CRANFIELD UNIVERSITY

ZEHRA CANAN ARACI

KNOWLEDGE CREATION AND VISUALISATION BY USING TRADE-OFF CURVES TO ENABLE SET-BASED CONCURRENT ENGINEERING APPLICATIONS

SCHOOL OF AEROSPACE, MANUFACTURING AND TRANSPORT
Lean Product and Process Development Research Group

PhD
Academic Year: 2014 - 2017

Supervisor: Dr. Ahmed Al-Ashaab
March 2017

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This thesis is submitted in partial fulfilment of the requirements for the degree of PhD

ABSTRACT

Inefficiencies that could be avoided during the product development process account for a large percentage of the manufacturing cost. To introduce innovative, high-quality products in a time- and cost-efficient manner, companies need to improve the performance of their product development processes. Set-based concurrent engineering (SBCE) has the capability of addressing this issue if the right knowledge-environment is provided. Trade-off curves (ToCs) are effective tools to provide this environment through knowledge creation and visualisation. However, there are several challenges that designers face during their product development activities such as rework, inaccurate decisions, and failure in design performance, which eventually cause waste. Therefore, the aim of this thesis is to eliminate waste by developing a systematic approach for generating and using ToCs. These then serve as a guide for designers to support their decision-making and achieve an efficient product development performance in an SBCE environment. To achieve this aim, qualitative research methods were employed. Following an extensive literature review, industrial field study and industrial applications, three processes were developed to generate ToCs and validated with five industrial case studies.

The process for generating knowledge-based ToCs describes how to create and visualise knowledge that is obtained from historical data and/or experience. This process facilitates the reuse of knowledge about existing products, in order to reduce the requirement for resources (e.g. product development time). The process for generating physics-based ToCs describes an approach to creating knowledge that is obtained from understanding the physics and functionality of the product under development. Thus, the practitioners gain sufficient confidence for identifying a compromise between conflicting design parameters. Finally, the process for using ToCs within the SBCE process model presents a technique to use generated knowledge-based and physics-based ToCs in order to enable key SBCE activities. These activities are (1) Identifying the feasible design area, (2) Developing a design-set, (3) Comparing possible design solutions, (4) Narrowing down the design-set and (5) Achieving the final optimal design solution.

For validation, the developed processes were applied in five industrial case studies, and two expert judgements were obtained. Findings showed that ToCs are essential tools in several aspects of new product development, specifically by reducing the lead time through enabling more confident and accurate decisions. Additionally, it was found that through ToCs, the conflicting relationships between the characteristics of the product can be understood and communicated effectively among the designers. This facilitated the decision-making on an optimal design solution in a remarkably short period of time. The design performance of this optimal design increased by nearly 60% in a case study of a surface jet pump. Furthermore, it was found that ToCs have the capability of storing useful data for knowledge creation and reusing the created knowledge for the future projects.

Keywords: Trade-off curves, knowledge creation, knowledge visualisation, physics knowledge, set-based concurrent engineering, lean product development, new product development.

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Dedicated to my dear family, and to the new, long and last chapter of my life:

Jan Hendrik Braasch!

ٱقْرَأْ وَرَبُّكَ ٱلْأَكْرَمُ ﴿٣﴾

ٱلَّذِى عَلَّمَ بِٱلْقَلَمِ ﴿٤﴾

عَلَّمَ ٱلْإِنسَٰنَ مَا لَمْ يَعْلَمْ ﴿٥﴾

Read, and your Lord is the most Generous!
Who taught by the pen;
Taught man that which he knew not.

(Qur'an 96: 3-5)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AHP	Analytical Hierarchy Process
CFD	Computational Fluid Dynamics
CONGA	Configuration Optimization of Next Generation Aircraft
IP	Internet Protocol
KVA	Key Value Attribute
LeanPD	Lean Product Development
LeanPPD	Lean Product and Process Development
PD	Product Development
R&D	Research and Development
SBCE	Set-based concurrent engineering
SECI	Socialisation, Externalisation, Combination, Internalisation
SJP	Surface Jet Pump
ToC	Trade-off curve
ToCs	Trade-off Curves
PLM	Product Lifecycle Management
PDM	Product Data Management
ASME	The American Society of Mechanical Engineers

LIST OF PUBLICATIONS

Journal papers:

1. Araci, Z.C., Al-Ashaab, A., Maksimovic, M. (2016), "Knowledge Creation and Visualisation by Using Trade-off Curves to Enable Set-based Concurrent Engineering", *Electronic Journal of Knowledge Management*, v.14 (1), p. 75-88.

2. Araci, Z.C., Al-Ashaab, A., Garcia Almeida, C., Young, S. (in progress), "Knowledge-Based Trade-off Curves to Enable Set-Based Concurrent Engineering Applications", *International Journal of Product Development.*

3. Araci, Z.C., Al-Ashaab, A., Garcia Almeida, C., McGavin, J. (on peer-review process), "Physics-based Trade-off Curves to Develop a Control Access Product in Set-based Concurrent Engineering Environment", *International Journal of Lean Six Sigma*.

Conference Papers:

4. Araci, Z.C.,Al-Ashaab, A., Lasisz, P.W., Flisiak, J.W., Mohd Maulana, M.I.I., Beg, N., Rehman,A. (2017), "Trade-off Curves Applications to Support Set-Based Design of a Surface Jet Pump", *27th CIRP Design Conference*, 10-12 May 2017, Cranfield, UK.

5. Mohd Maulana, M.I.I., Al-Ashaab, A., Flisiak, J.W., Araci, Z.C., Lasisz, P.W., Shehab, E., Beg, N., Rehman, A. (2017), "The set-based concurrent engineering application: a process of identifying the potential benefits in the surface jet pump case study", *27th CIRP Design Conference*, 10-12 May 2017, Cranfield, UK.

6. Araci, Z.C., Al-Ashaab, A., Garcia Almeida, C., McGavin, J. (2016), "Enabling Set-based Concurrent Engineering via Physics-based Trade-off Curves", *3rd International Conference on Aeronautical and Mechanical Engineering (AEME '16)*, 17-19 December 2016, Bern, Switzerland.

7. Mohd Maulana, M.I.I., Flisiak, J.W., Al-Ashaab, A., Araci, Z.C., Lasisz, P.W., Beg, N., Rehman, A. (2016), "The Application of Set-Based Concurrent Engineering to Enhance the Design Performance of Surface Jet Pump", *3rd International Conference on Aeronautical and Mechanical Engineering (AEME '16)*, 17-19 December 2016, Bern, Switzerland.

