 1. According to them, customer's acceptance can highly influence the time and money spent during the design project. Considering its importance, participants 1 believe that adding "acceptance" as an attribute that "customer" needs to possess is important. However, as mentioned above (HA7 and HA8), the architectural model developed and documented in this thesis is aimed to describe instead of prescribe. Furthermore, "acceptance" cannot be categorised as an attribute as it cannot be used to characterise customer. It may be viewed as a type of customer's involvement in collaborative design activity. Thus, "acceptance" is not added as an attribute of "customer" entity.	P3	Inapplicable	Not adding "acceptance" as an attribute of "customer" entity

HA10	Add "status" as an attribute of stakeholder, with value of "host" and "guest"	The participants in W2 suggested to group “host” and “guest” under one category, i.e. “status”. Lexically, status may be referred to position (The Oxford English Dictionary, 2013). In this view, being a host or a guest can be considered as a position of stakeholder in CED activity. However, in the second version of architectural model, being a “host” or a “guest” was referred to the function of stakeholders in CED activity as identified from the industrial investigation. This makes the feedback not aligned with the finding from the industrial investigation, and thus, inapplicable.	P3	Inapplicable	Not adding “status” as an attribute of “stakeholder”, with value of “host” and “guest”
HA11	Delete "technical minded", an attribute of "engineer"	As “engineer” was eliminated from the model (see HS1), its attribute, including "technical minded" was also eliminated from the model.	P5	Applicable	Delete "technical minded", an attribute of "engineer"
HA12	Delete "commercial minded", an attribute of "non-engineer"	Similar with the above analysis, as “non-engineer” was eliminated from the model (see HS2), its attribute, including “commercial minded” was also eliminated from the model.	P5	Applicable	Delete "commercial minded", an attribute of "non-engineer"
HA13	Delete "hard skilled" an attribute of "engineer"	As “engineer” was eliminated from the model (see HS1), its attribute, including "hard-skilled" was also removed from the model	P5	Applicable	Delete "hard skilled" an attribute of "engineer"
HA14	Delete "soft skilled" an attribute of "non-engineer"	As “non-engineer” was eliminated from the model (see HS2), its attribute, including “soft-skilled” was also eliminated from the model.	P5	Applicable	Delete "soft skilled" an attribute of "non-engineer"
HA15	Refine category of "host" from attribute to entity	In W2, several participants argued that “host” was an entity instead of attribute. According to them, “host” has its own existence. However, as mentioned in HA10, in the context of the model developed and presented in this thesis, “host” (as well as “guest”) refers to the function of stakeholder. In this sense, “function” can be viewed as an attribute and “host” as its value (value attribute). For this reason, “host” cannot be categorised as an entity. This makes the feedback not aligned with the research findings and thus it was deemed inapplicable.	P3	Inapplicable	Not refining “host” from attribute to entity

	Relationship				
HR1	Add feedback loops in the interaction between "internal" and "external" stakeholder	According to the participants in W1, one of the main interactions between external and internal stakeholder relates to the activity of evaluation. In this activity, external stakeholders provide feedback towards the design of technical system, normally presented by internal stakeholders. Such activity (providing feedback) has been covered and represented in the model, by the entity of “design review process” (see STAM-2, Section 7.5). Thus, adding feedback loops in the interaction between “internal stakeholders” and “external stakeholders” entities was deemed unnecessary.	P4	Inapplicable	Not adding feedback loops in the interaction between "internal" and "external" stakeholder
HR2	Add relationship between "stakeholders"	The participants in W2 mentioned that the relationship between stakeholders was not properly represented in the model. However, the feedback was given without further explanation on the type of relationship needs to be added. Relationship between stakeholders has been shown by the term “interact” in the architectural model version 2 (as discussed in Section 7.4.2.1). The existence of a different type of relationship was not evident in the industrial investigation as well as the literature. As such, the relationship between “stakeholders” was not added.	P3	Inapplicable	Not adding relationship between "stakeholder s"
HR3	Add "manage" to connect "risk" and "stakeholder"	The participants in W1 disagreed that risks are managed by the internal stakeholder solely. According to them, risks are managed by both, the internal and the external stakeholder. However, they remarked that the type of risk and the way it is managed can vary. This was supported by the industrial investigation, indicated the internal stakeholder allows the involvement of external stakeholder since the earliest stage of the design process to manage the risk of rework. From the external stakeholders’ perspective, this allows them to manage the risk of having a failed product (as mentioned by INT-2). Grounding on this, it can be concluded that risk	P1	Applicable	Add "manage" to connect "risk" and "stakeholder "

		is not managed by the internal stakeholders only. This makes the feedback from the participants aligned with the research finding, and thus, applicable.			
HR4	Add "supply" to connect "supplier" and "design information"	According to the participants of W1, the suppliers supply design information used to design technical system. As such, a relationship needs to be added to connect “supplier” and “design information”. As mentioned in Section 7.4.2.1, the supplier is asked to provide the specifications of the equipment needed in the product/system, designed by Company 1. In the context of the model developed and presented in this thesis, specification is a part of design information. It is a translation of design requirements and constraints given by customers (as explained in Section 7.4.2.1). In this view, supplier can be perceived as a supplier of design information, which makes the feedback from the participants applicable.	P1	Applicable	Add “supply” between “supplier” and “design information”
HR5	Add "plan" to connect "internal stakeholder" and "design process"	No justification regarding this feedback was identified during the workshop. Furthermore, as can be seen in the second version of the model (Chapter 7), relationship between "internal stakeholder" and "design process" was represented by the term "manages". In project management context, such term may be referred to the activity of planning, executing and evaluating (Boonstra, 2013). In this sense, the relationship "plan" has been covered by the relationship "manages" and thus, adding "plan" to connect "internal stakeholder" and "design process" was not needed.	P3 P4	Inapplicable	Not adding “plan” between “internal stakeholder” and “design process”
HR6	Add "plan" to connect "internal stakeholder" and "design review process"	The participants in W1 mentioned that during project planning, when internal stakeholders create a plan for the overall design process, design review process is included in the plan. For this reason, the participants suggested connecting “internal stakeholder” and “desgn review process” with “plan”.	P4	Inapplicable	Not adding “plan” between “internal stakeholder” and “design review process”

		The industrial investigation indicated that at a design review process is conducted regularly (see Section 7.4.2.9) to review the design. In this sense, design review process can be seen as an integrated part of design process. Thus, design review process can be considered as a sub-class of design process. Within the ERD concept, Elmasri & Navatel (2006, p. 247) mentioned that a sub-class participates in "all the relationships in which the superclass participates". This means, the relationship in which design process participates (i.e. being managed by internal stakeholder), design review process as its sub-class also participates. In other words, the connection between "internal stakeholder" and "design review" process has been represented by the connection between "internal stakeholder" and "design process". This makes the feedback inapplicable.			
HR7	Add "supply" to connect "supplier" and "technical system"	The participants in W2 defined technical system as product, a realisation of design. However, in the context of the architectural model, technical system is defined as a (designed) artefact. That is, the design itself. As mentioned in Chapter 7, the role of supplier during the design process is to supply information about specific parts of the product rather than the product (or technical system according to the participants) per se. This makes the feedback from the participants not aligned with the research findings.	P3	Inapplicable	Not adding "supply" between "supplier" and "technical system"

HR8	Delete "manage " that connects "risk" and "internal stakeholder"	As discussed and can be seen in HR3, risk is not managed by the internal stakeholder only. To represent this in the model, the relationship between “risk” and “internal stakeholder” needs to be deleted. Thus, the feedback is deemed applicable.	P1	Applicable	Delete "manage " that connects "risk" and "internal stakeholder"

Interaction

#	Feedback	Review	Premise	Conclusion	Action
		Entity			
IE1	Add "communication" entity	The participants in W2 remarked the absence of “communication” in the model. They believed that “communication” plays an important role in CED activity, and thus, it should be presented as an “entity” instead of “attribute” (as shown in the second version of the model). In the literature, the roles of communication in CED activity were identified, for example, to establish mutual understandings (Détienne, 2006), clarify different perceptions (Kleinsmann, Valkenburg and Buijs, 2007), and negotiate differences (Adelson, 1999; Kilker, 1999; McDonnell, 2012) towards the design-related issue. Furthermore, several studies show the effect of communication to collaborative design activity, suggesting its significance to the activity (e.g. Maier & Kleinsmann 2013; Kleinsmann & Valkenburg 2008; Sonnenwald 1996). As the feedback was aligned with the findings from the literature, it was deemed applicable.	P1	Applicable	Add "communication” entity

Attribute					
IA1	Add "value" as an attribute of "relationship" with the value of "positive" and "negative"	The participants in W2 argued that relationship between collaborative design participants can be described by its value (i.e. positive and negative), and how the CED participants value their relationship influence their action towards the others. Similar argument was implied in the industrial investigation. INT-2, for example, mentioned that in Company 1, internal stakeholders value their relationship with the other internal stakeholder less than they value their relationship with external stakeholder. Consequently, the communication between the internal stakeholders is often lacking, and thus, conflict occurs, which influences collaborative design activity. Considering this, it can be concluded that the "value" of relationship is an important element of CED, which makes the feedback from the participants aligned with the findings. As such, it was deemed applicable.	P1	Applicable	Add "value" as an attribute of "relationship
Relationship					
IR1	Add "cause" to connect "relationship" and "conflict"	In the social psychology context, conflict can be defined as "incompatibility" (Fisher, 1990). Klein (2003) specified the incompatibility as the differences on the decisions towards the design or design goals. In this sense, the cause of conflict is incompatibility rather than the relationship per se. As such, showing that relationship is a cause of conflict was deemed inappropriate. For this reason, the feedback was deemed inapplicable.	P3	Inapplicable	Not adding relationship "cause" between "relationship " and "conflict" entities

IR2	Add "influence" to connect "relationship" and "design process"	The participants in W2 stated that the relationship between the CED participants influences the design process. For example, according to them, design team that consists of "strangers" may find it difficult to design something together, and thus, it can take a longer time to design. As presented in Section 7.4.2.9, "design process" refers to the "course of designing the technical system". The industrial investigation indicated that the relationship between CED participants affects how they collaborate with each other (see Section 7.4.2.2). This was also implied in the study of Johnson (2005). As design process and collaboration are interrelated in CED activity (see Chapter 3), when the collaboration activity is affected, the design process can potentially be affected. In this sense, the connection between "relationship" and "design process" can be considered indirect. The direct connection between "relationship" and "design process" was not evident. For this reason, the feedback of the participants was deemed inapplicable	P3	Inapplicable	Not adding relationship "influence" between "relationship" and "design process"
IR3	Add relationship to connect "relationship" and "tenure"	In W1, the participants mentioned that collaborative design participants tend to form a relationship with those who have similar duration of work. Thus, the participants believed that there is a connection between relationship and tenure, and suggested to represent it in the model. However, when discussed further with the rest of the participants, they agreed that such connection is not influencing the company's CED activity as it only occurs to a certain group. The elements included in the model are those that considered significant to the activity of CED. On this basis, the connection between "relationship" and "tenure" is not added to the model.	P3	Inapplicable	Not adding connection between "relationship" and "tenure"

IR4	Add relationship to connect "relationship" and "assigned role"	Similar with IR2, the participants in W1 mentioned that relationships between CED participants are often segregated by their assigned role and responsibility. They emphasised that this has created a major challenge in the company's collaborative design practice. Thus, they believe that there should be a link between "relationship" and "assigned role". In the second version of the model (see Chapter 7), assigned role was presented as an attribute of human being. As stated in Chapter 7, attribute is a property that describes an entity. Thus, it can be concluded that all the relationships that an entity involves are influenced by the attributes that attached to the said entity. This means, any connection that involves human being is influenced by their assigned role. As shown in the second version of the model, stakeholders interact and form relationships. As a stakeholder is a sub-class of human being, it inherits the attributes of human being (see Appendix 6). Thus, the interaction between stakeholders and the relationship that they formed is influenced by their role. From this perspective, the relationship between "relationship" and "assigned role" has been covered in the architectural model and thus was deemed inapplicable.	P4	Inapplicable	Not adding connection between "relationship" and "assigned role"
IR5	Add "hampered by" to connect "prejudice" and "relationship"	As discussed in OS1, "prejudice" was not added in the model, and thus, the relationship that involves "prejudice" was not added.	P5	Inapplicable	Not adding "hampered by" between "prejudice" and "relationship"

IR6	Add "influence" to connect "relationship" and "level of trust"	The participants from both workshops suggested connecting “relationship” and “level of trust” rather than connecting “personal relationship” and “level of trust” (as explained in IR7). As concluded in IR7, there is a connection between “level of trust” and both, “personal” and “professional relationship”. For this reason, the connection between “relationship” and “level of trust” was added as suggested by the participants	P1	Applicable	Add "influence" to connect "relationship " and "level of trust"
IR7	Delete "influence" that connects "personal relationship" and "level of trust"	The participants from both workshops similarly argued that “level of trust” is influenced by both, personal and professional relationship. As such, they suggested eliminating the connection between “personal relationship” and “level of trust”. From the industrial investigation result, apart from the connection between “personal relationship” and “level of trust”, it was identified that five (INT-18; INT-14; INT-13; INT-6; INT-22) participants revealed the connection between “professional relationship” and “level of trust”. For example, INT-14 implied that, collaborative design participants who have worked together in the past project(s) and had formed a good professional relationship, are most likely trust each other more. In the literature, McDonnel (2012) shows two individuals who have a good professional relationship can trust each other, particularly, when accommodating disagreement between them. On these bases, it can be concluded that both personal as well as professional relationship influence the level of trust of a human being, which makes the feedback aligned with the research findings. Thus, the feedback was deemed applicable.	P1	Applicable	Delete "influence" that connects "personal relationship" and "level of trust"

Conflict

#	Feedback	Review	Premise	Conclusion	Action

Entity					
CE1	Refine the term "conflict" to "tension"	The participants believed that conflict may not always occur between the design participants, it can merely be tension. Hence the suggestion to refine the term “conflict” into “tension”. The term “conflict” was meant to represent incompatibilities in the design of technical system (i.e. technical conflict) and in the attributes of human being (i.e. social conflict) (See Section 7.4.2.3). In W2, the feedback to use “tension” only refers to social conflict. From this perspective, changing the term “conflict” into “tension” can only represent social conflict, which was not the purpose of using the term “conflict”. In other words, the feedback is not aligned with the research approach, and thus, was deemed inapplicable.	P2	Inapplicable	Not refining the term "conflict" to "tension"
Attribute					
CA1	Add "cause" as an attribute of "technical conflict" with value of "incorrect information" and "immature data"	In W1, the participants mentioned that technical conflict can be described by its cause, and thus, they suggested adding “cause” as an attribute of “technical conflict”. However, it was identified that “cause” can be used to describe “conflict” in general not only “technical conflict”. For example, personality difference can be used to describe social conflict, while incorrect information can be used to describe technical conflict. As such, instead of adding “cause” as an attribute of “technical conflict”, it was added as an attribute of “conflict”.	P2	Partly applicable	Add “cause” as an attribute of “conflict”

CA2	Refine category of "disintegrated design" from attribute to entity	"Disintegrated design" was viewed as a significant challenge in collaborative design by the participants in W2, and thus, they suggested refining its category from attribute to entity. In the second version of the model, "disintegrated design" was meant to show an example of "technical conflict". However, having more knowledge on the concept of ERD as well as the definition of entity and attribute, it became apparent that examples should not be included in the model. For this reason, instead of refining the category of "disintegrated design" from attribute to entity, it was deleted from the model.	P2	Partly inapplicable	Delete "disintegrate d design"
CA3	Refine category of "personality clash" from attribute to entity	With the similar reason as mentioned in CA2, the participants in W2 suggested refining the category of "personality clash" from attribute to entity. As discussed in CA2, "personality clash" was included in the model as an example of social conflict. However, in the concept of ERD, examples should not be included in the model. As such, "personality clash" was deleted from the model.	P2	Partly applicable	Delete "personality clash"
Relationship					
CR1	Add relationship "motivate" to connect "conflict" and "new policy"	The relationship between "conflict" and "new policy" has been presented in the second version of the model (see Chapter 7).	P4	Inapplicable	Not adding relationship "motivate" to connect "conflict" and "new policy"
CR2	Refine "influenced by" that connects "conflict" and "design process" to "impact"	According to the participants in W2, the relationship between "conflict" and "design process" needs to be emphasised, as conflict can significantly influences the CED activity. They believed that emphasising such relationship can be accomplished by refining the term "influence" to "impact".	P1	Applicable	Refine "influenced by" that connects "conflict" and "design process" to "impact"

		The industrial investigation suggests that conflict can delay the design process (as implied by INT-3), and thus, can potentially influences the cost needed to design the technical system (as mentioned by INT-20) as well as the reputation of the company in front of the customers (INT-14). From the company's perspective, such influence was considered significant. In this view, the influence between "conflict" and "design process" need to be emphasised to show its significance, aligned with the feedbacks from the participants of W2. From the dictionary perspective, the term "impact" may be defined as "a strong effect on someone or something", while "influence" may be defined as an effect (The Oxford English Dictionary, 2013). Based on these definitions, the term "impact" can be used to emphasise the influence of "conflict" to the "design process". As such, the term was used to connect "conflict" and "design process" in the model.			