8. Araci, Z.C., Al-Ashaab, A., Maksimovic, M. (2015), "A Process of Generating Trade-off Curves to Enable Set-based Concurrent Engineering", *Proceedings of the 16th European Conference on Knowledge Management (ECKM2015)*, 3-4 September 2015, Udine, Italy, p. 37-46.

Others:

9. Al-Ashaab, A., Golob, M., Oyekan, J., Araci, Z. C., Khan, M., Deli, D., and Al-Ali, E., (2014), "Flying into aerospace's next generation", Industrial Engineer Magazine, V. 46, N. 10, p.38-43.

10. Araci, Z. (2014), "Knowledge visualisation using trade-off curves to enable SBCE", 4th LeanPPD Industrial Workshop, 28 October 2014, Cranfield, UK, p. 97-110.

“PhD is a journey to learn how to learn”

Zehra Canan Araci

1 INTRODUCTION

1.1 Research Background and Context

The international competition in an open global market is pressurising manufacturing companies to improve the efficiency of their product development (PD) processes. This is required in order to continually produce a high-quality product in a cost-efficient manner, and in less time. Only companies with an efficient PD process can hope to sustain and improve their market share, as organisational survival and long-term growth depends on the timely introduction and development of new and better products. To this end, companies are applying various tools, techniques, and management systems that enable them to remain successful within their particular markets. New product development, as well as the organisational knowledge, have become important capabilities and assets of organisations (Wang and Wang, 2012; Nonaka *et al.*, 2014). This thesis, and its research context, provides a vital contribution to linking these two important assets, as is illustrated in Figure 1-1.

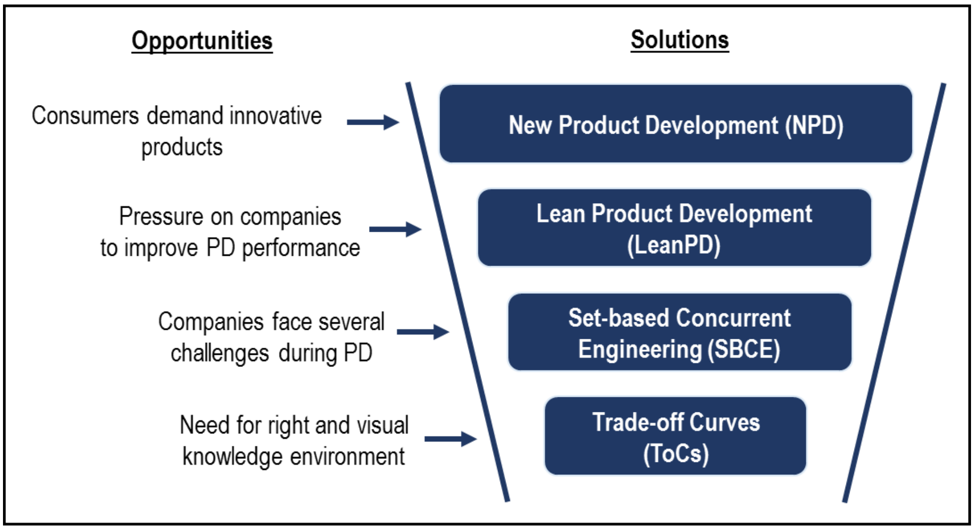


Figure 1-1: Overall scope of this thesis

As shown in Figure 1-1, consumers' demands for innovative products have been the trigger for companies to improve their new product development processes. However, there are several challenges that the manufacturing industry faces during their product development processes. Some of these challenges are (Khan *et al.*, 2011):

1. Rework
2. Late design changes
3. Lack of knowledge
4. Communication challenges between departments
5. Lack of process ownership
6. Ineffective planning and scheduling.

Academics and scholars have historically focused on defining principles and practices in order to address these challenges, and to increase the effectiveness and efficiency of PD. This has led to the development of the Lean Product and Process Development (LeanPPD) model, which is elaborated on in section 3.3. The LeanPPD model relies on several enablers; these are the set-based concurrent engineering (SBCE) process, chief-engineer technical leadership, value-focused planning and development, the knowledge-based environment, and the existence of a continuous improvement culture (Khan *et al.*, 2013). As a cornerstone enabler of LeanPPD, SBCE is recognised as an effective approach to product development (Al-Ashaab *et al.*, 2013). SBCE is a knowledge-intensive process that comprises the creation of a design-set, the communication, the trade-off and the narrowing down of the set of potential design solutions, while simultaneously proceeding throughout the PD process until an optimal solution is agreed upon (Sobek, Ward and Liker, 1999).

Companies have recognised the significance of creating a knowledge-environment in SBCE in order to enhance the quality of their decision-making throughout the development process, as well as to reuse and share the knowledge gained in this process (Baxter *et al.*, 2009; Lindlöf, Söderberg and Persson, 2013; Kennedy, Sobek and Kennedy, 2014; Maksimovic *et al.*, 2014). Knowledge creation has been defined in detail and explicitly by the SECI model (Nonaka, Toyama and Konno, 2000), which stands for Socialisation, Externalisation, Combination and Internalisation. Trade-off curves are considered to be a vital tool for the externalisation mode of the SECI model (Tyagi *et al.*, 2015). Externalisation is the process of converting tacit knowledge (i.e. experience, individual knowledge) into explicit knowledge such as documents, reports and drawings (Nonaka, Toyama and Konno, 2000). Trade-off curves (ToCs) not only provide a knowledge-based environment, but also document and illustrate existing knowledge, making it more useful (Raudberget, 2010; Correia, Stokic and Faltus, 2014). Dr. Allen Ward, who was a pioneer of LeanPPD, stressed the importance of using trade-off curves with the following words:

> *"If I teach you only one lean tool, trade-off curves would be the one."*

Trade-off curves are tools to create knowledge, and to visualise that knowledge in a simple manner. Thus, they enable PD processes, especially SBCE applications (Morgan and Liker, 2006; Kennedy, Sobek and Kennedy, 2014). ToCs allow designers and engineers to compare alternative design solutions, with conflicting attributes, in any aspect of the early stages of design (Ward and Sobek, 2014). Furthermore, ToCs prevent the designers from "*reinventing the wheel*" by visualising the knowledge from previous projects for reuse in the current project (Ward and Sobek, 2014). ToCs are also widely propagated tools to create and visualise the knowledge that is obtained from understanding the physical features and fundamental principles of the product under development, which is essential to making a rigorous and correct decision during the SBCE process (Araci *et al.*, 2016).

1.2 Research Aim and Objectives

The aim of this thesis is to develop processes for knowledge creation and visualisation, by using trade-off curves, in order to enable SBCE applications.

Five research objectives have been formulated to achieve this aim:

1. To synthesise the best practices of knowledge provision and visualisation in supporting the application of SBCE through an extensive literature review and industrial applications.
2. To capture the best practices of knowledge creation and visualisation with ToCs.
3. To investigate the role of knowledge creation and visualisation with ToCs, with a view of enabling the application of the SBCE process model.

4. To design processes that enable the generation of ToCs and to use generated ToCs in order to enable SBCE applications.
5. To evaluate the proposed ToC approach, regarding its contribution in enabling the application of SBCE, through industrial case studies and expert judgements.

1.3 Research Questions

Although ToCs are considered to be important tools for knowledge creation and visualisation to support SBCE applications, knowledge about the following issues is limited to date:

1. What type(s) of ToC should be used for different key activities of the SBCE process model?
2. How can ToCs that enable SBCE applications be generated?
3. How can non-scale ToCs be generated, based on the understanding of the product's functionality and physics?
4. How should generated ToCs be used to effectively apply SBCE?

This research attempts to address the above-mentioned questions by developing processes for designers and engineers who are involved in the development of a new product.

1.4 The Role of the Research in the CONGA Project

CONGA (Configuration Optimization of Next Generation Aircraft) is a project funded by the UK's Technology Strategy Board. Rolls-Royce Plc is one of the collaborating companies of this project. The aim of CONGA is to develop new multi-disciplinary SBCE capabilities that can deploy new aircraft and engine designs and configurations more quickly and with greater confidence. Such developments are essential if designers are to be able to deliver robust product concepts at the early stages of the design cycle for novel aircraft and power plant configurations, which also embed new technologies.

ToCs allow designers and engineers, by enabling the SBCE process model, to compare alternative solutions with conflicting attributes, in any aspect of the product life cycle. This thesis is investigating the development of such knowledge-environments to support the application of set-based design, and thereby to support the generation and evaluation of the set of conceptual designs within a company. Apart from the CONGA project, this PhD research has contributed to other research-based projects, in order to evaluate and validate the proposed approach to generating and using ToCs for knowledge creation and visualisation.

1.5 Thesis Structure

This thesis consists of seven chapters and several sections, subsections and sub-subsections within each chapter, as shown in Figure 1-2. Chapter 2 (Research Approach) explains the research paradigm, research design and the research approach that have been employed in this thesis. Chapter 3 (Literature Review) provides an overview of knowledge creation and visualisation practices using trade-off curves, and the role of ToCs within the SBCE process model. Moreover, the current practices for generating ToCs that enable SBCE applications were explored, as well as the research gaps identified. Practices of industrial applications of ToCs are captured by conducting interviews in chapter 4 (Industrial Field Study). Chapter 5 (Processes for Knowledge Creation and Visualisation that Enable SBCE) describes the approach taken for developing three processes for knowledge creation and visualisation to enable SBCE applications. It also includes detailed explanations of the three processes, which are listed below:

1. The Process for Generating Knowledge-based ToCs: Based on Historical Data
2. The Process for Generating Physics-based ToCs: Based on Knowledge about the Physics of the Product
3. The Process for Using Knowledge-based and Physics-based ToCs within the SBCE Process Model

These three processes are subsequently referred to as “the processes” in order to facilitate a clear flow throughout this thesis. Chapter 6 (Industrial Case Studies and Expert Judgements for Validation) presents the implementation of the processes in an industrial environment with industrial collaborators and the validation of the processes. Expert opinions are also presented in chapter 6.

Finally, chapter 7 concludes the research by presenting the discussions, limitations, contributions, implications and future work.