Organisation

#	Feedback	Review	Premise	Conclusion	Action
Entity					
OE1	Expand more on "organisation" entity	All elements of organisation identified from the literature and the industrial investigation had been presented in the model. As such, expanding the theme "organisation" is considered unnecessary at this point.	P3	Inapplicable	Not expanding "organisation" entity
Sub-entity					

OS1	Add "prejudice" as a sub-entity of "history"	The participants from W1 argued that past events in the company, especially the negative ones, have created problems during the CED process as it led to prejudice. For this reason, they suggested adding “prejudice” as part of “history”. From the dictionary perspective, “prejudice” can be defined as "preconceived opinion that is not based on reason or experience" (The Oxford English Dictionary, 2013). In Section 7.4.2.4, history was viewed as past-events, while past-events can create experience. In this view, connecting history, i.e. creator of experience and prejudice, i.e. opinion that is not based on experience, is inappropriate. Thus, the feedback was deemed inapplicable	P3	Inapplicable	Not adding “prejudice” as a sub-entity of “history”
Attribute					
OA1	Delete “history” attribute of “organisation”	The participants in W2 argued that “history” is not an attribute, as it cannot be used to describe an “organisation”. In the model, “history” was presented as both, an entity and an attribute. As mentioned in Section 7.4.2.4, the industrial investigation indicated that a company can be characterised by their history due to their unique establishment as a company. However, this may be specifically applied to Company 1 only, as the evident of “history” being a property that characterises other companies was not identified. As such, the term “history” needs to be removed from the attribute of “organisation”, which is aligned with the feedback from the participants. Thus, the feedback was deemed applicable.	P1	Applicable	Delete “history” attribute of “organisation”

OA2	Delete “strategy” attribute of “organisation”	Similar as point OA1, the participants in W2 argued that “strategy” is not an attribute, as it cannot be used to describe an “organisation”. Similar with “history”, “strategy” was presented in the model as both, an entity and an attribute. However, differ with the existence of “history” (mentioned in OA1), the existence of “strategy” as a property of organisation that describes an organisation had been discussed in various contexts. For example, in general business context, Dima (2013) who discussed how the company’s (competition) strategy characterises a company in Romania. On this basis, it can be concluded that “strategy” can be categorised as both, an entity and an attribute. As such, the term “strategy” was not deleted from the attribute of “organisation”, which is not aligned with the feedback from the participants. Thus, the feedback was deemed inapplicable.	P3	Inapplicable	Not deleting “strategy” attribute of “organisatio n”
Relationship					
OR1	Add "creates" between "history" and "prejudice"	As discussed in OS1, "prejudice" was not added in the model. As such, the relationship that involves “prejudice” was not added in the model.	P5	Inapplicable	Not adding “creates” between “history” and “prejudice”

Boundary

#	Feedback	Review	Premise	Conclusion	Action
Entity					
BE1	Refine term "location" to "colocation"	The participants in W2 suggested changing the term “location” to “colocation”. The term “colocation” originally comes from the term “collocate”, which can be lexically defined as "to place (two or more units) close together so as to share	P3	Inapplicable	Not refining the term “location” to “colocation”

		common facilities" (Merriam-Webster, 2013) . In the model, the term "location" was intended to represent the physical placement of an organisation. Considering the definition of the term "colocation", the term is considered inappropriate to replace the term "location". Based on this, the feedback to change "location" to "colocation" is concluded to be inapplicable.			
	Sub-entity				
BS1	Add "ways of working" as an attribute of "organisational culture difference"	"Ways of working" was mentioned by the participants in W1 as an example of culture differences in the company. The model was not intended to present an example of elements, specific to one company only, as examples of socio-technical elements can vary broadly. In other words, the feedback from the participants is not aligned with the research approach. For this reason, the feedback was deemed inapplicable	P3	Inapplicable	Not adding "ways of working" as an attribute of "organisational culture difference"
Attribute					
BA1	Add "time zone" as an attribute of "location"	The participants from W2 believed that within the context of collaborative design, "time zone" can be used to differentiate locations, and thus, they suggested adding "time zone" as an attribute of location.	P1	Applicable	Add "time zone" as an attribute of "location"

		The study of Fadel et al. (2000) indicated that “time zones” can be used to describe different locations of the participants in CED activity. For example, the participants located in South Carolina, US, have a different time zone with the participants located in Germany, Europe ((Fadel, Lindeman and Anderl, 2000). The influences of “time zones” in CED activity were also identified in the literature. For example, Ostergaard & Summers (2009) discussed the influence of time zones to team composition in a design project time. Considering the significance of “time zone” to CED activity, adding “time zones” as an attribute of “location” was viewed necessary, aligned with the feedback from the participants. Hence, the feedback was deemed applicable.			

Design information

#	Feedback	Review	Premise	Conclusion	Action
		Sub-entity			
DS 1	Add "design rules" as a sub-entity of "design information"	According to the participants of W1, design rules contain regulations that govern the design of the technical systems. In other words, design rules contain what needs to be included and/or excluded in the design of the technical system. Considering the content of design information, as mentioned in Chapter 7, i.e. “information about what needs to be included and/or excluded in the design”, they can be generally viewed as design rules. Furthermore, the utilisation of the term “design rules” may be applied specifically in the Company	P3	Inapplicable	Not adding “design rules” as a sub-entity of “design information”

		1's CED activity. The utilisation in the literature was not evident. On this basis, the feedback to add "design rules" as a sub-class of "design information" was deemed inapplicable.			
		Attribute			
DA 1	Add "technical drawing" as a sub-entity of "model type"	A technical drawing, according to the participants in W1 is a 2D model of the technical system being designed, consists of the technical properties of the technical systems such as dimension. In this sense, "2D model" (already presented in the model) and "technical drawing" is essentially the same thing. As such, adding "technical drawing" as was considered unnecessary.	P4	Inapplicable	Not adding "technical drawing" as a sub-attribute of "model type"
DA 2	Add "maturity" as a sub-attribute of "design information requirement"	As indicated by the participants in W1, "maturity" describes the quality of design information required to achieve in the company's CED activity. In this sense, "maturity" can be considered a value attribute of "quality", instead of a sub-attribute of "design information requirement". Adding value attribute is not aligned with the research approach, and thus, the feedback was deemed inapplicable.	P3	Inapplicable	Not adding "maturity" under "design information requirement"

DA 3	Refine category "2D" model from attribute to entity	The participants believed that the "2D" represents an independent existence, significant to the design process. Thus, it needs to be categorised as an entity instead of attribute. Including "2D" in the model was intended to show the different types of model in CED practice. However, having identified the concept of attributes in ERD further (See Appendix 6), instead of a sub-attribute, 2D can be considered as a value of attribute, as it describes a "type" of model. In ERD concept, value attribute is not represented in the model. As such, "2D" was eliminated from the model instead of refining it from attribute to entity.	P2	Partly applicable	Delete "2D"
DA 4	Refine category "3D" model from attribute to entity	Similar with the above (DA3), "3D" was viewed a value attribute, and thus, was eliminated from the model.	P2	Partly Applicable	Delete "3D"
DA 5	Refine the term "consistency" to "requirement consistency"	According to the participants in W1, the term "consistency" needs to be specified into "requirement consistency" as consistency in the requirement was considered a factor that creates the most challenge in the company's CED activity. However, the may only be the case in Company 1, as the case in other companies was not identified. Furthermore, in the model, the term "consistency" was referred to the consistency in the general "design information", which includes, such as, requirement consistency, content consistency, and form consistency. In this sense, refining the term into "requirement consistency" can alter its designated references. As such, refining the term "consistency" to "requirement consistency" was deemed inapplicable.	P3	Inapplicable	Not refining the term "consistency" to "requirement consistency"
Relationship					

DR 1	Add "restore" to connect "information system" and "model"	The participants in W1 mentioned that in their company (i.e. Company 1) design models are saved in “information system” such as database platform. For this reason, they suggested adding “restore” to connect “information system” and “model”. At its most literal sense, restore may be defined as “to store (i.e. save) again”. If the term was suggested to represent, “save”, then the term “restore” was considered inappropriate. The term “store”, on the other hand, may be defined as save or “retain” (The Oxford English Dictionary, 2013), which is aligned with the intended relationship between “information system” and “model” (i.e. save). The industrial investigation indicated that information system is used to store design information (e.g. model). As an example, INT-14 mentioned, “…they’re using Windchill [i.e. information system] to store modelled parts [of the technical system].” The function of information system to store model can also be identified in the literature, as can be seen in, for example, Chen & Liang (2000) and Wu et al. (2004) Chiu (2002). From these identified evidences, it can be concluded that in CED activity, “information system” is used to save “model”. However, instead of “restore”, the term "store" was considered more appropriate and thus was used to represent the connection between “model” and “information system”.	P2	Partly applicable	Add “stores” to connect “information system” and “model”
DR 2	Add "creates" to connect "design requirement and constraint" and "design rules"	As concluded in DS1, "design rules" was not added in the model. As such, the relationship that involves “design rules” is not added in the model.	P5	Inapplicable	Not adding “creates” to connect “design requirement and constraint”

					and “design rules”
DR 3	Add relationship to connect "design problem" and "design requirements and constraints".	In W2, the participants believed that “design problem” and “design requirements and constraints” are connected. However, the type of connection was not specified during the workshop. The connection between “design problem” and “design requirements and constraints” was also identified in the literature. For example, Dorst (2004) mentioned that design problems are partly "determined by needs, requirements and constraints". In this view, “design requirements and constraints” is seen as a determinant factor of “design problem”. On this basis, a relationship, i.e. “determines” needs to be added to connect "design requirements& constraints" with "design problems", which is aligned with the feedback from the participants	P1	Applicable	Add "determines" to connect "design requirements constraints" and "design problems"
DR 4	Add "build" to connect "design information" and "design process"	The participants in W2 remarked that a design process is built upon design information, and thus, they suggested adding “build” to connect “design information” and “design process”.	P2	Partly applicable	Add "utilises" to connect "design process" and "design information"

		According to Dieter & Schmidt (2013), design process can be divided into two main stages: conceptual design, where the design of artefact is still an idea; and embodiment design, where the idea starts to evolve in tangible form. In conceptual design, design information is identified and explored to form ideas that eventually will be generated, detailed and developed into design artefact in embodiment design (Ray, 1985). In this sense, it can be concluded that design information is used in the design process. In other words, it can be concluded that here is a relationship between "design information" and the "design process". However, instead of the term "build", the term "utilise" was considered more appropriate to represent the relationship, as "design information" is used not to build the design process. Instead, it is used in the design process to design the technical system.			
DR 5	Add "created in" to connect "model" and "design process"	In W2, the participants argued that in each stage of the design process, a model of design is created. As such, they recommended linking "model" and "design process" with the term "created in". The industrial investigation indicated that models are created in the first two stages of the design process (i.e. conceptual design and detailed design) (Chapter 7). The models are then used in the other two stages of design process (i.e. design review process for evaluation purposes, and post-design process for realisation purposes) (Chapter 7). The creation of model in each stage of design process was not identifiable in the literature and/or industrial investigation, which makes the feedback inapplicable.	P3	Inapplicable	Not adding "created in" between "model" and "design process"

DR 6	Add "influence" to connect "design requirement and constraint" to "design process"	The participants from W1 and W2 believed that "design requirements and constraints", coming from the customers is an influencing factor of the design process. The participants from W2 specified the influence as "define" (i.e. "design requirements and constraints" define "design process") while the participants from W1 did not specify the influence. The industrial investigation suggested that Company 1 follows a standard process regardless of the changing requirements from their customer. There is no evidence that supports the influence of design requirements and constraints to the design process can be identified from the literature. On this basis, a relationship between "design requirements and constraints" and "design process", as suggested by participants from both workshops, was not added as it was deemed inapplicable.	P3	Inapplicable	Not adding "influence" between "design requirement and constraint" to "design process"
DR 7	Add "influences" to connect "design information" and "design process"	As mentioned in DR6, the industrial investigation suggests that the company follows a standard design process regardless the requirements and constraints from the customers. In Chapter 7, it was described that design requirements and constraints is a sub-class of design information that unpins the other sub-classes of design information (i.e. design specification and design problem). In this sense, if the design requirements and constraints were not perceived as an influencing factor of the design process, it seems reasonable to perceive design information the same. For this reason, the feedback from the participants was deemed inapplicable. Thus, the relationship between "design information" and "design process" was not added.	P3	Inapplicable	Not adding relationship "influences" between "design information" and "design process"

DR 8	Add "defines" to connect "Design requirements and constraints" with "design process"	See DR6	P3	Inapplicable	Not adding relationship "defines" between "Design requirements and constraints" with "design process"
DR 9	Add relationship to connect "design information" and "communication"	The participants in W2 remarked that during CED activity, "design information" is exchanged through "communication" between CED stakeholders, and thus, they argued that a connection between "design information" and "communication" needed to be added. However, from the aforementioned feedback, there is no direct relationship between "design information" and "communication". Instead, two direct relationships can be derived: 1) between "design information" and "stakeholders", and 2) between "communication" and "stakeholders". The relationship presented in the model is only direct relationship. Thus, adding the connection between "design information" and "communication" is not aligned with the research findings.	P3	Inapplicable	Not adding relationship between "design information" and "communica -tion"
DR 10	Add "represent" to connect "model" and "technical system"	In W2, the participants argued that the model created in CED activity is a representation of a technical system. When clarified, the participants defined technical system as a product, a realisation of design, which was not aligned with the definition of "technical system" used in the model. Furthermore, as described in Chapter 7, in the study presented in this thesis, a model is viewed as a representation of design information, used for communication purposes. The view of model as a representation of product/system, as argued by	P3	Inapplicable	Not adding "represent" between "model" and "technical system"

		the participants cannot be identified in the literature. Based on this, a connection (i.e. "represent") to add "model" and "technical system" was deemed inapplicable.			
DR 11	Add "affect" to connect "design rules" and "technical system"	See DR1	P3	Inapplicable	Not adding "affect" between "design rules" and "technical system"

Tools

#	Feedback	Review	Premise	Conclusion	Action
Sub-entity					
TS1	Add "information tool" as a sub-entity of "tools"	In W1, the participants remarked that the model was missing one important tool, i.e. information tool, which is a computer-based tool to store and manage information.	P2	Partly applicable	Refine "information system" from an entity to a

		The type of tool remarked by the participants was already discussed in Section 7.4.2.6, presented in the second version of the model, however regarded as a different term, i.e. "information system". Based on the discussion with the participants of W1, information system can be considered as a tool, as it supports the design process by storing the design information and managing it. On this ground, "information system" was categorised as a sub-class of "tools". Additionally, to emphasise its identity as a tool, the term was refined from "information system" to "information tools".			sub-entity of "tools" Refine the term "information system" to "information tools"
Attribute					
TA1	Refine the category of "calculation" from sub-attribute to entity	According to the participants in W2, "calculation" was as an entity, instead of a sub-attribute. The reason behind this feedback cannot be identified. In the model, "calculation" was considered a sub-attribute of "function" (i.e. an attribute of "technical tool"), as it describes a function of tool, derived from the industrial investigation. Refining the categorisation of "calculation" into entity can indicate a different meaning, for example, an element of CED activity, which was not evident from the preliminary investigation and the industrial investigation. As such, the category of "calculation" was not refined from a sub-attribute to an entity.	P3	Inapplicable	Not refining "calculation" from sub-attribute to entity
TA2	Refine the category of "visualisation and representation"	The participants in W2 argued that "visualisation and representation" was viewed as an entity rather than a sub-attribute.	P3	Inapplicable	Not refining "visualisatio n and representatio n" from a

	from attribute to entity	Similar with the above analysis (TA1), "visualisation and representation" was considered a sub-attribute of "function" (i.e. an attribute of "technical tool"), as it describes a function of tool, derived from the industrial investigation. Refining the categorisation of "visualisation and representation" into entity can indicate a different meaning. For this reason, changing the category of "visualisation and representation" from sub-attribute to entity was deemed inapplicable			sub-attribute to an entity
Relationship					
TR1	Add "resolve" to connect "communication tool" and "conflict"	Based on the experience of the participants in W1, they remarked that the utilisation of communication tool can help to resolve conflict between stakeholders. In other words, communication tool support the conflict resolution, instead of resolve the conflict directly. In this manner, the relationship between communication tool and conflict was indirect. In other words the feedback to add "resolve" between "communication tool" and "conflict" was not aligned with the research approach, and thus, was deemed inapplicable.	P3	Inapplicable	Not adding "resolve" between "communica -tion tool" and "conflict"
TR2	Add "cause" to connect "communication tool" and "conflict"	Similar with TR1 above, the participants in W1 believed that one of the main causes of conflict was the utilisation of communication tool. They argued that the CED participants typically communicating through email more than face-to-face. This often triggers conflict caused by, for example, misunderstanding. From this perspective, the cause of conflict is the person who made a choice to communicate through email rather than face-to-face, instead of the communication tool. For this reason, the feedback to link "communication tool" and	P3	Inapplicable	Not adding "cause" between "communica -tion tool" and "conflict"

		"conflict" was deemed not aligned to the research findings, and thus, inapplicable.			