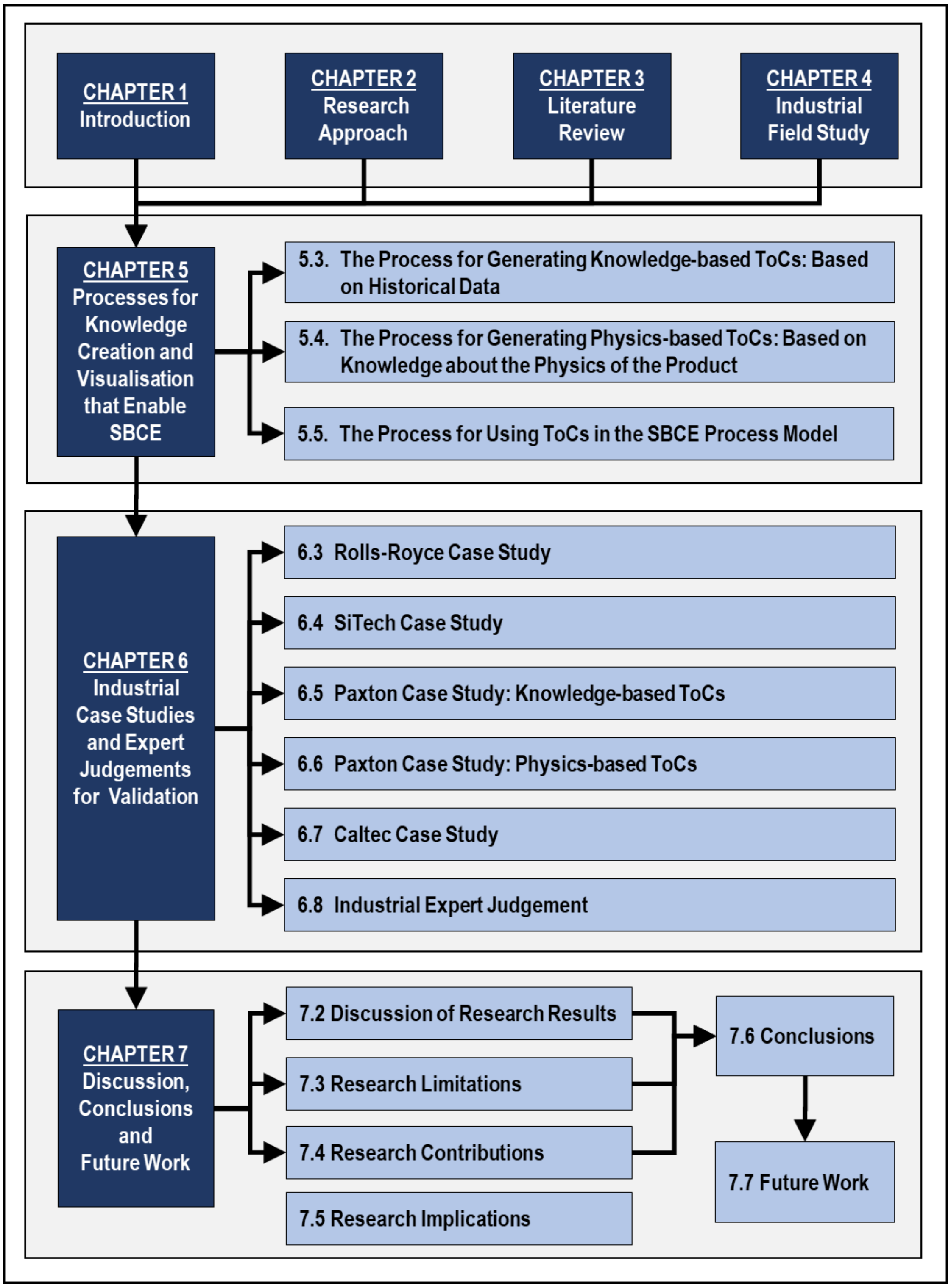


Figure 1-2: Thesis Structure

2 RESEARCH APPROACH

2.1 Introduction

This chapter, as illustrated in Figure 2-1, presents the research methodology that was employed in this thesis.

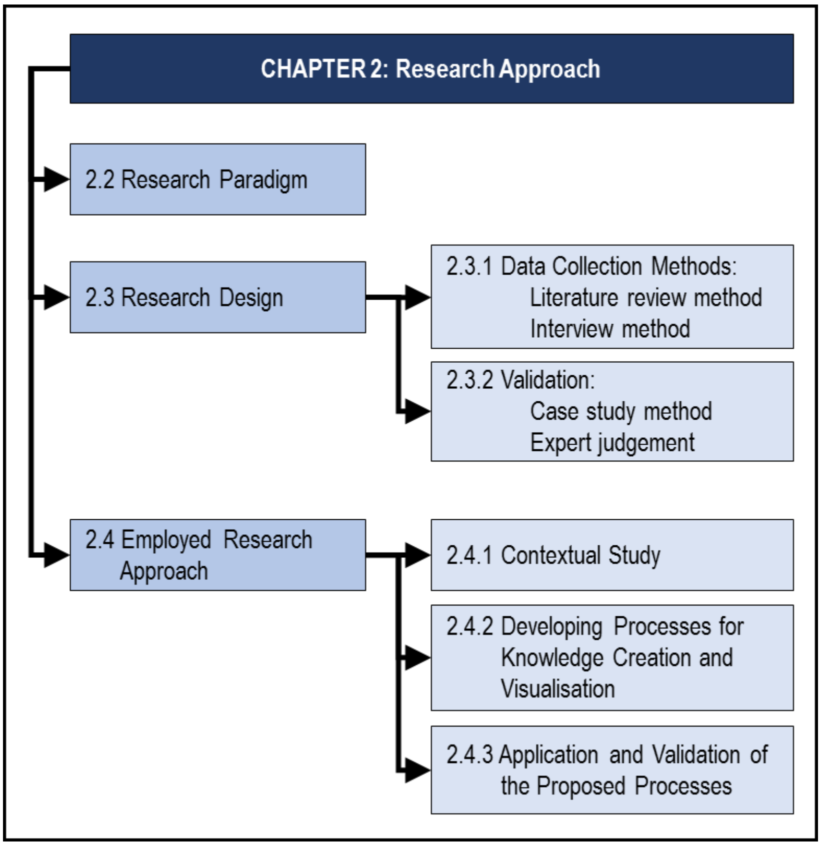


Figure 2-1: Structure of chapter 2

The research paradigm is explained in detail in section 2.2. Data collection, validation tools, and methods related to the research paradigm have been selected, given the research aim and objectives, and presented in section 2.3. With the research design defined, the approach employed in this thesis is developed in order to achieve the research aim and objectives, and it is presented in section 2.4. The employed research approach consists of three main phases:

1. Contextual study,
2. Developing processes for knowledge creation and visualisation to enable SBCE applications,
3. Application and validation of the proposed processes.

Each phase includes key tasks as described in section 2.4. Research Ethical Approval from Cranfield University has been considered during this research.

2.2 Research Paradigm

Research requires a well-organised, structured and rigorously employed methodology in order to detect problems and focus on solving these problems by gathering data, analysing them and producing valid conclusions (Sekaran and Bougie, 2016). In order to discover true knowledge, researchers apply different pragmatic approaches depending on their subjects (Robson and McCartan, 2016). There are four different research paradigms: Epistemology, ontology, axiology and methodology. In this thesis, the problem is stated in section 1.1, and the research aim and objectives to address this problem have been presented in section 1.2. Since this thesis addresses real-life applications, it is considered as an application of social sciences.

Epistemology and ontology are the most commonly applied research paradigms in social science. Epistemology is defined as the study of knowledge that seeks acceptable knowledge in a discipline, while ontology is the study of “being” which differentiates between what exists and what the reality is like (Bryman and Bell, 2015). It is a common practice to select one research paradigm and follow its approaches throughout the research. This thesis seeks true knowledge in generation and application of trade-off curves that enable SBCE processes, as stated in Section 1.2. Therefore, epistemology is selected as an appropriate research paradigm for this thesis. Epistemological commitments are associated with certain research methods as illustrated in Figure 2-2. Positivism and interpretivism are the different research approaches under the umbrella of epistemology.

Posivitism is a widely-used research approach which aims at relating an event, observation or other phenomenon to a general law. In the positivist approach, knowledge can only be based on sensory experience (see, hear, touch etc.) (Neuman, 2011; Bryman and Bell, 2015; Robson and McCartan, 2016). However, as the research in social science developed, it has become clear that the positivist approach was not appropriate for all questions. Hence, interpretivism is an alternative approach to positivism. The interpretivist approach describes meaningful social actions by using qualitative approaches (Neuman, 2011).

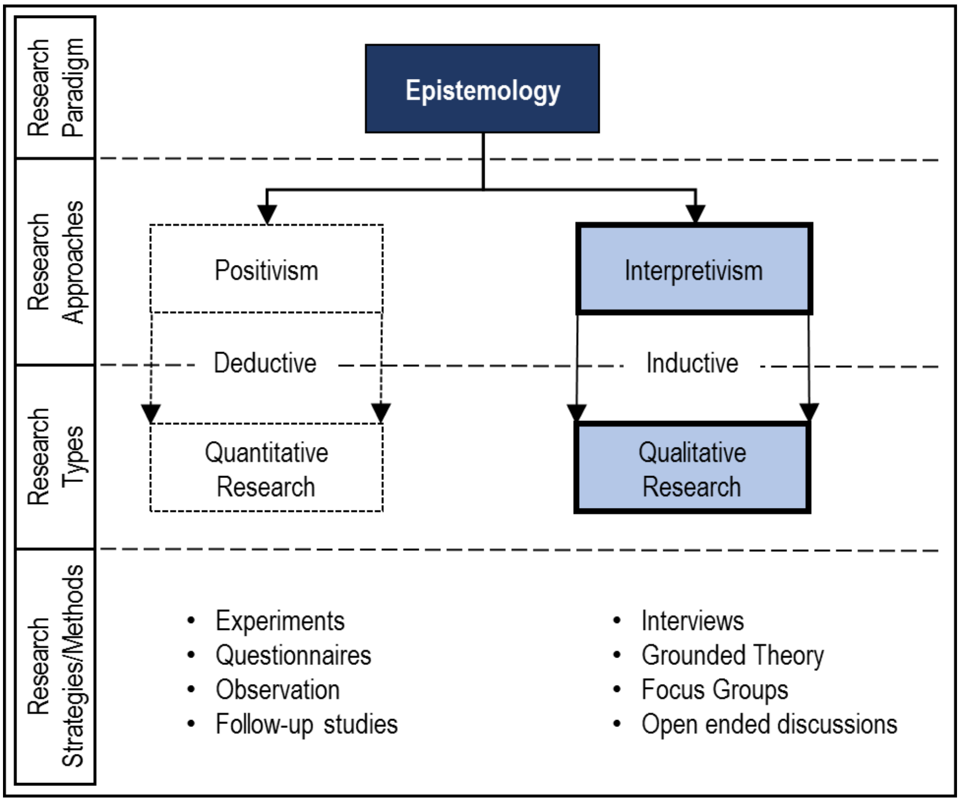


Figure 2-2: Overall view of research tools and methods

Before deciding which research approach to commit to, it is important to understand whether the research questions require an inductive or deductive research. The deductive research is associated with positivism, while the inductive research is considered in the area of interpretivism. The main difference between deductive and inductive research is the manner in which explanations for observations are reached. In deductive research, explanations are derived from theories and then tested against the data. On the contrary, inductive research derives theories and explanations from the data (Bryman and Bell, 2015; Robson and McCartan, 2016). Since the aim of this thesis is to develop processes for creating a knowledge-environment for SBCE applications, inductive research is considered as a suitable research approach. It is conducted by using qualitative methods and qualitative data (Bryman, 2012). The following section explains the qualitative methods that have been employed and the reason for using these methods.

2.3 Research Design

The research design is an important element of research. It facilitates data collection, measurement, and analysis in order to reach true knowledge. The use of different research methods is dependent on the subject at hand. The subject of this thesis requires qualitative research methods as discussed in the previous section. Therefore, qualitative methods for data collection and validation will be explained in detail in this section.

2.3.1 Data collection methods

There are two types of data: primary and secondary. Primary data is observed or collected directly from first-hand experience. Commonly known qualitative primary data collection methods are interviews, grounded theory, focus groups, and open-ended discussions (Neuman, 2011; Bryman and Bell, 2015; Robson and McCartan, 2016). Primary data has been collected by performing interviews, and is presented in section 4.3. The reason for applying interviews was to capture the real-life practices, experiences and views of practitioners about trade-off curves in an industrial environment. On the other hand, secondary data is the data that has previously been collected by others for a different aim than the purpose of the current research (Sekaran and Bougie, 2016). The literature review is a form of secondary data collection from several sources, such as academic publications, government publications, statistical bulletins, and others. The following sub-subsections present the data collection methods, literature review and interviews.

2.3.1.1 Literature review method

Literature review is one of the most important data collection methods for research (Bryman and Bell, 2015). This method helps the researcher to identify the research gaps that would guide to contribute to the existing knowledge (Robson and McCartan, 2016). Bryman and Bell (2016) suggest that the researcher should develop an approach in order to carry out a literature review. Figure 2-3 illustrates the approach for the literature review of this thesis.

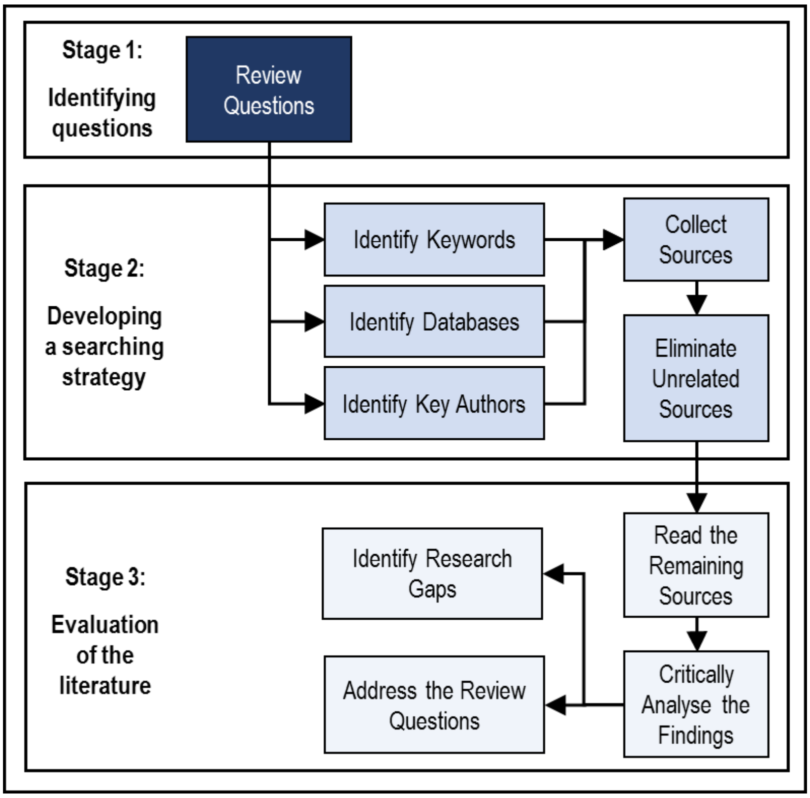


Figure 2-3: Process flow for the literature search strategy

<u>Stage 1: Identifying a well-defined literature review question</u>

Considering the research aim and objectives, three literature review questions were identified and are presented in Table 2-1.