Technical system

#	Feedback	Review	Premise	Conclusion	Action
Entity					
TSE1	Refine term "technical system"	According W2's participants, in the concept of socio-technical systems, technical systems may be defined as technology. Thus, the utilisation of the term in the model was deemed inappropriate by the participants. However, in the second version of the model, the term "technical system" was meant to represent the result of the design process. The term was derived from the theory of technical systems, written by Hubka and Eder (1988), broadly applied in the context of engineering design. According to Hubka and Eder (2002, p.49), technical systems may be defined as, "a designed artefact…" or in other words, the result of the design. On this basis, the term was not refined as it is not aligned with the research finding from the literature.	P3	Inapplicable	Not refining the term "technical system"
Relationship					

TSR1	Add relationship between "technical system" and "design information"	According to the participants in W2, technical system is built based upon design information and thus, a link needs to be added to connect “technical system” and “design information”. As mentioned in Chapter 7, one of the objectives on designing technical system is to fulfil the requirements of the customers (and users). Thus, the design of technical system has to comply with the requirements. However, design requirements and constraints are not the only factor that a design of technical system needs to comply. Legislation is one example (Chapter 7). Furthermore, design requirements and constraints are translated into design specification, adding other factors that need to be complied. From which, design problem(s) can be identified. All of these are utilised as the basis to design technical system (See Chapter 7). As design requirement and constraints, design specification and design problem can be categorised as design information, it can be concluded that technical system is designed based on design information. In other words, design information underpins technical system being designed. This relationship was perceived more general. Additionally, the relationship also addresses the compliance of technical system to design requirements and constraints. As such, “design information” and “technical system” was linked through “underpins” relationship, as suggested.	P1	Applicable	Add relationship between “technical system” and “design information”

Design process

#	Feedback	Review	Premise	Conclusion	Action

Entity					
PE1	Add "decision information" as an entity	The participants in W1 defined "decision information" as the information considered in decision-making process. The definition is perceived similar with the definition of the term "design information" used in the model (Chapter 7). As such, adding "decision information" was considered unnecessary as it is already represented in the model.	P4	Inapplicable	Not adding "decision information"
PE2	Expand more on "design process"	The participants in W2 stated that "design process" was poorly elaborated. They argued that the activity of designing needed to be shown in a more detail sense. However, the focus of the model was to present the elements of CED practice where design process is identified as one of the elements. The detail activity of the design process was not presented in the model, as it was not within the model scope. Thus, "design process" was not expanded as suggested by the participants.	P3	Inapplicable	Not expanding "design process"
Sub-entity					
PS1	Add "operation" as a sub-entity of "post-design process"	The participants in W1 participants referred "operation" to the used of the end product, after the design is realised. This is already represented in a general as "post-design process". Detailing such process is not within the scope of the model. Thus, the feedback to add "operation" in the model was deemed inapplicable.	P3	Inapplicable	Not adding "operation" after "post-design process"

PS2	Add "market" as a sub-entity of design process	The participants in W2 argued that the condition in the market (i.e. demand) drives the design of the product, which can eventually drive the design process. Thus, the participants suggested adding "market" in the model, as a sub-class of the design process. Within the concept of ERD, a sub-entity (i.e. sub-class) denotes a division of an entity. However, based on the argument of the participants, "market" was viewed as an influencing factor of design. The existence of "market" as a division of "design process" was not identified. As such, adding "market" to the model as a sub-class of design process was considered inapplicable.	P3	Inapplicable	Not adding "market" as part of design process
Attribute					
PA1	Add "structural unit" as a sub-attribute of "zone"	According to W1's participants, structural unit is a part of division in designing technical system. However, the utilisation of such term in CED activity was not evident in the literature as well as in W2. The term "structural unit" seems to be specifically applied to the activity in Company 1 only. For this reason, adding "structural unit" was considered inapplicable.	P3	Inapplicable	Not adding "structural unit" as a sub-attribute of "zone" of "technical system" entity
PA2	Add "schedule" as an attribute of "design process"	The participants from both workshops argued that the model lacks an important attribute of design process, i.e. schedule. The participants similarly emphasised the importance of "schedule" in CED practice. According to them, schedule interrelates with the cost of the project, both determine workloads and tasks assigned to the participants, and typically utilised as a parameter to measure the performance of design process. Furthermore, in Company 1, "schedule" (and "cost") can be used to describe (the scale) of a design project (i.e. design process), as	P1	Applicable	Add "schedule" as an attribute of "design process"

		indicated by INT-20. As the feedback is aligned with the research finding, adding “schedule” as an attribute of “design process” was considered applicable.			
PA3	Add "acceptance" as a sub-attribute of "operation"	As discussed in PS1, "operation" was not added in the model, and consequently, no feedbacks pertinent to “operation” were added. Thus, “acceptance” was not added in the model.	P5	Inapplicable	Not adding "acceptance" as a sub-class of "operation"
PA4	Add "in-service" as a sub-attribute of "operation"	Similar with PA3, “in-service” was not added in the model as it is related with “operation”, and as discussed in PSI, “operation” was not added in the model.	P5	Inapplicable	Not adding "in-service" as a sub-class of "operation"
PA5	Add "technical" as a value of "parameter" attribute	An attribute can be defined as a property that characterises or describes entity (Chapter 7). However, “parameter” cannot be used to characterise nor describe a design process. Instead, it can be used to describe how a performance is measured (i.e. performance measurement). In the model, performance measurement was categorised as an attribute of design process in this model. As “parameter” describes “performance measurement” (i.e. attribute), “parameter” can be categorised as a value attribute. In ERD, value attribute is not represented in the model. Thus, “parameter” was deleted from the model, and consequently, “technical” was not added in the model as suggested by the participants. This is not aligned with the	P3	Inapplicable	Not adding “technical” as a value of “parameter” Delete “parameter”, an attribute of “design process”

		feedback from the participants, which makes it inapplicable.			
PA6	Add "financial" as a value of "parameter" attribute	As discussed in PA5, “parameter” was deleted from the model, and consequently, no elements pertinent to it were added. Furthermore, as mentioned in Section 8.5.1.2, value attribute is not represented in ERD. For these reasons, “financial” was not added in the model as suggested by the participants.	P5	Inapplicable	Not adding “financial” as value of “parameter”
PA7	Add "parameter" with the value of "cost" and "quality" in "design review process"	See PA5. Additionally, value attribute (i.e. “cost” and “quality”) is not represented in ERD, as mentioned in Section 8.5.1.2. Thus, “parameter” and their value were not added in the model as suggested by the participants.	P5	Inapplicable	Not adding “parameter” with the value of “cost” and “quality” under “design review process”
PA8	Add "project" as a value of "requirement" in design process	The participants in W2 believed that the model is lack of project management-related elements, such as schedule and cost. Thus, they suggested adding “project” as a value of “requirement” (i.e. an attribute of “design process”). According to the concept of ERD, value attribute is not represented in the model (Section 8.5.1.2). Adding “project” is not aligned with the research approach.	P3	Inapplicable	Not adding “project” as a value of “requirement” in design process
PA9	Add "speed" as a value of "requirement" in design process	The evidence supporting "speed" as a requirement of design process cannot be identified from the literature and from the industrial investigation. Furthermore, in the concept of ERD, value attribute is not represented in the model. As such, "speed" is not added as a value of “requirement” as suggested by the participants.	P3	Inapplicable	Not adding "speed" as a value of "requirement" in “design process” entity

PA10	Refine term "zone"	The term "zone" used in the model was obtained from the industrial investigation, may be defined as a specific area of the technical system based on which design team and design process is divided. As its utilisation in the literature or other companies is not evident, a more general term, i.e. “area” is utilised to replace the term, which makes the feedback aligned to research finding. Thus, applicable.	P1	Applicable	Refine the term "zone" to “area”
Relationship					
PR1	Add "reviewed in" to connect "post-design process" and "operation"	As discussed in section PS1, “operation” was not added in the model. Consequently, any relationship that involves “operation” was not added, and thus, “reviewed in” was not added to connect “post-design process” and “operation”.	P5	Inapplicable	Not adding "reviewed in" between "post-design process" and "operation"
PR2	Add "influence" to connect "design process" and "post-design process"	The participants in W2 mentioned that the result of the design process influences the result of post-design process. Thus, they suggested linking “design process” and “post-design process” entity. However, the participants also mentioned the influencing relationship exists between the results of design process (i.e. the design of technical system) and the result of post-design process (i.e. product) rather than the process per se. As such, their feedback to add influencing relationship between “design process” and “post-design process” was deemed inapplicable, and was not added in the model.	P3	Inapplicable	Not adding "influence" between "design process" and "post-design process"
PR3	Add "consists of" to connect "design review process" and "decision information"	As discussed in PE1, “decision information” was not added in the model, and consequently, the relationship that involves “decision information” cannot be added. Thus, “consists of” was not added to connect “design review process” and “decision information” as suggested by the participants in W2.	P5	Inapplicable	Not adding relationship "consists of" between "design review process" and "decision information"

PR4	Add "influences" to connect "market" and "design process"	As discussed in PS2, "market" was not added in the model, and consequently, the relationship that involves "market" was not added. Thus, "influences" was not added to connect "market" and "design process" as suggested by the participants in W2.	P5	Inapplicable	Not adding relationship "influences" between "market" and "design process"

Appendix 12: Additional refinements

Human being

#	Topic	Review	Conclusion
		Entity	
HE1	The entity of "human being" and "stakeholder"	From the dictionary perspective, the term "human being" can be seen as a common term defining all type of human being in general (e.g. man and woman) (The Oxford English Dictionary, 2013). On this basis, representing the actor of CED activity as "human being" was considered too general, potentially lead to misinterpretation. Contrarily, "stakeholder" can be perceived as a specific type of human being (See Section 7.4.2.1) derived from the industrial investigation. On this basis, the entity "stakeholder" was deemed more appropriate to represent the (human) actor of CED activity. Thus, to avoid confusion and misinterpretation as commented by the participants, the actor of CED activity was represented by "stakeholders" only, eliminating the entity "human being" from the model. In addition to the above, concerning the attributes of human being, as stakeholder is a sub-class of human being; it inherits all attributes that the human being possesses (as mentioned in Section 7.4.2.1). As "human being" was eliminated from the literature, instead of eliminating the attributes of human being as well, they were transferred to the "stakeholder" entity in the refined architectural model.	Delete "human being" entity Transfer the attributes of "human being" (i.e. personality, priority, affective, conative, cognitive, assigned role, assigned responsibility, socio demographic, tenure, experience, age, gender) to "stakeholders"
HE2	"Opinion" as an entity	The participants in W1 suggested adding "prejudice" as an entity in the model. Having discussed with the participants on their definition of the term "prejudice", it was apparent that they defined the term as "preconceived opinion". From the dictionary perspective, it can be defined as a personal view about something based on past event (i.e. history). In this sense, history can be seen as the basis of an opinion. The participants also highlighted the influence of such opinion in human beings behaviour during CED practice. For example, in an individual context, due to bad experience in the past project, team members can have bad opinion towards their colleagues, develop bad relationships, and consequently, reluctant to collaborate again. On the contrary, having a pleasant experience can create a good relationship where people are keen to work together. In an organisational context, a participant explained that due to unpleasant experience regarding the application of company's policies in the past, employees tend to	Add "opinion" as an entity Add "underpins" to connect "opinion" and "history" Add "has" to connect "opinion" and "stakeholder"

		be more reluctant when new policies are introduced. From this perspective, opinion and its relationship with history seem to have a role in CED activity and thus it was viewed necessary to be included in the model. In addition to the above, as aforementioned, opinion can be defined as a personal view of an individual (i.e. stakeholder). In this sense, stakeholder can be viewed as an owner of opinion. On this ground, it seems reasonable to link “stakeholders” with “opinion”, using the term “have”.	
Attribute			
HA16	Attribute of “internal stakeholder”	“Performance” and “objective” were categorised as the attributes of “internal stakeholder”. Although they can be considered as a property of “internal stakeholder”, as described in Section 7.4.2.1, whether they can be utilised to describe “internal stakeholder” was rather unclear. Furthermore, studies in the literature of general collaboration and CED mainly concern on the team performance (e.g. Zhijun et al. 2008; Boos 2007; Kleinsmann et al. 2012; Dong et al. 2004; Gonzalez et al. 2008), team objectives (goals) (e.g. Adler & Chen 2011; Chatman & Flynn 2001). Studies into individual performance and objective and their significance to the team performance and objective, and even, to CED, was not evident. On this basis, “performance” and “objective” eliminated from the model. In addition to the attributes discussed above, another attribute of “internal stakeholder”, i.e. host, was eliminated. Mentioned in HA15, “host” referred to a function of “stakeholders” in CED activity. In this sense, “host” can be seen as a descriptor of function (role) while function as a descriptor of stakeholder. As “stakeholder” was categorised as an entity and function was a descriptor of a stakeholder (entity), this makes function an attribute of stakeholder, and thus, makes “host” a value attribute (i.e. a descriptor of attribute). In the concept of ERD, value attribute is not presented in the model (see Section 6.5.1.2). Based on this, “host”, a value attribute was eliminated from the model.	Delete “performance” and “objective”, attributes of “internal stakeholders” Delete “host”, an attribute of “internal stakeholder”
HA17	Attribute of “external stakeholder”	Similar with HA16, “guest” describes the function of “stakeholder” (i.e. external stakeholder) in the CED activity. Thus, “guest” can be categorised as a value attribute instead of an attribute. As value attribute is not presented in the model based on the concept of ERD, “guest” was removed from the model.	Delete “guest”, an attribute of “external stakeholder”
HA18	Attribute of “suppliers”	“Product quality”, “delivery time”, and “price” were used as the basis to describe the performance of suppliers in Company 1 (See Section 7.4.2.1). In this sense, “product quality”,	Delete “product quality”, “delivery

		"delivery time", and "price" can be categorised as descriptors of attribute (i.e. value attribute). Owing to this, they were removed from the model.	time" and "price", sub-attributes of "suppliers"
Relationship			
HR9	Relationship between "internal stakeholders"	As mentioned in Section 7.4.2.1, to design technical system, engineers and non-engineers (i.e. internal stakeholders) interact with each other. This was presented in the second version of architectural model. Based on the feedbacks from the workshops, "engineers" and "non-engineers" were eliminated from the model (See Table 17). Consequently, the interaction between them was also eliminated. The interaction between internal stakeholders was considered one of the key elements in CED activity (See Section 7.4.2.2) and therefore, needs to be represented in the model. For this reason, a relationship loop, representing the interaction between internal stakeholders was added to "internal stakeholders" entity. As the main interaction between the CED participants were through communication, the term "communicate" was considered more appropriate to represent the interaction between CED participants, (see HR13).Thus, to represent interaction between internal stakeholders, the term "communicate" was used to the relationship loop.	Add "communicate" as a relationship loop attached to "internal stakeholders"
HR10	Relationship between "engineers" and "non-engineer"	One of the feedbacks applied to refine the model was to delete "engineers" and "non-engineers" (see HS1 and HS2). In the model, these two sub-entities were connected through "interact" relationship. As "engineers" and "non-engineers" were deleted, consequently, everything that attaches to it (i.e. relationship, attributes and sub-attributes) were also deleted.	Delete "interact", that connects "engineers" and "non-engineers" Delete "requirement" and "type", attributes of "interact" Delete "communication" and "trust" sub-attributes of "interact" Delete "informal" and "formal", sub-attributes of interact
HR11	Relationship between "customers" and "users"	Based on the feedbacks from the participants, "customers and users" were represented as one entity in the model. Accordingly, the relationship and everything that attached to it (i.e. attributes	Delete "interact" that connects

		and sub-attributes) was deleted. However, the relationship between "customers" and "users" were deemed important, particularly in the formulation design requirements and constraints (See Section 7.4.2.2). Thus, their relationship needs to be redefined and presented in the model. As aforementioned, customers and users communicate to formulate design requirements and constraints (See Section 7.4.2.2). To represent such communication, a relationship loop was attached to "customers and users" entity. Similar with HR9, the term "communicate" was used to the relationship loop.	"customers" and "users". Delete "communication" and "trust" sub-attributes of "interact" Delete "informal" and "formal" sub-attributes of interact Add "communicate" as a relationship loop attached to "customers and users"
HR12	Relationship between "customers and users" and "design requirement and constraint"	The industrial investigation indicated that customers and users communicate to form the design requirements and constraints provided to Company 1, and used as the basis to design the technical system (see Section 7.4.2.6). From this, a relationship between "customers and users" and "design requirement and constraint" can be identified (i.e. "provide"). However, the relationship was overlooked, and thus, was not presented in the second version of the model. In the third version of the model, this relationship was added.	Add "provide" to connect "customers and users" and "design requirement and constraint"
HR13	Relationship between "internal stakeholders" and "external stakeholders"	From the two workshops and further literature exploration, it was identified that the interactions between the CED participants are mainly consists of social interaction, i.e. communication. It was also identified that the term "interaction" and "communication" were used interchangeably in the literature. For example: (Sonnenwald, 1996; Wu and Duffy, 2002; Maier *et al.*, 2009).From this perspective, the two terms can be considered as synonyms. However, in a general context, the two terms have distinct definitions. For example, the Oxford English Dictionary defines interaction as "reciprocal action" whereas communication as "exchanging information" between two person or more. As the term "communication" used in the model was intended to represent the activity of exchanging information (see Section 7.4.2.6), to avoid misinterpretation, the term "interact" was changed into "communicate" in the model.	Refine "interact" that connects "internal stakeholders" and "external stakeholders" into "communicate"

Interaction

#	Topic	Review	Conclusion
Entity			
IE2	The term "level of trust"	The utilisation of the term "level" was intended to describe the term that follows it, i.e. "trust". In other words, "level" was a descriptor of "trust" (i.e. entity). In the model, the descriptor of entity was represented as an attribute. To ensure the consistency of the model, the term "level of trust" was refined to "trust", and "level" (i.e. the descriptor of trust) was attached as its attribute.	Refine "level of trust" to "trust" Add "level" as an attribute of "trust"
Attribute			
IA2	Sub-classes of "communication"	As can be seen in the second version of the model (Section 7.5), two divisions of communication were identified: formal and informal. In this sense, formal and informal can be seen as divisions (i.e. sub-classes) of "communication". To determine the type of relationship between "communication" and its sub-classes (i.e. overlapping or disjointed), transcripts from the industrial investigation was revisited. From which, it was identified that the way people communicate cannot be both formal and informal at the same time. For example, INT-12 mentioned that a formal communication mostly occur in the meeting with relatively small portion of an informal communication (e.g. for ice breaking). Differ from a formal communication; an informal communication takes place in various places such as kitchen area, the individual's desk, and the office's hallway with no portion of formal communication. For this reason, the relationship between communication and its sub-classes can be categorised as "disjointed".	Add "formal" and "informal" as sub-entities of "communication" with "disjointed" relationship
IA3	Attributes of "professional" and "personal" relationship	The industrial investigation indicated that professional relationship was established through work related interactions while personal relationship through non-work related interactions. From these, two points can be concluded: 1) way of establishment describes relationship as personal and professional, and thus, can be categorised as an attribute of relationship, and 2) "work related" and "non-work related" describes the way of establishments (i.e. attributes) of relationship, and thus, can be categorised as value attributes. Based on these points, "way establishment" was added as an attribute of relationship. Additionally, as value attribute was excluded in ERD, "work related" and "non-work related" were eliminated from the model.	Add "way of establishment" as an attribute of "relationship" Delete "work related" and "non-work related" as sub-attributes of "professional" and "personal" relationship
Relationship			

IR8	Relationship between “stakeholder” and “communication”	As mentioned in HR13, communication was identified as the main form of interaction performed by stakeholders in CED activity. In this sense, stakeholders can be seen as the performer of communication. As such, in the model, “stakeholder” and “communication” were linked through a relationship “perform”	Add "perform" between "stakeholder" and "communication
IR9	Relationship between “communication” and “relationship”	As described in Section 7.4.2.2, a relationship between participants of CED (i.e. stakeholders) can exist if there is an interaction between them. In this sense, it can be perceived that interaction creates relationship between collaborative design participants. Since interaction was refined into “communication” entity in the model (see HR13), the relationship “creates” were used to link “communication” and “relationship”.	Add "create" between "communication" and "relationship"
IR10	“Interact” as identifying relationship	In the second version of the architectural model, “interact” (changed into “communicate” as discussed in HR13) was categorised as an identifying relationship, i.e. a relationship that determines the existence of another entity (Section 7.4.2.2). However, identifying relationship was inappropriately defined. Identifying relationship may be defined as a relationship that connects between a weak and a strong entity (Pol and Ahuja, 2007; Elmasri and Navathe, 2011). As mentioned in Appendix 6, recognising different types of entity (i.e. weak and strong) was excluded from the study. Accordingly, the application of identifying relationship was also excluded from the model. Thus, all relationships that was categorised as identifying relationship (i.e. “communicate”) were refined to relationship.	Refine the category of "communicate" from identifying relationship to relationship

Conflict

#	Topic	Review	Conclusion
		Entity	
CE2	The term “new policy”	The significance of “new policy” to the socio-technical elements of collaborative design was questioned by a participant in W2. According to them, the influence of “new policy” to CED activity was not significant, and thus, no need to include in the model. In the second version of the architectural model, the term “new policy” was referred to a policy that none existed before. From this perspective, “new policy” can be seen as a type of policy. However, its relationship with the other elements of CED activity presented in the model was not evident. As such, representing “new policy” as an entity was considered unnecessary. For this	Delete the term “new policy” Delete “motivates” that connect “conflict” and “new policy” Add “influences” to connect “conflict” and “policy”

		reason, the term "new policy" was deleted from the model. The industrial investigation indicated that conflict motivates the emergence of new policy (i.e. a type of policy). In this sense, it seems reasonable to view conflict as an influence to policy. On this ground, "conflict" and "policy" was connected, using the relationship "influences".	
	Relationship		
	The term "hampered by" between "conflict" and "relationship"	To ensure the consistency throughout the model, all relationship types in the model were determined to be presented as "active verbs" (see Section 6.5.1.3). On this basis, the term "hampered by" that links "relationship" and "conflict" (i.e. relationship hampered by conflict) was refined to "hampers". Accordingly, the direction of relationship was changed from "relationship" to "conflict", into "conflict" to "relationship". To show this direction, an arrow is added.	Refine "hampered by" that connects "conflict" and "relationship" to "hampers"

Organisation

#	Topic	Review	Conclusion
Attribute			
OA3	"Politics" as an attribute of "organisation"	The industrial investigation revealed that the organisation was influenced by (the government and organisational) politics (See Section 7.4.2.4), and it influences its CED activities. From this perspective, politics can be viewed as an influencing factor to an organisation. In this sense, *politics* is a value of influencing factor (of organisation). Furthermore, the evident to support that politics can be used to differentiate between on organisation to another was not identified. Based on these points, *politics* cannot be categorised as an attribute of organisation. To show the influence of politics to collaborative design activity, "politics" was represented as an entity and connected with "organisation", using the term "influences" as identified aforementioned.	Refine "politics" from attribute to entity Add "influences" to connect "politics" and "organisation"
Relationship			
OR2	Relationship between "organisation" and "history"	In the second version of the model, "organisation" and "history" was connected by "learns from" relationship. However, as mentioned in Section 7.4.2.4, the industrial investigation indicated that Company 1 was not only learns from history, it also conditioned by history. In this sense, history can influence organisation in more than one way. To present the various influence of history to the organisation, the term utilised to connect	Refine "learns from" that connects "history" and "organisation" into "influences" relationship

		"history" and "organisation", was changed into a more general term, i.e. "influence".	
OR3	Relationship between "organisation" and "stakeholder"	The term "belongs to" that connects "organisation" and "stakeholder" was intended to present the position of stakeholder as a part of organisation (Section 7.4.2.4). However, from the dictionary perspective, the term "belongs to" represents ownership (The Oxford English Dictionary, 2013). This was considered inappropriate for the mentioned intention. As mentioned in Section 7.4.2.1, stakeholders are employed by organisations. On this basis, the term "employs" was deemed more appropriate to connect "stakeholders" and "organisations", rather than the term "belongs to".	Refine "belongs to" that connects "organisation" and "stakeholder" to "employs"
OR4	Relationship between "organisation" and "legislation"	In the model, "organisation" and "legislation" were linked by "creates" relationship. In this context, the term "organisation" was referred specifically to the governing body (i.e. government). However, the term "organisation" in the model was intended to represent all organisations directly involved in the CED activity. In this sense, the relationship between "organisation" and "legislation" was deemed inappropriate. The industrial investigation indicated that legislation was applied by the organisation involved in CED activity as a basis to design the technical system. From this perspective, organisation and legislation can be connected by the term "applies" (i.e. organisation applies legislation), and thus, the relationship between "organisation" and "legislation" was changed from "creates" to "applies".	Refine "creates" that connects "organisation" and "legislation" to "applies"

Boundary

#	Topic	Review	Conclusion
Entity			
BE2	The term "culture difference"	The term "culture difference" in the model consists of two words: "culture", which is a noun, and "difference" which contextualised the noun (i.e. a modifier). Such composition of term was considered inconsistent with the other entities presented in the model. For this reason, the term "culture difference" was refined into "culture". Consequently, the relationship between "culture" and "location" needs to be redefined. The redefinition can be seen in BR6.	Refine the term "culture difference" to "culture"
	Attribute		
BE3	Attribute of "culture difference"	From the industrial investigation, two types of culture were derived: social and organisational culture. Basing on this, "type" was presented as	Delete "type", an attribute of "culture"

		an attribute in the second version of the model, with social and organisational as its sub-attributes. From the dictionary perspective, the term "type" may be referred as category or division, which is not a property of an entity. As such, type cannot be viewed as an attribute. Rather, "type" denotes a division of an entity (i.e. sub-entity), and thus, "social" and "organisation" can be viewed as divisions (i.e. sub-entities) of "culture". On this basis, the model was refined. In addition to the above, although the industrial investigation revealed some indications on how social culture and organisational culture influence CED activity (See Section 7.4.2.4), the evident of culture can be both social and organisational (i.e. overlapping) was not identifiable from the industrial investigation result. As such, the relationship between culture and its sub-classes was presented as "disjointed" in the model.	Refine "social" and "organisational" from sub-attributes of "culture" to sub-entities of "culture" with "disjointed" relationship
Relationship			
BR1	Relationship between "organisation" and "location"	Within the organisation theme, "location" was presented as a property of organisation that can be used to describe it (i.e. an attribute). However, location has significance in CED activity. This can be seen from its relationship with the other identified socio-technical elements, presented in the model (e.g. culture). To show its significance to CED activity, "location" was also presented as an entity. With respect to its relationship with "organisation", as aforementioned, "location" was a property of "organisation". From this perspective, organisation can be seen as the owner of location. To present ownership, "organisation" and "location" were connected by the term "has".	Add "has" to connect "organisation" and "location"
BR2	Relationship between "organisation" and "organisational" culture	As described in Section 7.4.2.5, organisational culture, a sub-entity of culture may be defined as a custom embedded in an organisation. From this perspective, organisational culture can be perceived as a property of an organisation. To present the ownership of organisational culture by an organisation, "organisational culture" and "organisation" were linked by the term "has".	Add "has" to connect "organisation" and "organisational" culture
BR3	Relationship between "location" and "communication"	As described in Section 7.4.2.4, the industrial investigation suggested that location was a boundary of communication. However, this relationship was not presented in the second version of the model. To present this in the model, "location" and "communication" was connected with the term "bounds".	Add "bounds" to connect "location" and "communication"
BR4	Relationship between "culture difference" and "conflict"	Since the term "culture difference" was changed into "culture" (see BE2), the relationship that initially linked "culture difference" and "conflict" (i.e. "may causes") was considered no longer appropriate to link "culture" and "conflict". As shown in Section 7.4.2.4, culture difference may	Delete "may causes" that connects "culture differences" and "conflict"

		cause conflict. This was supported by the industrial investigation result and a number of literatures in organisational context (e.g. (Lloyd and Härtel, 2010; Voss, Albert and Ferring, 2014). However, the evidence that support the relationship between "culture" and "conflict" only was not identifiable in the industrial investigation result and the literature. For this reason, the relationship between "culture" and conflict" is eliminated.	
BR5	Relationship between "location" and "culture"	As discussed in BE2, the term "culture difference" was refined into "culture". Such change made the relationship that initially linked "location" and "culture difference" (i.e. "leads to") was considered no longer appropriate to link "location" and "culture". As identified and presented in Section 7.4.2.4, the industrial investigation indicated that location was an influence on culture. On this basis, "location" and "culture" were linked by the term "influences"	Refine the term "leads to" that connects "location" and "culture" to "influences"
BR6	Relationship between "relationship" and "policy"	As mentioned in Section 6.5.1.3, the terms used to represent the relationship between entities were determined as "active verb" throughout the model. As such, the terms "bounded by" that connects "relationship" and "location", as well as "policy" and "rule" was changed to "bounds".	Refine the term "bounded by" that connects "relationship" with "location", "policy" and "rule" to "bounds".

Design information

#	Topic	Review	Conclusion
		Attribute	
DA6	Attributes of "design information"	With respect to the attributes of "design information" there are two attributes commented by the participants in W2 ("amount" and "importance") as being overly specific to the CED activity in Company 1. According to them, a more generic term that represents the attributes of information was needed. From the general perspective of information theory, the importance of information can be related to its value (Hilbert, 2012). From the dictionary perspective, the term "value" may be related with the importance and the amount of something (The Oxford English Dictionary, 2013). On this basis, the term "value" was perceived appropriate to represent "amount" and "importance", and thus, was used to replace them. In addition to the above, motivated by the aforementioned comment from the participants,	Add "quality" as an attribute of "design information" Add "value" as an attribute of "design information" Delete "amount", an attribute of "design information" Delete "importance", an attribute of "design information"

		the term "consistency" was evaluated. Eppler (2006) revealed eight attributes of information that can be related as the quality of information: comprehensiveness (e.g. complete), accuracy (e.g. detail), clarity (e.g. easy to understand), applicability (e.g. useful), conciseness (e.g. brief but comprehensive), consistency (e.g. no contradictions), correctness (e.g. no error) and currency (e.g. reflective). From this perspective, the term "quality" covered "consistency" and other attributes of design information in a more general sense. The term "quality" was perceived more generic, and thus, more appropriate than "consistency". For this reason, the term was added to replace the term "consistency".	Delete "consistency", an attribute of "design information"
DA7	Sub-attribute of "nature"	"Inter-related" was presented as a sub-attribute of "nature" in the second version of the architectural model. However, the term "inter-related" describes the nature of design information rather than describes a division of "nature". From this perspective, "inter-related" suits the definition of value attribute rather than sub-attribute. As aforementioned, in ERD, value attribute is not included in the model, and thus, "inter-related" was eliminated from the model.	Delete "inter-related", a sub-attribute of "nature"
DA8	Attribute of "information system"	Mentioned in Section 7.4.2.6, "design information was stored in computer-based information systems". For this reason, "computer-based" was presented as an attribute of information systems, as it was initially perceived as a property that describes information systems. However, the term "computer-based" describes the basis of information system, instead of describing the "information system" itself. From this perspective, "computer-based" cannot be categorised as an attribute of "information system". Instead, it can be categorised as a value attribute (i.e. the value of "basis"). As aforementioned, value attribute was not included in ERD, and thus, "computer-based" was deleted from the model.	Delete "computer-based", an attribute of "design information"
		Relationship	
DR12	Relationship between "stakeholder" and "design information"	To ensure the consistency of the model, all terms that represent relationships were presented in active form, as discussed in Section 6.5.1.3. For this reason, the term "exchanged by" that connects "stakeholder" and "design information" was changed to "exchanges".	Refine the term "exchanged by" that connects "stakeholder" and "design information" to "exchanges"
DR13	Relationship between "design information" and "model"	For the same reason mentioned in DR12, the term "represented as" that connects "design information" and "model" was changed to "represents".	Refine the term "represented as" that connects

			“design information” and “model” to “represents”.
DR14	Relationship between “information system” and “design information”	For the same reason mentioned in DR12, the term “stored in” that connects “design information” and “information system” was changed to “stores”.	Refine the term “stored in” that connects “information system” and “design information” to “stores”
DR15	Relationship between “design process” and “design information”	For the same reason mentioned in DR12, the term “utilised in” that connects “design process” and “design information” was changed to “utilises”.	Refine the term “utilised in” that connects “design process” and “design information” to “utilises”
DR16	Relationship between “design requirements and constraints” and “design specification”	For the same reason mentioned in DR12, the term “translated into” that connects “design specification” and “design requirements and constraints”.	Refine the term “translated into” that connects “design requirements and constraints” and “design specification” to “translates”
DR17	Relationship between “design specification” and “design problem”	The connection between “design specification” and “design problem” was represented by the term “aid to identify”. In this sense, the term “aid to identify” can have two main functions: 1) to describe the relationship between the “design specification” and “design problem” (i.e. “aid”), and 2) to specify (describe) the “aid” that design specification does to design problem (i.e. to identify). This was considered inconsistent with the other terms used to represent the relationships between entities, which commonly consist of a single active verb, describing the relationship only. As mentioned in Section 7.4.2.6, “design specifications” can be used to identify (and resolve) design problem. From this perspective, the term “aid to” was deemed unnecessary to show the connection between design specification and design problem. Thus, it was eliminated, leaving the term “identifies” to represent the connection between “design specification” and “design problem”.	Refine “aid to identify” that connects “design specification” and “design problem” to “identifies”