No.	Literature Review Questions	Research Objectives
1.	What are the best practices of knowledge provision and visualisation in supporting SBCE?	To synthesise the best practices of knowledge provision and visualisation in supporting the application of SBCE through an extensive literature review and industrial applications.
2.	What are the best practices of using ToCs?	To capture the best practices of knowledge creation and visualisation with ToCs.
3.	What are the practices of using ToCs in SBCE?	To investigate the role of knowledge creation and visualisation with ToCs, with a view of enabling the application of the SBCE process model.

Table 2-1: Literature review questions according to the research aim and objectives

Stage 2: Developing a searching strategy

A search strategy has been developed based on three parallel steps: identifying keywords, databases, and authors. A list of keywords is presented in Table 2-2, which also shows the relevant databases and key authors in the subject area covering this thesis. Numerous data sources have been found during the literature search, and these include textbooks, journal papers, theses, conference proceedings and unpublished manuscripts. Unrelated sources have been eliminated and the literature review focuses mainly on journals and theses, resulting in a robust secondary data collection.

Search strategy step	**Identified search parameters and sources**
Key Words	• Set-based concurrent engineering/set-based design/set-based thinking • New product development/product design • Lean product development • Knowledge provision/knowledge visualisation/knowledge representation/communicating knowledge/visual knowledge/previous knowledge/knowledge creation/knowledge sharing/knowledge management • Trade-off curves/trade-off • Product history/previous project/previous product • Decision-making/decision support
Databases	Scopus, EBSCO, ProQuest, Web of Science and Google Scholar
Key Authors	Ahmed Al-Ashaab, Allen Ward, Brian M. Kennedy, Christoffer Levandowski, Durward K. Sobek, Endris Kerga, Jeffrey K. Liker, Maksim Maksimovic, Michael N. Kennedy, Muhammad S. Khan.

Table 2-2: Literature review stage 2 activities for developing a searching strategy

Stage 3: Evaluation of the literature

After removing unrelated sources, the remaining sources have been read thoroughly. Findings from the literature have been critically analysed. Finally, the review questions have been addressed and research gaps have been identified and documented in chapter 3.

2.3.1.2 Interview method

The interview is one of the most widely used methods for qualitative research (Robson and McCartan, 2016). There are two major types: unstructured and semi-structured interviews, and both have flexibility and advantages in primary data collection (Bryman and Bell, 2015). However, the semi-structured interview is a more useful method since it helps the interviewee to avoid misunderstanding the questions (Bryman and Bell, 2015). In addition, the semi-structured interview gathers data and information individually to build the research foundation, for example to understand the industrial perspective of using ToCs for knowledge creation and visualisation in product development processes. During a semi-structured interview, the researcher employs a close-ended questionnaire which helps to gain straightforward information within a limited time. By using semi-structured interviews and a close-ended questionnaire, rich and in-depth information and feedback from the participants can be captured. Therefore, this research focuses on interviews with semi-structured questions as a primary data collection method. Figure 2-4 illustrates the process for employing semi-structured interviews throughout this research.

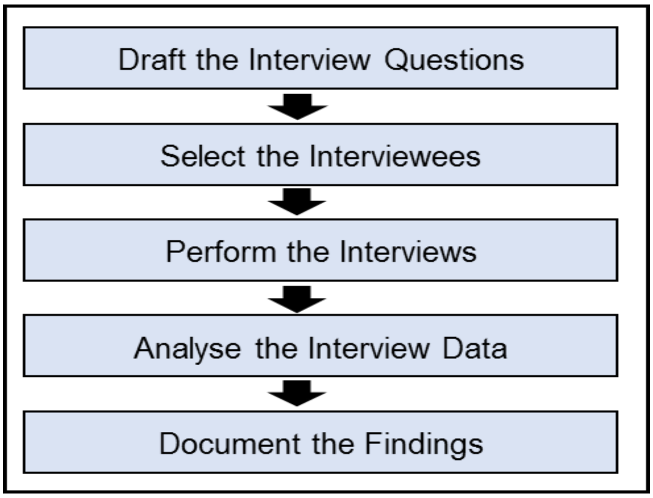


Figure 2-4: Stages in developing and using interviews (adapted from Wilkinson and Birmingham, 2003)

The questions are identified based on the information gathered from the literature review. Interviewees are identified based on their area of expertise. Subsequently, interviews are conducted in face-to-face meetings as well as

WebEx meetings. Eventually, interview data has been analysed and the findings are documented in chapter 4.

2.3.2 Validation

Validation is the most important part of social research, as it reflects the quality of the research (Bryman, 2012). Two validation methods were implemented: case study and expert judgement, which are explained in the following sub-subsections.

2.3.2.1 Case study method for validation

A case study is a strategic qualitative research method and commonly used in sociology and industrial relations (Noor, 2008). Yin (2014) describes case study as “an empirical enquiry that investigates a contemporary phenomenon within its real-life context”, further suggesting that a case study is preferred when “how” and “why” questions are to be answered. In order to successfully conduct a case study, a linear, iterative process has been recommended by Yin (2014). It consists of six main steps: Plan, design, prepare, collect, analyse, and share.

Five industrial case studies were conducted throughout this research. They are presented in chapter 6. Results of the case studies are discussed and documented in section 7.2.

2.3.2.2 Expert judgement method for validation

Expert judgement is a way of reducing the level of bias within the research (Inglis, 2008). Expert judgement is a method widely used for content validity fulfilment and as an alternative strategy to ensure content validity from relevant research (Joo and Lee, 2011). In order to conduct this method, experts are identified from the area related to the research. Then, the proposed approach/model/process is presented to the experts in order to obtain their comments and feedback. Finally, expert opinions are documented and analysed. This thesis captured the views of two experts, and the discussions with the experts are documented in section 6.8.

2.4 Employed Research Approach

The methodology defined for this research consists of three main phases, which are based on the research objectives as presented in section 1.2. Each phase has key tasks, methods to complete these tasks, and deliverables as shown in Figure 2-5. Each phase will be explained in detail in this section.