Tools

	Topic	Review	Conclusion
Attribute			
TA3	Attribute of "technical tools"	In the second version of the model, the term "function" was used to represent an attribute of "technical tools" only. However, having gained a better understanding of the phenomena of CED activity, it becomes apparent that "technical tools" were not the only division of tools that has "function" as a property that describes them. As can be seen in Section 7.4.2.7, the tools were classified into communication tools, i.e. the type of tool that used to exchange information between stakeholders, and technical tools, i.e. the type of tool used to design the technical system. From the dictionary perspective, the use of something (e.g. tools) may be regarded as a function (The Oxford English Dictionary, 2013). From this perspective, the two types of tools (i.e. communication and technical tools) possess "function" that can be used to describe them. Thus, the term "function" was used to represent an attribute of "tools". Additionally, as sub-entities inherit the attributes of their parent (Appendix 6) the attribute "function" in the "technical tools" (sub-entity) was deleted as it has been covered by the attribute "function" in the "tools" (parent).	Add "function" as an attribute of "tools" Delete "function", an attribute of "technical tools"
TA4	Attribute of "communication tool"	In the second version of the model, "type" was presented as an attribute of "communication tools" with "synchronous" and "asynchronous" as its sub-attributes. As discussed in the previous points (e.g. BE3), the term "type" denotes the divisions of an entity instead of describing the entity, and thus, "type" cannot be categorised as an attribute. As type denoted the divisions of an entity, its members (i.e. synchronous and asynchronous), can be regarded as sub-entities (of communication tools). To link the entity with its sub-entities, a type of relationship (i.e. disjointed or overlapping) needs to be defined (See Appendix 6). In Section 7.4.2.7 where the examples of communication tool derived from the industrial investigation were listed, it can be seen that a communication tools (i.e. Lync video conferencing and instant messenger) can be a member of synchronous and asynchronous tool. In ERD, the relationship between an entity and its sub-entities, where the entity can be a member of more than one sub-	Delete "type", an attribute of "communication tool" Refine "synchronous" and "asynchronous" from sub-attributes to sub-entities of "communication tools" with "overlapping" relationship

		entity may be regarded as "overlapping". On this basis, the relationship between "communication tools" and its sub-entities (synchronous and asynchronous) was defined as "overlapping".	
TA5	Sub-attributes of "technical tools"	In the second version of the model, "calculation" and "visualisation and representation" were presented as sub-attributes (i.e. division of attribute) of "function". However, these terms were intended to describe the two basic functions of technical tools, indicated from the industrial investigation. As they were intended to describe an attribute (i.e. function), they can be categorised as value attributes (i.e. descriptors of attribute) rather than sub-attributes. According to the ERD concept, value attribute was not presented in ERD, and thus "calculation" and "visualisation and representation" were deleted from the model.	Delete "calculation" and "visualisation and representation", sub-attributes of "technical tools"
Relationship			
TR3	Relationship between "communication tools" and "communication"	As mentioned in Section 7.4.2.7, the industrial investigation revealed the role of communication tool as facilitating communication between different locations. On this basis, in the second version of the model, "communication tool" and "location" were connected by the sentence "facilitate communication between". This sentence was considered inconsistent with the other terms used to represent the relationships between entities, which commonly consist of an active verb. Having analysed the aforementioned sentence, it can be seen that the main relationship exists between communication tools and communication (i.e. communication tools facilitate communication), while "between different locations", from grammatical perspective, can be perceived as an *adverbial adjuncts*. Adverbial adjuncts add more information to the sentence, however, without them; the sentence can still make sense. From this perspective, the relationship that needs to be represented in the model was between communication tools" and communication" instead of between "communication tool" and "location". For this reason, the relationship between "communication tool" and "location" was deleted, and the relationship between "communication tools" and "communication was added using the term "facilitate".	Add "facilitates" to connect "communication tools" and communication" Delete "facilitate communication between" that connects "communication tools" and "location"
TR4	Relationship between "stakeholders" and "tools"	As indicated from the industrial investigation and mentioned in Section 7.4.2.7, stakeholders use various tools to support their work in CED activity. For example, to exchange design information they use communication tools such as email and telephone; to create 3D models they use technical tools such as software called FORAN. From this perspective, stakeholders can be viewed	Add "utilises" to connect "stakeholders" and "tools"

		as a user of tools. The relationship between "stakeholders" and "tools" was not represented in the second version of the model, and thus, was added.	
TR5	Relationship between "design information" and "technical tools"	To ensure consistency throughout the model, the terms utilised to represent relationship between entities were determined as "active verbs". The terms used to connect "design information" and "technical tools", i.e. "processed through" and "created through" were considered as passive verbs, and thus, they were changed into "process" and "create", respectively.	Refine the term "processed through" that connects "design information" and "technical tools" to "processes"
TR6	Relationship between "technical tools" and "model"	For the same reason as TR5, the term "created through" that connects "technical tools" and "model" was changed to "create" to be changed to "create".	Refine the term "created through" that connects "technical tools" and "model" to "creates"

Technical system

#	Topic	Review	Conclusion
		Attribute	
TSA1	"Interrelated" as an attribute of "technical system"	As described in Section 7.4.2.8, technical system was described as being interrelated. From this perspective, the term "being" can be considered as an attribute, as it describes the technical system, while the term "interrelated" can be considered as a value attribute (of "being) as it describes the "being" of the technical system. As aforementioned, a value attribute is not presented in the model, and thus, "interrelated" was deleted. From the dictionary perspective, the term "being" can be related with a nature of something (i.e. technical system). As nature can be used to describe technical system and the industrial investigation identified the influence of nature (e.g. interrelated) to CED practice (See Section 7.4.2.8), "nature" was added as an attribute of technical system.	Add "nature" as an attribute of "technical system" Delete "interrelate", an attribute of "technical system"
TSA2	"Complex" as an attribute of "technical system"	Also described in Section 7.4.2.8, technical system was described as being complex. As such, similar with the analysis of the term "interrelated" (see TSA1), the term "complex" can be regarded as a value attribute (i.e. a value of "being") instead of an attribute, and thus, was deleted from the model.	Delete "complex", an attribute of "technical system"

TSA3	"Integrated" as an attribute of "technical system"	Also described in Section 7.4.2.8, technical system was described as being integrated. As such, similar with the analysis of the term "interrelated" (see TSA1) and the term "complex" (see TSA2), the term "integrated" can be regarded as a value attribute (i.e. a value of "being"), and thus, was deleted from the model.	Delete "integrated", an attribute of "technical system"
		Relationship	
TSR2	Relationship between "technical system" and "design information"	As discussed in TSR1, the term "underpins" that connects "technical system" and "design information" was already covered the relationship between "technical system" and "design requirements and constraints". To avoid redundancy, the relationship between "technical system" and "design requirements and constraints" (i.e. "complies to") was deleted.	Delete "complies to" that connects "technical system" and "design requirements and constraints"
TSR3	Relationship between "technical system" and "technical conflict"	The term "influenced by" was considered as a passive verb. As pointed out in Section 6.5.1.3, active verbs were utilised throughout the model to represent the relationship between entities. For this reason, the term "influenced by" "technical system" and "technical conflict" was changed to "influences" that connect.	Refine "influenced by" that connects "technical system" and "technical conflict" to "influences"

Design process

	Topic	Review	Conclusion
		Entity	
PE3	The term "new policy"	See CE2	Delete the term "new policy"
PE4	The entity "design review process"	The industrial investigation indicated, design review process was mainly conducted to evaluate the design as well as to decide if the design process can be continued to the next stage (as described in Section 7.4.2.9). In other words, without the design review process, design process cannot be progressed. From this perspective, design review process can be seen as an integrated part of the design process. As design review process is a part of an entity (i.e. design process), it can be categorised as a sub-entity. To present design review process in the model, it was connected to "design process" as its sub-class.	Add "design review process" as a sub-entity of "design process"
		Attribute	
PA11	Sub-attributes of "requirement"	In the second version of the model, the tern "requirement" was presented as an attribute of "design process". As shown in the model, the requirement has three sub-attributes, "communication", "awareness", and "consistency". Within the context of ERD, a sub-	Delete "communicati on", "awareness", and "consistency",

		attribute denotes the divisions of an attribute. However, as can be seen in Section 7.4.2.9, the terms “communication”, “awareness”, and “consistency” were intended to describe the requirements of design process (e.g. to ensure that the design is well integrated, design teams are required to intensively communicate). As communication, awareness and consistency describe requirements (i.e. attribute of design process), they can be categorised as value attributes instead of sub-attributes of “requirements”. According to ERD concept, value attribute is not presented in the model, and thus “communication”, “awareness”, and “consistency” were removed from the model.	sub-attributes of “requirement”
PA12	Attribute of “design process”	As discussed in PA2, “schedule” and “cost” can be used to describe a design process, and thus, they were added in the model, as attributes of “design process”. The addition of “schedule” was presented in PA2. In this point (PA12), the addition of “cost” was documented.	Add “cost” as attribute of “design process”
Relationship			
PR5	Relationship between “design process” and “risk”	As mentioned in Section 7.4.2.1, stakeholders share a common goal(s) and risk(s) related to the design of technical system and the process of designing it. From this perspective, it can be concluded that a design process has a goal(s), as well as risk(s), that stakeholders are shared in CED activity. However, this relationship between “design process” with “goal” and “risk” was not presented in the second version of the model. Their existence need to be shown as having a shared-goal and risk were identified as one of the characteristics of CED activity (see Chapter 1). To present this in the model, the term “has” was used as a relationship that connects “design process” and “goal”, as well as “design process” and “risk”	Add “has” to connect “design process” and “risk” Add “has” to connect “design process” and “goal”
PR6	Relationship between “concept design process” and “design review process”	In the second version of the model, “concept design process” and “design review process” were connected by the term “reviewed in” relationship (i.e. concept design process is reviewed in design review process). However, as mentioned in Section 7.4.2.9, design review process reviews the result of design process instead of the process. As such, the connection between “concept design process” and “design review process” was deemed inappropriate. Thus, the connection (i.e. “reviewed in”) was deleted from the model.	Delete “reviewed in” that connects “concept design process” and “design review process”
PR7	Relationship between “detailed design process” and “design review process”	For the same reason mentioned in PR6, the connection between “detailed design process” and “design review process” was deemed inappropriate, and thus, was deleted from the model.	Delete “reviewed in” that connects “detailed design process” and “design

			review process”
PR8	Relationship between “design problem” and “design review process”	In the second version of the model, “design problem” and “design review process” were connected by the term “resolved in” as a relationship type. The term “resolved in” may be categorised as a passive verb. As described in Section 6.5.1.3, the terms that represent relationship between entities were uniformed to active verb. For this reason, the term “resolved in” was changed into its active form, i.e. “resolves”.	Refine “resolved in” that connects “design review process” and “design problem” to “resolves”
PR9	Relationship between “model” and “design review process”	For the same reason as mentioned in PR8, the term “utilised in” that connects “model” and “design review process” in the second version of the model was changed into “utilises”	Refine “utilised in” that connects “design review process” and “model” to “utilises”
PR10	Relationship between “design process” and “conflict”	For the same reason as mentioned in PR8, the term “influenced by” that connects “design process” and “conflict” in the second version of the model was changed into “influences”	Refine “influenced by” that connects “design process” and “conflict” to “influences”

Appendix 13: Aggregation of relationships

#	Themes		Analysis	Aggregated relationship
AG1	Human being	Design process	As mentioned in Chapter 6, "human beings" are viewed the main actor of CED activity who conducts the design process. When conducting a design process, human beings perform a number of activities as shown in the model (i.e. share goal, share and manage risk, and manage design process). From this perspective, the term "conduct" that connects "human beings" and "design process" can be used to represent the other relationships between "human being" and "design process" outlined in Table 40: "share" and "manage".	Conduct
AG2	Human being	Design information	Three relationships between the member of "human being" and "design information" theme were derived from the model (see Table 40): 1. "Exchange" (connecting "human being" and "design information" 2. "Provide" (connecting "customers and users" and "design requirement and constraints") 3. "Supply" (connecting "suppliers" and "design specification"). From the dictionary perspective, the terms "supply" and "provide" can be viewed as synonyms (The Oxford English Dictionary, 2013). In the context of the model presented in this thesis, "supply" and "provide" relates to the act of giving (information). This can be seen as a part of the act of "exchange", which lexically consists of the act of giving and receiving (The Oxford English Dictionary, 2013). On this basis, the term "exchange" was viewed as a representation of the identified relationship between "human being" and "design information" (i.e. provide and supply), and thus, it was used in the aggregated model of collaborative design.	Exchange
AG3	Organisation	Human being	Two relationships between the member of "organisation" and "human being" theme were derived from the model (see Table 40): 1. "Employs" (connecting "human being" and "organisation") 2. "Underpins" (connecting "history" and "opinions") As mentioned in Appendix 3, experience on the past event (i.e. history) in the organisation underpins the opinion of the participants, and eventually influence their behaviour. For example, due to unpleasant experience regarding the application of	Employs

			company's policies in the past, employees have opinion that new policies are "useless", and they tend to be more reluctant when new policies are introduced. However, from this perspective, it can be concluded that stakeholders opinion is influenced by its organisational history, if they are part of (i.e. employed by) the organisation. As such, the relationship between the "organisation" and "stakeholders" entity (i.e. employs) can be seen as a determinant relationship between "history" and "opinions". On this basis, to aggregate the relationship between the "organisation" and "human being" theme, the relationship "employs" was used.	
AG4	Tools	Design information	Two relationships between the members of "tools" and "design information" theme were derived from the model (see Table 40): 1. "Process" (connecting "technical tools" and "design information") 2. "Store" (connecting "information tools" and "design information") From the derived relationships, it can be concluded that tools perform services to design information by processing and storing it. Thus, the term "serve" was deemed appropriate to connect "tools" and "design information", and to represent the aforementioned relationships between the member of "tools" and "design information" theme.	Serve
AG5	Design process	Design information	Two relationships between the member of "design process" and "design information" were identified from the model (see Table 40): 1. "Utilises" (connecting "design process" and "design information") 2. "Resolves" (connecting "design review process" and "design problem") The term uses to represent the relationship above denote the role of design process to design information. From this perspective, semantically, these terms cannot be aggregated as they were viewed denoting a different concept: the term "utilises" denotes that design process *make use* of design information while the term "resolves" denotes that design process *handle* design information. For this reason, to aggregate the relationship, the relationship between design process and design information was analysed from the industrial investigation. As mentioned in Section 7.4.2.9, during the design review process, when resolving design problem, a model (a representation of design information) is typically used for communication purposes. In this sense,	Utilises

			design information is also utilised in the design review process. On this basis, the term "utilised" was perceived more appropriate to connect "design process" and "design information" as it also addresses the process of design review (i.e. "design review process") to resolve the "design problem".	

Appendix 14: Findings from B1 and B2

Citations	Source		Findings
	B1	B2	
"…the less **competent people** are, the more they overestimate their performance, partly because they don't know good performance when they see it." (p.7)	√		Human beings have competency
"Problems result from ego, bad attitudes, abrasive personalities, neurotic tendencies, **stupidity or incompetence**." (p. 25)	√		
"…these qualities [of manager] that develop over time, nurtured by **self-awareness and a willingness to make mistakes, listen to feedback and adapt your approach accordingly**. In the next chapter, we look at ways in which you can develop **these competencies.**" (p.30)		√	
"People's skills, attitude, energy, and **commitment** are vital resources that can make or outbreak an enterprise" (p.117)	√		Human beings have commitment
"Such bonds give the team a cohesion that allows it to ride out the bad times, as well as boosting the contentment of team members, improving work performance, and **commitment** to the job" (p.20).		√	
"Once you have succeeded in getting people to be honest about their needs, values, and **what they want** from the team, you can work with everyone" (p.74)		√	Human beings have desire
"People's skills, attitude, **energy**, and commitment are vital resources that can make or outbreak an enterprise" (p.117)	√		Human beings have energy
"The structural frame emphasizes the importance of formal roles, traditionally defined by a title or a formal job description. In groups and teams, **individual roles are often much more informal** and implicit on both task and personal dimensions" (p.175)	√		Human beings have natural (informal) role
"**Needs** are a central element in everyday psychology" (p.118)	√		Needs are an important element of a human being's psychology
"Common sense tells us that **needs** are important because we all have them… **Needs** energize and guide behaviour and vary in potency at different times." (p.119)	√		
"Once you have succeeded in getting **people to be honest about their needs**, values, and what they want from the team, you can work with everyone" (p.74).		√	
"The most direct **forms of communication** are active listening, speaking, and non-verbal communication." (p.52)		√	There are two forms of communication: verbal and non-verbal
"Both individual satisfaction and organisational effectiveness depend heavily on the **quality of interpersonal relationships**." (p.182)	√		Relationship has quality
"Every organisation needs to respond to a universal set of internal and external parameters. These parameters or contingencies, include **the organization's** size, **age**, core process, environment, strategy, and goals, information technology and workforce characteristics" (p.60)	√		Organisations have age
"Clear, **well-understood goals**, roles, and relationships and adequate coordination are essential to performance. This is true for all organisations: family, business, hospitals, etc." (p.44)	√		Organisations have organisational goals
"The objective for a telesales team might be to "boost monthly sales figures from cold-calling by 20 per cent by the end of the		√	Organisational goals have focus

year". This statement clarifies what the team needs to achieve by a certain deadline, enabling them to see if and when they have failed, or are likely to fail, so that steps can be taken to remedy the situation. The **focus of the objective** in this example is an increase in productivity." (p.92)			
To be effective, objectives should be **specific, measurable, challenging, and scheduled** (p.92)		√	Organisational goals have quality
"Every organisation needs to respond to a universal set of internal and external parameters. These parameters or contingencies include the **organizations size,** age, core process, environment, strategy, and goals, information technology, and workforce characteristics." (p.60)	√		Organisations have size
"Rules, **policies, standards, and standard operating procedures limit individual** discretion and help ensure that behaviour is predictable and consistent." (p.52)	√		Policies limit human beings
"**Norms (rules)** are established by members observing what behaviour is accepted. For example, team members can arrive late for meetings if they are busy; it's good for people to offer supportive comments to each other." (p.65)		√	Rules consist of norms
"**Rules**, policies, standards, and standard operating procedures limit individual discretion and help ensure that behaviour is predictable and consistent." (p.52)	√		Rules limit human beings
"**A variety of goals is embedded in strategy**." (p.60)	√		Organisational goals are embedded in strategy
"Problem exploration **involves establishing all the relevant facts**, then **trying out different ways of understanding the problem.** Idea generation **consists of pooling the ideas of team members** to arrive at a repertoire of possible solutions." (p.100).		√	Process consists of activities
"Within the context of a team, **risk management is a process that aims to make team members aware of what can go wrong and enable them to assess the impact** of various possible scenarios and act accordingly." (p.110).		√	Risk has impact
"To manage risk, you need to consider **its impact** and probability of occurrence." (p.111)		√	
"To manage risk, you need to consider its impact and **probability of occurrence**." (p.111)		√	Risk has probability (of occurrence)
"**Often the two factors (schedule and budget) are related:** either a delayed completion date results in extra costs, or else a cost shortfall takes time to resolve, with consequent damage to the schedule." (p.109)		√	Schedule and cost influence each other
"**Planning takes place at all levels and stages of activity throughout the course of a team's life and is important as a way to make sure that the team achieve its goals - on schedule and (if applicable) on budget**. The degree of detail in the planning is critical to success. Too little, and you are at the mercy of unforeseen complications." (p.108)		√	Team work requires planning

Appendix 15: Review of findings from B1 and B2

#	Findings	Review	Refinements
		Human being	
HB1	Human being have competency	In human resource management, competency can be defined as the ability of a human being to perform something satisfactory using their sets of knowledge and skills (Herling, 2000). A CED team commonly consists of members possessing diverse competencies (Dym, 2003; Legardeur, Minelb and Savoieb, 2007). Their individual contribution to the design tends to be grounded upon these (Yang et al., 2012). From this perspective, *competency* can be used to differentiate the contribution of *human beings* in CED team, and thus, can be used to characterise them. On this basis, *competency* was categorised as an attribute of human being (i.e. *stakeholders*). Different competencies can produce multiple perspectives towards the design (Bucciarelli, 2002; Legardeur, Minelb and Savoieb, 2007). Furthermore, it creates different perceptions towards their responsibilities (Dym, 2003) to the design process as well as towards the design. This becomes a challenge in collaborative design, especially in the early stage of idea exploration (Sonnenwald, 1996). Contrary to this, Toh and Miller (2015) argued that the wide range of competency aids the development of ideas. According to Pulm and Stetter (2009), there are two types of competencies: social and technical. Technical competency relates to the ability of human actors to accomplish design-related tasks (e.g. computer-aided design utilisation competency), while social competency refers to the ability to facilitate collaboration (e.g. communication and teamwork competency). Bucciarelli (1988) stated that actors' views, beliefs and interest towards the design are based on their technical competency. These often reflect in the design that they made. Social competency, on the other hand, underlies actors' behaviour and action. In collaborative design, actors are suggested to have both types of competency (López-Mesa and Thompson, 2006; Koutsikouri et al 2008). Based on the significance of competency in CED practice as discussed above, it can be concluded that *competency* needs to be presented in the model. Thus, it was added as an attribute of *stakeholders*.	Add *competency* as an attribute of *stakeholders*
HB2	Human beings have commitment	From the industrial investigation, *commitment* was identified as an attribute of customers (Section 7.4.2.1). One factor that differentiated collaboration with cooperation and coordination is the commitment of the participants (Lu *et al*. 2007). That is, the "time, work, and loyalty that someone	Refine the category of *commitment* from an attribute of *customers and users* into an

		devotes to a job" (The Oxford English Dictionary, 2013). Collaboration involves the highest degree of commitment from its participants compared to cooperation and coordination (Lu et al., 2007). From this perspective, commitment cannot be seen as an attribute of *customers and users* only, instead, it is an attribute of all CED participants (i.e. stakeholders). On this basis, the *commitment* attribute was refined from an attribute of *customers and users* into an attribute of *stakeholders*. This particular finding and refinement also triggered an evaluation to the attributes of *customers and users*, i.e. *satisfaction* and *interest* as can be seen in Section 7.4.2.1 they are interrelated. The term "interest" can be defined as "the state of wanting to know about something …" (The Oxford English Dictionary, 2013). From a dictionary perspective, "wanting" is a synonymous of the term "desire", which as can be seen in #HB4 can be considered a feeling. In this sense, the term "interest" can be considered as a synonym of "feeling". In the model, "feeling" had been represented as the *affective* attribute. Based on this, *interest* was developed from the model. The term "satisfaction" can be generally defined as "the feeling of pleasure…" (The Oxford English Dictionary, 2013). In this sense, *satisfaction* can be considered as a (type of) feeling. As aforementioned, "feeling" has been represented in the model. For this reason, *satisfaction* was deleted from the model.	attribute of *stakeholders.* Delete *interest* from the model Delete *satisfaction* from the model.
HB3	Human being have desire	From the dictionary perspective, the term "desire" is defined as "a strong feeling of wanting to have something" (The Oxford English Dictionary, 2013). In this sense, desire can be considered a (type of) feeling. In the model, "feeling" had been represented by the "affective" attribute. Thus, the finding was considered inapplicable to refine the model.	N/A
HB4	Human beings have energy	In this context, the term "energy" may be related with "enthusiasm", which in psychological field, can be viewed as a form of affective attribute of a human being (Huitt, 2005). As *affective* has been represented in the model, this finding was considered inapplicable.	N/A
HB5	Human beings have natural (informal) role	The existence of natural role was identified in the preliminary investigation as an attribute of human beings (Chapter 6). As its existence was not evident in the industrial investigation, it was not included in the model. However, the social literature pointed out the importance of acknowledging and considering natural role in assigning tasks and responsibilities. Without acknowledging and considering natural role, "individuals feel frustrated and dissatisfied, which may foster unproductive or disruptive behaviour" (Bolman & Deal 2013,	Add *natural role* as an attribute of *stakeholders*

		p.175). For this reason, *natural role* was re-added to the model.	
HB6	Needs are an important element of a human being's psychology	According to Bolman & Deal (2013), "human needs" may be identified as a common element of human beings everyday life. They added that all human beings have needs, and thus, it is important to recognise them. Furthermore, they believe that needs motivate the human beings to act a certain way. For example, the need for recognition motivates employees to work hard. Bolman & Deal (2013) argued that human needs are fundamentally similar, what makes it different is their priority towards these needs. In this sense, instead of (human) needs, (human) priority can be used to characterise a human being, and *priority* was already included in the model. In CED context, design of technical system is aimed towards satisfying the needs (i.e. requirements) of customers and users (Section 7.4.2.1). These needs were represented as *design requirements and constraint* in the model, and thus, adding *needs* to the model was deemed unnecessary. For this reason, this finding was considered inapplicable to refine the model.	N/A
	Communication		
C1	There are two forms of communication: verbal and non-verbal	According to West (2004), the most direct forms of communication consist of active listening and speaking, or may be regarded as verbal communication, and non-verbal communication such as gestures. They believed that when people are interacting, they tend to focus on what is conveyed through verbal communication. However, Guye-Vuilieme et al. (1999) remarked that psychological studies revealed, in face-to-face interaction, 65% of information exchanged is conveyed through nonverbal communication. They argued that nonverbal communication amplifies verbal communication to convey information by "helping people express their feelings or thoughts through the use of their bodies, their facial expressions, their tone of voice..." (Guye-Vuilieme et al. 1999, p.49). Along the same line, Michael (1988) outlined five functions of non-verbal communication, where two of them are to support verbal communication, and to express emotions. In this sense, the form of communication can be used to describe communication from the way information is conveyed (i.e. verbal through speaking, non-verbal through, for example, gestures) and the function of communication (i.e. verbal - to convey information, non-verbal-to express emotion and support verbal communication). On this basis, *form* can be used to characterise communication, and thus, can be viewed as an attribute of *communication*.	Add *form* as an attribute of *communication*

		Within the context of collaborative design, the discussions on the forms of communication were identifiable in the literature. For example, (Bierhals et al. (2007) highlighted that to achieve shared understanding in a complex situation, explicit verbal interaction is essential. Cross & Cross (1995) Similarly discussed about the role of verbal communication, particularly to frame design problem. Acknowledging the importance of non-verbal communication aside from verbal communication, Van Dijk and van der Lugt (2013) included non-verbal communication as a parameter to study how participants in collaborative design achieve shared understanding. According to Larsson (2002), both verbal and non-verbal communications affect collaborative design practice. As such, participants need the ability to communicate in both forms. As Johnson (2005) identified the ability to communicate verbal statements and non-verbal signs as two out of seven abilities needed in collaborative design. Recognising that both forms of communication influence CED, studies to develop tools that support them had been carried out. For example, Tang's study in 1991 (Tang 1991, p.150) identify the meaning of hand gestures in drawing activity as the basis to develop computer tools to support collaborative work and concluded that hand gestures are "a significant resources for communicating information… accompanied by verbal communication", and thus, need to be addressed by the tool's function. Having identified the significance of the form of communication to CED, as presented above, *form* was added as an attribute of *communication*.	
C2	Relationship has quality	Bolman & Deal (2013) argued that the quality of relationship between individuals in an organisation influences the individual satisfaction and organisational effectiveness. Settoon & Mossholder (2002) through their literature exploration revealed that the quality of relationship between individuals can be indicated by support, trust, perspective taking (i.e. taking the perspective of other individuals) and empathic concern (i.e. compassion towards other). Others, aside from trust, also include satisfaction (Crosby, Evans and Cowles, 1990) , commitment and conflict (Kumar, Scheer and Steenkamp, 1995), adaptation, communication, and cooperation (Naudé and Buttle, 2000). From this view, "quality" can be used to describe a relationship, and thus, can be categorised as an attribute. Recognising the quality of relationship may be considered essential. In the context of supplier-	Add *quality* as an attribute of *relationship*

		customer relationship, for example, Walter et al. (2003) remarked that it can aid to maintain a long-term relationship, while (Fynes, de Búrca and Mangan, 2008) posit that it influences supplier-customer performance. However, the influence was not apparent in CED context. Thus, the CED practice in Company 1 was explored. In the case of Company 1, the participants communicate limited to their tasks, as necessary (as mentioned by INT-22 and INT-23). The relationships between participants are formed in a perfunctory manner, and thus, the quality of the relationship can be considered poor. This became one of the main causes of the company's major challenges such as conflicts (i.e. social and technical) (INT-5) and segregated relationship (INT-9) in their CED practice, as indicated during the industrial investigation. However, INT-7 and INT-9 implied that the participants generally focus on their task accomplishment, unaware of the quality of relationship between them. As such, the effort to enhance the quality of relationship between the participants is relatively little. Owing to this, it can be concluded that recognising the quality of relationship is essential in CED. For this reason, *quality* was added in the model as an attribute of *relationship*.	
	Organisation		
O1	Organisations have age	Bolman & Deal (2013) argued that the age, as well as the size of organisation, influences organisational structure. For example, small organisations In this sense, "age" and "size" can be used to describe an organisation from its structural perspective, and thus, they can be considered as an attribute of *organisation*. However, the evidence that the age of organisation influences collaboration in general, teamwork, and CED were not identified from both, the literature and the industrial investigation. Owing to this, the finding was considered inapplicable to refine the model.	N/A
O2	Organisations have organisational goals	According to Cochran and Kleiner (1992, p. 13), organisational goals can serve as guidance, foundation, and motivation to the individuals and groups within the organisation. They implied that when organisational goals are determined, all activities within the organisation, conducted by different departments (groups) should be commonly directed towards the organisational goals. For example, if an organisation's goal is to increase profit by 20% in five years, their research and development activity needs to aim at identifying low cost material, their design team needs to aim at creating product that needs less material and have short production time. From this perspective, organisational goal can be seen as a determinant factor of the goal of activities in an organisation, including design activities in CED. This is aligned	Add *organisational goal* as an entity and an attribute of *organisation* Add *has* to connect *organisation* and *organisational goal* Refine the term *goal* in the model into *design process goal*

		with the statement of Wiltschnig et al. (2013, p.536), "in real design practice… collaborating designers work on the development of innovative concepts to meet the commercial goals of a company." Further influence of organisational goal to CED can be seen through its influence to organisational structure. Bolman & Deal (2013) mentioned that organisational goal forms the structure of organisations. In CED context, organisational structure was identified as a determinant factor of stakeholders' roles and responsibilities (Section 7.4.2.4), and thus, was considered as an influencing factor to CED activity. Popova & Sharpanskykh (2011) argued that organisational goals vary between organisations depending on their strategy. For example, the main goal of a company could be the realisation of a maximal amount of profit, whereas the goal of another company could be to be the first in the market. In this sense, organisational goals can be used to characterise an organisation, and thus, can be categorised as an attribute. However, considering its significance to CED activity and its relationship with another entity of CED (i.e. the goal of CED), *organisational goal* was presented as both, an *entity* and an *attribute*. As organisational goal is owned by an organisation, it was connected with the *organisation* entity with the relationship *has*. Additionally, as mentioned above, organisational goals can be seen as a determinant factor of the CED goal. In the model, the CED goal was represented under the term *goal*. However, To make it more specific and differentiate it with the *organisational goal*, this term was changed to *design process goal*. To present the relationship between *organisational goal* and *design process goal*, a relationship, i.e. *determines* was added to the model.	Add *determines* to connect *organisational goal* and *design process goal*
O3	Organisational goals have focus	Four attributes of goals were derived from the different types of goals presented by Cochran & Kleiner's (1992, p.14): 1. "Function" characterises goals based on its role to the organisation's operational function. For example, a goal can serve to increase profitability or market share. 2. "Focus" characterises goals based on its area of enactment. For example, the goal for the design team is to reduce design rework by 50%, while the goal for marketing is to increase sales by 30%. 3. "Time-span" characterises goals based on its duration achievement. For example, a goal can be categorised as a long- term goal (when the target to achieve is more than 10 years), and conversely, others can be categorised as a short-term goal.	Add *focus* as an attribute of *organisational goals*

		4. "Level" characterises goals based on the level of detail of the goal's description. For example, a goal can be described in its most general description such as "to support the government", while other can be described in a more specific way such as "to retain 200 customers in one year". As can be seen above, the focus of the goals determines the goal of the design team (i.e. reduce design rework by 50%). This influences the design process. In the industrial investigation, due to similar focus of the goal (i.e. reduce design rework), the CED activity was changed (e.g. involving customers since the earliest stage of the design process) (Section 7.4.2.4). In this sense, the focus of organisational goals can be viewed as a direct influence to the CED. The influence of the goal's function, time-span, and level to CED was not evident in the industrial investigation as well as the identified literature. On this basis, only *focus* was added as an attribute of *organisational goal*.	
O4	Organisational goals have quality	Janz et al. (1997) characterised a good quality goal as being easily understood by all team members. Cochran & Kleiner (1992) revealed significant, reasonable, challenging, clear and specific, and measurable as the criteria of a good quality of goal. In this sense, it can be concluded that goals can be characterised by its quality. With respect to its relationship with teamwork, the study of Janz et al. (1997) revealed a correlation between the qualities of goals to the success of team effectiveness. They believe that high quality goals positively influence the team effectiveness. In collaboration activity, team effectiveness is identified as one of its key success factors (Lu *et al.*, 2007; Koutsikouri, Austin and Dainty, 2008). From this perspective, the quality of goals can be seen as an influencing factor of collaboration activity (i.e. CED activity). Thus, *quality* was added as an attribute of *organisational goals*.	Add *quality* as an attribute of *goals*
O5	Organisations have size	Similar with #O1, the influence of organisational size to CED practice cannot be identified from the literature and from the industrial investigation. Owing to this, the finding was considered inapplicable to refine the model.	N/A
O6	Policies limit human beings	The role of policies and rules to limit human beings-related cognitive attributes such as their decision, judgement, and preferences an organisation was indicated by Bolman & Deal (2013) in B1. In CED, this relationship between policies to the stakeholders (human beings) was also identified from the industrial investigations (Section 7.4.2). However, the relationship was only identified between policies to the stakeholders' cognitive (i.e. way of thinking) and conative (i.e. way of doing) attribute. For example, one of the policies introduced in Company 1' design process	N/A

		is design maturity, which involves, one of them, the application of a certain set of codes to describe the level of design maturity. Since this policy was introduced, their perception towards design maturity changed, as well as the way they conduct their design process (e.g. not sending/receiving the design from other team unless it is matured). A relationship between policies and the other attributes of stakeholders (e.g. personality) cannot be identified. In EER, a relationship between two entities involves all attributes and subclasses that attached to the said entities. As the relationship between *policies* and *stakeholders* only identified in the stakeholders' *cognitive* and *conative* attribute, their relationship was not added in the model. Thus, this finding was considered inapplicable.	
O7	Rules consist of informal rules	According to West (2004) in organisations, aside from the formal written rules, informal, implicit rules also exist. They regard such rule as as "norms". West (2004, p.65) remarked that norms are derived from what is considered as "an acceptable behaviour". For example, when a team member was 15 minutes late to a meeting, they received no warning. However, when they late more than 15 minutes, warning was given. From this, an informal rule can establish, i.e. they can arrive to a meeting, maximum 15 minutes late. As such, norms can be seen as an influencing factor to the behaviour of human beings. Hackman (1992) perceived it as a guide of behaviour. Within the context of teamwork, acknowledging norms is considered important. It can be identified as an influencing factor to the team success. For example, Dong et al. (2004) mentioned that aside to be successful, a team must show a level of shared understanding of norms in the group. They exemplified norms as, one of them, the way to communicate between team members. Furthermore, Ellemers & Rink (2015) believed that group member needs to recognise the norms of the group where they belong. They added that deviating from the group norms might negatively influence the relationship of a group member with the other team members. Based on the significance of informal rules mentioned above, it seemed reasonable to conclude that recognising the existence of both categories of rules are important to understand the phenomena of CED. Thus, *formal* and *informal* rules were added on the model as sub-classes of *rules*. Additionally, as mentioned above, formal and informal rules have distinct characteristics (e.g. formal rules are written, informal rules are implicit). In this sense, it is virtually impossible that a rule can be both, formal and informal at the same time. Thus, the	Add *informal rule* as a sub-entity of *rule* Add *formal rule* as a sub-entity of *rule* Connect *rules* and its subclasses with *disjointed* relationship