2.4.1 Key tasks of phase 1: Contextual study

1.1 Synthesising the best practices of knowledge provision and visualisation in the SBCE process model:

Knowledge provision and visualisation applications of enabling the SBCE process model have been synthesised by an extensive literature review and industrial applications.

1.2 Capturing the best practices of ToCs:

The best practices of knowledge creation and visualisation using ToCs in different areas are captured by an extensive literature review.

1.3 Investigating the role of using ToCs in enabling SBCE applications:

The role of knowledge provision and visualisation using ToCs to enable the application of the SBCE process model is investigated by an extensive literature review.

1.4 Understanding the industrial perspective of ToCs:

Semi-structured interviews with a close-ended questionnaire are performed to investigate companies' best practices regarding the knowledge creation and visualisation in the form of ToCs during the early stages of product development processes.

Deliverables of this phase are documented and presented in detail in chapters 3 and 4.

PHASE 1: Contextual Study

Key Tasks	Methods
1.1. Synthesising the best practices of knowledge provision and visualisation within the SBCE process model **1.2.** Capturing the best practices of ToCs **1.3.** Investigating the role of using ToCs in enabling SBCE applications **1.4.** Understanding the industrial perspective of ToCs	• Extensive literature review • Interviews with semi-structured questionnaire

Deliverables

- Identification of different types of ToCs
- Identification of the role of ToCs within SBCE
- Research gaps

PHASE 2: Developing processes for knowledge creation and visualisation to enable SBCE

Key Tasks	Methods
2.1. Analysing the data collected from the literature review and interviews **2.2.** Designing and developing processes for generating ToCs for knowledge creation and visualisation	• Primary data analysis • Secondary data analysis • Understanding research gaps

Deliverables

- A process for generating knowledge-based ToCs
- A process for generating physics-based ToCs
- A process for the integrated use of ToCs within the SBCE process model

PHASE 3: Application and validation of the proposed processes

Key Tasks	Methods
3.1. Applying the proposed processes to generate ToCs of knowledge creation and visualisation in companies **3.2.** Receiving feedback from experienced researchers and practitioners	• Case studies • Expert judgement

Deliverables

- Validated processes of knowledge creation and visualisation in enabling SBCE applications

Figure 2-5: Employed research approach

2.4.2 Key tasks of phase 2: Developing processes for knowledge creation and visualisation to enable SBCE

2.1 Analysing the data collected from the literature review and interviews:

Primary data, collected from interviews, and secondary data, collected from the review of the related literature, are analysed.

2.2 Designing and developing processes for generating ToCs for knowledge creation and visualisation:

Analysing the obtained information, from both the literature review and interviews, and understanding the research gaps helped the author to develop three processes for providing a knowledge-environment to enable the SBCE applications. These three processes are:

1. The process for generating knowledge-based ToCs
2. The process for generating physics-based ToCs
3. The process for the integrated use of ToCs in the SBCE process model

Deliverables of this phase are documented and presented in detail in chapter 5.

2.4.3 Key tasks of phase 3: Application and validation of the proposed processes

3.1 Applying the proposed processes to generate ToCs for knowledge creation and visualisation in companies:

The proposed processes, as listed in the previous subsection, are applied and validated in different companies from a variety of industries by using the case study method.

3.2 Receiving feedback from experienced researchers and practitioners:

The applied processes are validated by receiving feedback from experienced researchers and practitioners who are called “experts” in this research by using expert judgement method.

Deliverables of this phase are documented and presented in detail in chapter 6.

2.5 Summary of Chapter 2

Different research paradigms were discussed, and epistemology was selected as an appropriate paradigm for this research. Considering the research aim and objectives, an interpretivist approach and, accordingly, an inductive research type were deemed appropriate to be applied in conducting this research. Therefore, the author decided to implement qualitative research methods. The research approach employed in this thesis was developed by the author and described in section 2.4. Literature review and interviews were the methods chosen for data collection, in order to conduct a contextual study. Case studies and expert judgement methods were selected for validating the proposed processes for creating and visualising knowledge-environment for SBCE applications.

3 LITERATURE REVIEW

3.1 Introduction

This chapter, as is illustrated in Figure 3-1, presents the current practices of knowledge creation and visualisation for using ToCs that enable SBCE applications in section 3.2. It also provides a definition and an overview of ToCs in general, as well as of different ToC types. Section 3.3 highlights the main features of the lean product and process development (LeanPPD) model and SBCE. A review of the role of ToCs in SBCE is also presented in this section. Section 3.4 provides an insight into current practices of generating ToCs that enable SBCE applications. Finally, the research gaps found in the literature are presented in section 3.5.