		relationship between *rules* and its subclasses was deemed *disjointed*.	
O8	Rules limit human beings	Similar with policies, as discussed in #O6, the relationship between rules and stakeholders (i.e. regulate) was not include all attributes of stakeholders, presented in the model. For example, one of the rules in Company 1's CED practice is not allowing the engineers to communicate the suppliers directly. Instead, the communication needs to be facilitated by supply chain officers. Such rule can potentially limits the action of engineers and changes how they see their relationship with the suppliers. On this basis, this finding was considered inapplicable to refine the model.	N/A
O9	Organisational goals are embedded in strategy	As mentioned in Section 7.4.2.4, the term "strategy" was defined as a plan(s) (or approach) to achieve (organisational) goals. From this perspective, organisational goals can be seen as the basis of organisational strategy, which was considered as an influencing factor of CED. As such, they were connected through the relationship *underpins*. In addition to the above, the *strategy* represented in the model was referred to *organisational strategy*, created by the organisation. This relationship was not presented in the literature. To clarify the definition of *strategy*, the relationship (i.e. *creates*) between *organisation* and *strategy* was added.	Add *embeds* to connect *strategy* and *organisational goals* Add *creates* to connect *organisation* and *strategy*
	Design process		
DP1	Process consists of activities	In a general sense, the term "process" may be defined as a series of activity (The Oxford English Dictionary, 2013). In other words, as Browning & Eppinger (2002) remarked, activities are the elements of a process. Design process can be generally described based on its activities and stages (Wynn and Clarkson, 2005). This difference description can be seen in the model of design process, identifiable from the literature. For example, in Pahl and Beitz's model, design process is described on chronological order of stages (i.e. planning and clarifying-conceptual design-embodiment design-detail design) (Pahl et al. (2007), while in Pugh's model, design process is described based on different activities therein (e.g. market analysis, decision making) (Pugh, 1991). From this perspective, aside from *stage* (presented in the model), *activity* can be used to describe design process and thus, can be considered as attributes of *design process*. To manage design process, the activities involved in the design process need to be recognised (Austin	Add *activity* as an attribute of *design process*

		et al. 2001, p.213). Furthermore, the organisation of process activities can help to improve the process (Browning and Eppinger, 2002). In this sense, it can be concluded that understanding design activity as an attribute of design process can help to improve the design process, and thus, it needs to be presented in the model. For this reason, *activity* was added as an attribute of *design process*.	
DP2	Risk has impact	In risk management, impact and probability are used to measure risk (Goncalves and Heda, 2014). In this context, "impact" refers to the consequence of the risk when occurs while "probability" to the possibility of the risk to occur. Risks with high impact and high probability of occurrence receive high priority to mitigate (Goncalves and Heda, 2014). To manage risk throughout engineering design process, its impact and probability needs to be monitored and updated overtime (McMahon and Busby 2011). From this perspective, two conclusions can be derived: 1) impact and probability are two key factors to manage risk, 2) impact and probability can be used to characterise risk (severity), and therefore, they can be categorised as attributes of risk. As mentioned in Section 7.4.2.1, stakeholders share and manage risks during CED. McMahon and Busby (2011, p. 287) remarked, "risk management has become a standard engineering technique, contractually required in many engineering projects". To manage risk, the impact of risk and probability (of occurrence) need to be identified. Thus, recognising that risk has *impact* and *probability* as attributes was considered important. Based on this, *impact* and *probability* were added in the model as attributes of *risk*.	Add *impact* as an attribute of *risk*
DP3	Risk has probability	See #DP2	Add *probability* as an attribute of *risk*
DP4	Schedule and cost influence each other	*Schedule* and *cost* are categorised as attributes within the context of the study documented here. The relationship between attributes is not within the scope of the model development, and thus, this finding was considered inapplicable to refine the model.	N/A
DP5	Team work requires planning	In B2, the importance of planning for the success of teamwork is discussed, i.e. to ensure that the team "achieve its goals on schedule and (if applicable) on budget". In the context of design, Maher et al. 1996 (p.27) argued that "planning the design activity seems to be a common procedure followed by designers". The importance of "planning" in CED was also discussed by the participants of W1 (Chapter 8) as well as identified in the literature. For example, Cai (2002) remarked that design planning can affect the quality of the technical system and the cost of the	Add *design process planning* as a sub-entity of *design process*

		design process as during design planning design tasks are determined and organised. Due to its importance, managers seeking to improve their design process care for their process planning (O'Donovan, Eckert and Clarkson, 2004). In addition to determining and organising design tasks, design planning also entails selecting an appropriate "methods and strategy to decompose design problems" (Jacome & Director 1996, p.197). To decompose design problem, designers need to identify the design problem first. In French's model of design process, identifying design problem is a part of design process, prior to conceptual design, embodiment and detailing design (French, 1999). Based on this, design process planning was viewed as a part of design process. Additionally, the participants in W1 revealed that design process planning is an integrated part of the design process as it presents in every stage of the design process. For example, a participant mentioned that during a design review meeting, a plan for the next few months is established. Considering the importance of design planning and management as discussed above, *design process planning* was added in the model as a sub-entity of *design process*.	

Appendix 16: Example of printed model for industrial evaluation

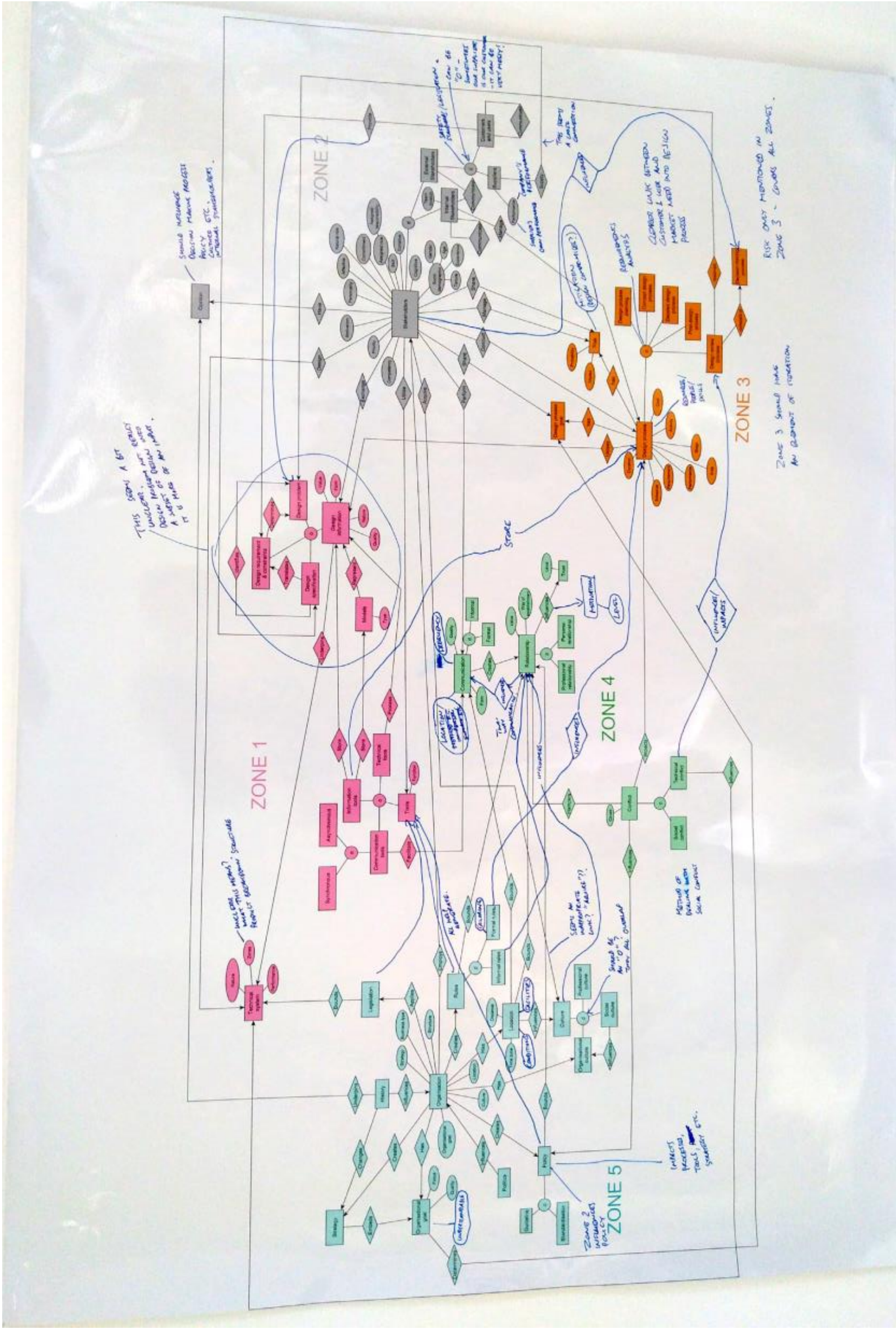


Figure 92 Example of the printed model for industrial evaluation

Appendix 17: Questionnaire form

Collaborative engineering design process

This questionnaire focuses on the company's collaborative engineering design process. Through your experience and knowledge, we intend to identify the usefulness of the model.

All responses will be treated in strict confidence and anonymised. Personal information is sought in case there is a need to clarify any information given.

The questionnaire is 3 (three) pages (including this page), divided into three parts. It will take no more than 10 minutes to complete. If you have any questions regarding the questionnaire, please do not hesitate to contact me.

Thank you for your participation.

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Phone: 01415745290

Personal information (optional)

Name : ……… ……………………………………………………

Email address : ……………………………………………………………………………………

Phone number : ……………………………………………………………………………………

Experience and role information (required)

Current position : ……… ..

Tenure :

1. In the company : … ……..
2. In the current position : … ……..

Please rate the following aspects of the model

Note: please put quotation mark ("….") if you allow us to quote the comment in the thesis

PART 1. Model function

The model provided insights into the collaborative engineering design process

Strongly disagree	Disagree	Neutral	Agree	Strongly agree

Comment:

" SOME PRE-POSITIONING ON MODEL MATURITY MAY HAVE BEEN USEFUL "

My understanding towards the collaborative engineering design process increased after reviewing the model.

Strongly disagree	Disagree	Neutral	Agree	Strongly agree

Comment:

" AWARE OF THE "ISSUES" BUT THE NOVEL WAY OF INTEGRATING INTO THE "DESIGN PROCESS" IN NEW TO US "

PART 2. Model Quality

The model effectively explains the collaborative engineering design process from the socio-technical perspectives

Strongly disagree	Disagree	Neutral	Agree	Strongly agree

Comment:

THE COMPLEXITY ON PAPER IS NOW DRIVING TOWARDS THE NEED FOR A COMPUTERISED MODEL

The model was easy to understand

Strongly disagree	Disagree	Neutral	Agree	Strongly agree

Comment:

See part 1 x 2 above.

The model covers the socio-technical elements of the general collaborative engineering design process

Strongly disagree	Disagree	Neutral	Agree	Strongly agree

Comment:

The model covers the socio-technical elements of [illegible] collaborative engineering design process

Strongly disagree	Disagree	Neutral	Agree	Strongly agree

Comment:

SOME ELEMENTS ABSENT – (SEE MARK-UP)
FOR EXAMPLE SAFETY IN HIGH HAZARD ENVIRONMENT

PART 3. Model Applicability

The model would be useful for [illegible] collaborative engineering design process

Strongly disagree	Disagree	Neutral	Agree	Strongly agree

Comment:

OPENS UP AN AREA POTENTIALLY UN-TAPPED

Additional comment (if any)

GOOD!

Thank you for your input

--**End of questionnaire**---

Appendix 18: Evaluation findings from Company 3

Model changes suggestions

Element of the model	Category of refinement	Suggestions
Human beings		
Sub-entity	Addition	Add "suppliers" as a sub-class of "stakeholders"
Sub-entity	Addition	Add "customers and users" as a sub-class of "stakeholders"
Sub-entity	Addition	Add "employee" as a parent of "stakeholder"
Sub-entity	Deletion	Delete "suppliers" as a sub-class of "external stakeholders"
Sub-entity	Deletion	Delete "customers and users" as a sub-class of "external stakeholders"
Sub-entity	Deletion	Delete "internal stakeholder"
Sub-entity	Deletion	Delete "external stakeholder"
Attribute	Addition	Add "authority" as an attribute of "stakeholders"
Attribute	Addition	Add "performance" as an attribute of "stakeholders"
Attribute	Addition	Add "loyalty" as an attribute of "stakeholders"
Attribute	Addition	Add "bias" as an attribute of "stakeholders"
Attribute	Addition	Add "values" as an attribute of "stakeholders"
Attribute	Addition	Add "influences" as an attribute of "stakeholders"
Attribute	Addition	Add "tangibility" as an attribute of "supply"
Attribute	Expansion	Expand "socio demographic" into for example "sexual orientation"
Relationship	Addition	Add "influences" to connect "opinion" and "relationship"
Relationship	Addition	Add "acquire" to connect "employee" and "culture"
Relationship	Addition	Add "define" to connect "stakeholders" and "design process"
Relationship	Addition	Add "influence" to connect "external stakeholders" and "design process"
Relationship	Addition	Add "define" to connect "stakeholders" and "strategy"
Relationship	Addition	Add "influences" to connect "socio demographic" and "culture"
Relationship	Deletion	Delete "acquire" that connects "stakeholders" and "culture"
Relationship	Expansion	Expand the influence of "opinion"
Communication		
Sub-entity	Addition	Add "governance bodies" as a sub-entity of "professional relationship"
Sub-entity	Addition	Add "customer" as a sub-entity of "professional relationship"
Sub-entity	Addition	Add "local" as a sub-entity of "professional relationship"
Sub-entity	Addition	Add "public" as a sub-entity of "professional relationship"
Sub-entity	Category refinement	Refine subclass of "communication" from "disjoint" to "overlap"

Attribute	Addition	Add "goals" as an attribute of "communication"
Attribute	Addition	Add "balanced teams" as an attribute of "personal relationship"
Attribute	Addition	Add "method" as an attribute of "communication"
Relationship	Addition	Add "influences" to connect "relationship" and "stakeholders"
Relationship	Addition	Add "influences" to connect "relationship" and "organisation"
Relationship	Addition	Add "influences" to connect "relationship" and "design process"
Relationship	Expansion	Expand the influence of "relationship"
Conflict		
Relationship	Addition	Add "influences" to connect "conflict" and "technical system"
Relationship	Deletion	Delete "influences" that connects "technical conflict" and "technical system"
Organisation		
Entity	Addition	Add "governmental politics" and "internal company's politics" as a sub-class of "politics"
Entity	Addition	Add "vision" as an entity
Entity	Addition	Add "work environment" entity
Sub-entity	Addition	Add "environment" as an attribute of "location"
Attribute	Addition	Add "purpose" as an attribute of "organisation"
Attribute	Addition	Add "financial resources" as an attribute of "organisation"
Attribute	Addition	Add "credibility" as an attribute of "organisation"
Attribute	Addition	Add "facility" as an attribute of "organisation"
Attribute	Addition	Add "ways of working" as an attribute of "organisation"
Relationship	Addition	Add "influences" to connect "policy" and "organisational culture"
Relationship	Addition	Add "has" to connect "organisation" and "structure"
Relationship	Addition	Add "impacts" to connect "structure" and "communication"
Relationship	Addition	Add "influences" to connect "culture" and "relationship"
Relationship	Addition	Add "characterises" to connect "legislation" and "design process"
Relationship	Addition	Add "employs" to connect "organisation" and "internal stakeholders"
Relationship	Addition	Add "impacts" to connect "legislation" and "design requirements and constraints"
Relationship	Addition	Add "has" to connect "organisation" and "vision"
Relationship	Addition	Add "influences" to connect "vision" and "strategy"
Relationship	Addition	Add "has" to connect "organisation" and "work environment"
Relationship	Addition	Add "influences" to connect "work environment" and "culture"
Relationship	Addition	Add "influences" to connect "policy" and "strategy"
Relationship	Addition	Add "influences" to connect "culture" and "conflict"

Relationship	Addition	Add "influences" to connect "social culture" and "organisational culture"
Relationship	Addition	Add "influences" to connect "business type" and "culture"
Relationship	Addition	Add "influences" to connect "social culture" and "organisational culture"
Relationship	Addition	Add "influences" to connect "business type" and "culture"
Relationship	Deletion	Delete "changes" that connects "history" and "strategy"
Relationship	Deletion	Delete "employs" that connects "organisation" and "stakeholders"
Relationship	Term refinement	Refine “underpins” that connects “history” and “opinion” into “influences”
Relationship	Expansion	Expand the influence of "culture"
Design information		
Relationship	Addition	Add "influences" to connect "design requirements" and "design process goals"
Relationship	Addition	Add "inputs" to connect "design information" and "technical system"
Relationship	Addition	Add "determines" to connect "requirements" and "design process"
Relationship	Addition	Add "drives" to connect "design information" to "design process"
Tools		
Sub-entity	Deletion	Delete "asynchronous communication tools"
Sub-entity	Deletion	Delete "synchronous communication tools"
Relationship	Expansion	Expand the relationship between "information system" to other type of information
Design process		
Entity	Addition	Add "safety" as an entity in "design process" theme
Entity	Expansion	Expand "post-design process"
Sub-entity	Addition	Add "social safety" as an attributes of "safety"
Sub-entity	Addition	Add "product safety" as an attribute of "safety"
Sub-entity	Addition	Add "personal safety" as an attribute of "safety"
Sub-entity	Addition	Add "prototyping" as a sub-class of "post-design process"
Sub-entity	Addition	Add "procurement" as a sub-class of "post-design process"
Sub-entity	Addition	Add "manufacturing" as a sub-class of "post-design process"
Sub-entity	Addition	Add "commissioning" as a sub-class of "post-design process"
Sub-entity	Addition	Add "delivering" as a sub-class of "post-design process"
Sub-entity	Addition	Add "validation" as a sub-entity of "design review process"
Sub-entity	Addition	Add "verification" as a sub-entity of "design review process"
Sub-entity	Addition	Add "acceptance" as a sub-entity of "design review process"

Sub-entity	Addition	Add "design realisation" as a sub-class of "design process"
Sub-entity	Addition	Add "technical risk" as a sub-entity of "risk"
Sub-entity	Addition	Add "commercial risk" as a sub-entity of "risk"
Attribute	Addition	Add "resources" as an attribute of "design process"
Attribute	Addition	Add "compliance" as an attribute of "design process"
Attribute	Addition	Add "regulation" as an attribute of "design process"
Attribute	Addition	Add "success criteria" as an attribute of "design process"
Attribute	Addition	Add "quality" as an attribute of "design process"
Attribute	Addition	Add "threat" as an attribute of "risk"
Attribute	Addition	Add "opportunity" as an attribute of "risk"
Attribute	Addition	Add "hazard" as an attribute of "design process"
Attribute	Addition	Add "resource" as an attribute of "cost"
Attribute	Addition	Add "funding source" as an attribute of "design process"
Attribute	Addition	Add "cost" as a sub-attribute of "impact" in risk
Attribute	Addition	Add "technical" as a sub-attribute of "impact" in risk
Attribute	Category refinement	Change "requirement" an attribute of "design process" to entity
Relationship	Addition	Add "resolves" to connect "design process" and "design problem"
Relationship	Addition	Add "produces" to connect "design process" and "technical system"
Relationship	Addition	Add "has" to connect "design process" and "safety"
Relationship	Addition	Add "develops" to connect "design process" and "design information"
Relationship	Deletion	Delete "resolves" that connects "design review process" and "design problem"

Questionnaire response from Company

Table 87 Recap of the questionnaire response from the participants in Company 3

Statement	Evaluation criteria	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
The model covers the socio-technical elements of the general collaborative engineering design process	E2			7%	93%	
The model covers the socio-technical elements of Company 3’s collaborative engineering design process	E2		7%	43%	50%	

The model would be useful for Company 3's collaborative engineering design process	E4			21.5%	50%	28.5%
The model was easy to understand	E5		43%	28.5%	28.5%	
The model effectively explains the collaborative engineering design process from the socio-technical perspectives	E6		14%	36%	50%	
The model provided insights into the collaborative engineering design process	E6			-	86%	14%
My understanding towards the collaborative engineering design process increased after reviewing the model	E6			28.5	57.5%	14%

Appendix 19: Evaluation findings from Company 4

Model changes suggestions

Element of the model	Category refinement	Suggestions
Human beings		
Entity	Addition	Add entity "teams"
Sub-entity	Addition	Add "legislation" as a sub-entity of "external stakeholders"
Sub-entity	Category refinement	Refine the relationship between "external stakeholders" and its sub-classes from "disjoint" to "overlap"
Attribute	Addition	Add "partners" as an attribute of "external stakeholders"
Attribute	Addition	Add "values" as an attribute of "stakeholders"
Attribute	Addition	Add "limitations" as an attribute of "customers and users"
Attribute	Addition	Add "intelligent" as an attribute of "customers and users"
Attribute	Addition	Add "culture" as an attribute of "customers and users"
Attribute	Addition	Add "background knowledge" as an attribute of stakeholders
Attribute	Addition	Add "dominate" as an attribute of "stakeholders"
Relationship	Addition	Add "influences" to connect "teams" and "design solution"
Relationship	Addition	Add "delivers" to connect "teams" and "design process"
Relationship	Addition	Add "build" to connect "stakeholders" and "relationship"
Relationship	Addition	Add "break" to connect "stakeholders" and "relationship"
Relationship	Addition	Add "influences" to connect "stakeholders" and "design process"
Relationship	Addition	Add "conduct" to connect "internal stakeholders" and "design process"
Relationship	Addition	Add "influences" to connect "stakeholders" and "decision making process"
Relationship	Addition	Add "resolves" to connect "stakeholders" and "conflict"
Relationship	Addition	Add "create" to connect "stakeholders" and "conflict"
Relationship	Deletion	Delete "conduct" that connects "stakeholders" and "design process"
Relationship	Term refinement	Refine the term "supply" that connects "supplier" and "design information" into "satisfy"
Relationship	Term refinement	Refine "acquire" that connects "stakeholders" and "culture" into "determine"

Relationship	Term refinement	Refine the term "acquire" that connects "stakeholders" and "culture" into "determines"
Relationship	Expansion	Expand the relationship of "opinion" with all other elements of CED process
Communication		
Attribute	Addition	Add "frequency" as an attribute of "communication"
Attribute	Addition	Add "location" as an attribute of "communication"
Attribute	Addition	Add "structure" as an attribute of "communication"
Relationship	Addition	Add "builds" to connect "relationship" and "teams"
Relationship	Addition	Add "resolves" to connect "communication" and "conflict"
Relationship	Addition	Add "influences" to connect "communication" and "relationship"
Relationship	Addition	Add "influences" to connect "relationship" and "communication"
Relationship	Addition	Add "influences" to connect "relationship" and "motivation"
Conflict		
Sub-entity	Addition	Add "organisational conflict" as a sub-class of "conflict"
Relationship	Addition	Add "influences" to connect "technical conflict" and "design review process"
Relationship	Deletion	Delete "influences" that connect "conflict" and "policy"
Relationship	Expansion	Expand the relationship of "conflict" to other elements of the model
Relationship	Expansion	Expand the relationship of "social conflict" to other elements of the model
Organisation		
Entity	Addition	Add "motivation" as an entity in the "organisation" theme
Sub-entity	Category refinement	Refine the relationship between "culture" and its "sub-classes" from "disjointed" to "overlap"
Sub-entity	Category refinement	Refine the relationship between "culture" and its sub-classes from "disjoint" to "overlap"
Attribute	Addition	Add "conditions" as an attribute of "location"
Attribute	Addition	Add "facility" as an attribute of "location"
Attribute	Addition	Add "tailoring" as an attribute of "formal rules"
Attribute	Addition	Add "level" as an attribute of "motivation"
Attribute	Addition	Add "growth" as an attribute of "organisational goal"
Attribute	Addition	Add "profit" as an attribute of "organisational goal"
Attribute	Addition	Add "management style" as an attribute of "organisation"
Attribute	Addition	Add "fact" as an attribute of "history"
Attribute	Addition	Add "fake" as an attribute of "history"
Attribute	Addition	Add "transparency" as an attribute of "culture"

Attribute	Addition	Add "values" as an attribute of "culture"
Attribute	Addition	Add "real" as a sub-attribute of "values"
Attribute	Addition	Add "stated" as a sub-attribute of "values"
Attribute	Deletion	Delete "organisational goal" as an attribute of "organisation"
Relationship	Addition	Add "influences" to connect "culture" and "conflict"
Relationship	Addition	Add "constraints" to connect "legislation" (i.e. organisational legislation) and "stakeholders"
Relationship	Addition	Add "generates" to connect "rules" and "tools"
Relationship	Addition	Add "generates" to connect "legislation" and "tools"
Relationship	Addition	Add "generates" to connect "policy" and "tools"
Relationship	Addition	Add "influences" to connect "culture" and "relationship"
Relationship	Addition	Add "influences" to connect "formal rules" and "design process"
Relationship	Addition	Add "influences" to connect "informal rules" and "relationship"
Relationship	Addition	Add "create" to connect "organisation" and "conflict"
Relationship	Addition	Add bi-directional relationship between "politics" and "organisation"
Relationship	Term refinement	Refine "embeds" that connects "strategy" and "organisational goal" into "influences"
Relationship	Expansion	All zone 2 influences policy
Entity	Addition	Add "market need" as an entity in "design information" theme
Entity	Term refinement	Refine the term "design requirements and constraints" into "product requirements"
Relationship	Addition	Add "input" to connect "design problem" to "design information"
Relationship	Addition	Add "influences" between "market need" and "design requirements and constraints"
Relationship	Addition	Add "satisfy" to connect "design information" and "design problem"
Relationship	Addition	Add "satisfy" to connect "design solution" and "design problem"
Relationship	Addition	Add "satisfy" to connect "design specification and requirement" and "design solution"
Tools		
Relationship	Addition	Add "store" to connect "information tools" and "design process"
Technical systems		
Entity	Term refinement	Refine the term "technical system" into "design solution"
Attribute	Term refinement	Refine the term "zones" an attribute of "technical system"
Attribute	Expansion	Expand the attribute of "technical system"
Design process		

Entity	Category refinement	Refine the category of "decision making process" from entity into sub-entity of "design process"
Sub-entity	Addition	Add "requirement analysis" as a sub-class of "design process"
Attribute	Addition	Add "resources" as an attribute of "design process"
Attribute	Addition	Add "mitigation" as an attribute of "risk"
Attribute	Addition	Add "company performance" as a sub-attribute of "performance"
Attribute	Addition	Add "suppliers performance" as a sub-attribute of "performance"
Attribute	Addition	Add "weakness" as an attribute of "design process"
Attribute	Addition	Add "quality" as an attribute of "design process goal"
Attribute	Addition	Add "compliance" as an attribute of "design process goal"
Relationship	Addition	Add "validates" to connect "design review process" and "design requirement and constraints"
Relationship	Addition	Add "trigger" to connect design specification and "decision making process"
Relationship	Deletion	Delete "consist of" that connects "design review process" and "decision making process"

Questionnaire response

Table 88 Recap of the questionnaire response from the participants in Company 4

Statement	Evaluation criteria	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
The model covers the socio-technical elements of the general collaborative engineering design process	E2	-	-	-	100%	-
The model covers the socio-technical elements of Company 4's collaborative engineering design process	E2	-	8%	30.5%	61.5%	-
The model would be useful for Company 4's collaborative engineering design process	E4	-	-	46%	46%	8%
The model was easy to understand	E5	-	8%	69%	23%	-
The model effectively explains the	E6	-	8%	46%	46%	-

collaborative engineering design process from the socio-technical perspectives						
The model provided insights into the collaborative engineering design process	E6	-	15%	8%	77%	-
My understanding towards the collaborative engineering design process increased after reviewing the model	E6	-	8%	46%	46%	0

Appendix 20: Glossary

Word	Definition	Example (s)
A		
Activity	Actions that constitute a design process	Draw a model, calculate cost
Affective	Emotion, feeling towards something	Happy, sad, angry, frustrated
Age	A length of time a person has lived	N/A
Area	A particular part of the technical system	Structure, equipment
Assigned responsibility	Task(s) required to fulfilled, attached to the assigned role	Authorise the design, design the x part of the technical system
Assigned role	Function In collaborative design practice or in the company as appointed by the company, often relates with hierarchical position	Manager, secretary, designer
Asynchronous (communication tools)	Tools utilise for communication that occurs at a different time	Email
B		
Business type	The type of business that the company focusses into	Non-profit, governmental, partnership, private
C		
Cause (of conflict)	The reason or motivation why the conflict occurs	Misunderstanding, miscommunication
Cognitive	Relates to intelligence, knowledge, and way of thinking	Perception, interpretation, knowledge
Commitment	The time, work, and loyalty that someone devotes to something	A person commits to work 8 hours a day
Communication	Exchanging information between two persons or more	N/A
Communication tools	A type of tools to facilitate information exchange between stakeholders	Telephone
Competency	The ability of a person to perform something satisfactory using their knowledge and skills	CAD utilisation, communication, leadership
Conative	Behaviour, action, or way of doing	Approach to design tasks, reaction to changes
Concept design process	The earliest stage of design process that focusses on identifying the basic conceptual design of technical system	N/A
Conflict	Disagreement, incompatibility	Disintegrated design, personality clash
Cost	The amount of money needed to do or buy something	N/A
Culture	Customs embedded in human beings	Drinking tea with milk (English culture)
Customers and users	Buyers (or potential buyers) of the product	N/A
D		
Decision making process	The process of making decision regarding the design of the technical system	N/A

Design information	Information used as the basis to design the technical system	Type of material, dimension, speed
Design problem	Issues related to the design of technical system that need to be considered	The interface between human and the technical system
Design process	The process to design the technical system	N/A
Design process goal	The ultimate goal of conducting the design process	Designing a low cost, high speed, product
Design process planning	The process of organising the design process, commonly done prior to the design process, and adapted throughout the design process	N/A
Design requirements and constraints	What needs to be included and/or excluded in the design of technical system	Maximum level of noise, minimum speed
Design review process	The process to review the design of technical system by comparing the design against design information, and resolve design problem	N/A
Design specification	Translation of design requirements and constraints into technical specifications	Dimension
Detailed design process	The stage of design process where the focus is to specified concept design into physical integration of the design	N/A
Duration	Length of time	N/A

E

Experience	Being contact with something or have done something in the past	N/A
External stakeholders	Stakeholders who are involved in the collaborative design process, but employed by other company	N/A

F

Focus (of organisational goals)	The centre of interest of the organisational goals	Profit, market share
Form (of communication)	A particular way in which communication exists	Verbal, non-verbal
Form (of design information)	A particular way in which design information exists	A printed drawing, a written document, an email , verbal information
Formal (communication)	Communication between stakeholders through official forms, that can be more structured, following specific rules	Design review meeting
Formal rules	Regulations that clearly defined and needs to be followed	Use safety helmet when in workshop floor
Function	The utilisation of tools	To create simulation

G

Gender	State of being male or female	N/A
Guideline	General rules of conducting something	Process guidelines

H

History	Past-events	The company used to be owned by xx

I

Impact	Noticeable effect or influence	N/A
Informal (communication)	Communication between stakeholders through unofficial forms, often in a relaxed information	Discussion during lunch time

Informal rules	What is considered as an acceptable behaviour	It is ok to arrive in a meeting 15 minutes late without notice
Information tools	Tools to organise, store, and communicate information	Database systems
Internal stakeholders	Stakeholders who are involved in the collaborative design process, employed by the company	N/A

L

Legislation	Law related to the whole life cycle of technical system (e.g. its design, its manufacturing process)	Defence standard
Level (of trust)	The level of believe in someone else's reliability	N/A
Location	Physical placement of an organisation	Plymouth, London

M

Models	Representation of the design	Prototype, 2D drawing
Motivation	Reason(s) that underpins a particular behaviour	Coming 5 minutes early to the meeting to reserve a strategic position

N

Natural role	Function of a human being that links to their personality	A motivator, an organiser
Nature (of design information)	The characteristics of design information	Being inter-related, being ill-defined
Nature (of technical system)	The characteristics of technical system	Being complex

O

Opinion	A personal view not necessarily based on fact or knowledge	N/A
Organisation	A group of people with purpose	The company
Organisational culture	Customs that are embedded in an organisation	Using casual clothing every Friday
Organisational goal	The strategic goal that an organisation is intend to achieve	Increase profit by 20%

P

Performance (of suppliers, of design process, of technical system)	Levels of success compare to predetermined objectives	Good performance of supplier: delivering on time
Personal relationship	Relationship that is established through non-work related interaction	Friendship
Personality	A set of characteristics of an individual	Introvert, extrovert
Policy	Principle of action, adopted or proposed by the company	How to conduct design process, the remuneration policy to employees
Politics	All activities that relate to the acquisition of power	Government politics
Post-design process	The stage of design process where the design has been approved and is being prepared for production	N/A
Priority	Things that perceived by human beings to be more important than others	N/A
Probability	The possibility of an incident to be occurred	N/A

Professional culture	Customs that are embedded in the profession of a human being	Marketing people view design problem from commercial point of view
Professional relationship	Relationship that is established through work interaction	N/A
Q		
Quality (of communication, of design information, of goals)	How good or bad communication/design information/ goal is	Clarity, tone, clarity of purpose
R		
Relationship	The state of being connected	N/A
Requirement	Something needed to conduct a design process	Communication
Risk	Possibility of incident to happen	Late delivery, product fails to perform
Rules	Regulations that must be followed	Working hours
S		
Schedule	A timetable	N/A
Skill	A particular ability to do something well	Engineering skill
Social conflict	Conflict related with the stakeholders of collaborative design	Personality clash
Social culture	Customs embedded in the society	It is considered rude to call your boss by their first name in Asian culture
Socio demographic	The profile of a human being related to their demographic and sociological characteristics	Age, gender
Stage	A step in a design process	Concept design, detailed design
Stakeholders	All human beings who are involved in collaborative design practice and affected by any decision taken in the practice	Customers, users, designers, marketing, HR
Standardisation	A framework to which all relevant parties in the company are required to follow	The design process consists of 4 stages
Strategy	Company's plan of action to achieve their long-term aims	Manufacture in China to reduce production cost
Structure	The arrangement of authority, roles, and responsibility	N/A
Suppliers	The source from which the company order the part of the end product during production	N/A
Synchronous	Tools utilise for communication that occurs at the same time	Telephone
T		
Team division	Division of team members into different group	N/A
Technical conflict	Conflict related with the design of technical systems	Disintegrated design
Technical system	The result of design process, utilise as the basis of product realisation	N/A
Technical tools	The type of tools that used to design the technical system	CAD, FORAD
Tenure	The duration of holding a position and/or role and/or responsibility in a company	N/A
Time zones	A region where the same standard time is used	GMT+1

Tools	Instruments and/or application that execute a particular function	CAD, telephone
Trust	Belief in someone else's reliability	N/A
Type (of models)	Category of models	2D, 3D
V		
Value (of design information and of relationship)	The level of importance	N/A
W		
Way of establishment	The way a relationship is established	N/A
Z		
Zones	A physical area of the technical system	Front, back