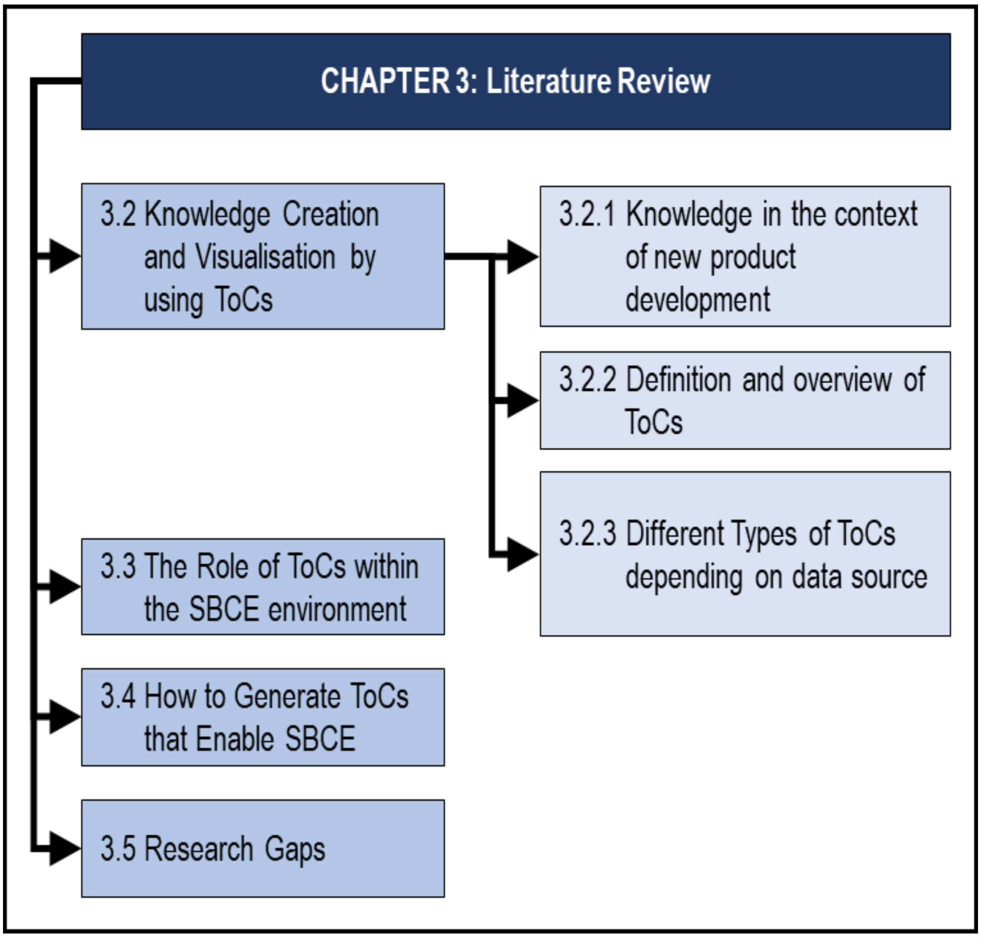


Figure 3-1: Structure of chapter 3

3.2 Knowledge Creation and Visualisation by Using Trade-off Curves

3.2.1 Knowledge in the context of new product development

Production equipment was the most valuable asset of a company in the 20th century, whereas in the 21st century, knowledge has become a gateway for achieving a competitive advantage (Nonaka, 1994; Tseng, 2009; Wang and Wang, 2012). Knowledge also plays an important role in the product development performance (Zhang *et al.*, 2009).

Data, information and knowledge are three different concepts (Stamm, 2008; Andriopoulos and Dawson, 2009). However, information and knowledge are often used interchangeably, although they are different from one another (Andriopoulos and Dawson, 2009). Data refers to observations, facts and figures (Andriopoulos and Dawson, 2009), which are not categorised or analysed. Information is the more useful and organised form of data (Stamm, 2008; Andriopoulos and Dawson, 2009). On the other hand, knowledge is considered as consisting of truths, perspectives, judgement and know-how (Stamm, 2008).

Knowledge is classified in various forms in the literature. For instance, Blackler (1995) sorts knowledge in five groups: encoded knowledge, embedded knowledge, embodied knowledge, embrained knowledge, and encultured knowledge. On the other hand, the common practice in the literature is dividing knowledge in two types: tacit and explicit, which have a better-established definition. Tacit knowledge is informal knowledge, present as a personal possession in individuals' minds. Once individuals leave the company, knowledge is lost since it is not available in a written or documented form, and thus not suitable for communication and education of others (Nonaka 1994; Goffin and Mitchell, 2010). Therefore, tacit knowledge should be stored in the form of explicit knowledge, which can be formulated, articulated, codified, stored and reused (Nonaka and Takeuchi, 1995). Explicit knowledge is also considered as being systematic and easy to access, communicate and share (Goffin and Mitchell, 2010). However, although explicit knowledge has become very popular among top managers and academics, there is still a gap in the literature regarding how to create and utilise it to enhance the performance of PD activities in companies. Trade-off curves are considered to be important tools to convert tacit knowledge into explicit knowledge (Tyagi *et al.*, 2015), but there is no systematic approach to generating such ToCs. Therefore, this PhD research focuses on developing a step-by-step guide to generating ToCs, which are representing tacit knowledge in the form of explicit knowledge.

Knowledge creation is a vital part of knowledge management, which is studied broadly in the literature. Due to the scope of this thesis, knowledge management is briefly mentioned in order to clarify the meaning of knowledge creation in the context of product development process.

There are numerous definitions of knowledge management in the literature. Some academics define it as utilising expertise (Alavi and Leidner, 2001), while it is also defined as an integration of capabilities, abilities, organised information, and technology applications that are useful for new product development (Forcadell and Guadamillas, 2002). Figure 3-2 illustrates a common practice of a knowledge management process, which consists of the steps of knowledge creation, storage and retrieval, transfer and sharing, and application (Alavi and Leidner, 2001).

Figure 3-2: Knowledge management processes (Alavi and Leidner, 2001)

Knowledge creation is the combination of generating new organisational knowledge and capability (Nonaka, 1994) and obtaining the knowledge from external partners (Alavi and Denford, 2011). Storage and retrieval is the process of storing the created knowledge in a documented form and recalling it when it is needed (Rebolledo and Nollet, 2011). Transfer and sharing is the process of diffusing knowledge from its original location to a required location (Alavi and Denford, 2011). Finally, application is the process of utilising knowledge for PD activities, such as decision-making and problem-solving (Alavi and Denford, 2011).

3.2.2 Definition and overview of trade-off curves

Trade-off curves are tools to visualise and trade-off the relationships between conflicting factors/parameters/elements to help engineers make an accurate decision (Otto and Antonsson, 1991; Bitran and Morabito, 1999). The most relevant definition to this thesis' context has been made by Sobek, Ward and Liker (1999): A trade-off curve establishes a relationship between two or more design parameters, which is more useful than trade-off data. During the conceptual design stage of PD, there are several conflicting parameters which have a major impact on design decision-making. It is important to identify these conflicting parameters and understand the relationships between them in a visual manner (Maksimovic *et al.*, 2012; Correia, Stokic and Faltus, 2014; Kennedy, Sobek and Kennedy, 2014). This is integral to the application of SBCE and in order to produce a set of design solutions; as there may be many design parameters to be considered simultaneously (Sobek, Ward and Liker, 1999; Kennedy, Sobek and Kennedy, 2014). Trade-off curves are useful tools to be employed in this context. Figure 3-3 shows an example of the key elements of trade-off curves: Design parameters 1 and 2 are represented on the X and Y axes. Design parameter data is plotted against these axes. Three customer requirements are plotted against the trade-off curve. These define the feasible area, within which a design solution's parameter data has to lie in order to meet all design requirements.

As shown in Figure 3-3, a trade-off curve has several key elements. The existing literature highlights these key elements as follows, and stipulates that they are imperative in order to develop suitable trade-off curves which support the product design and development (Burke *et al.*, 1988; Hong, Nahm and Doll, 2004; Catalão *et al.*, 2008; Maksimovic *et al.*, 2012; Kerga *et al.*, 2013; Ringen and Holtskog, 2013; Kennedy, Sobek and Kennedy, 2014; Levandowski, Michaelis and Johannesson, 2014):

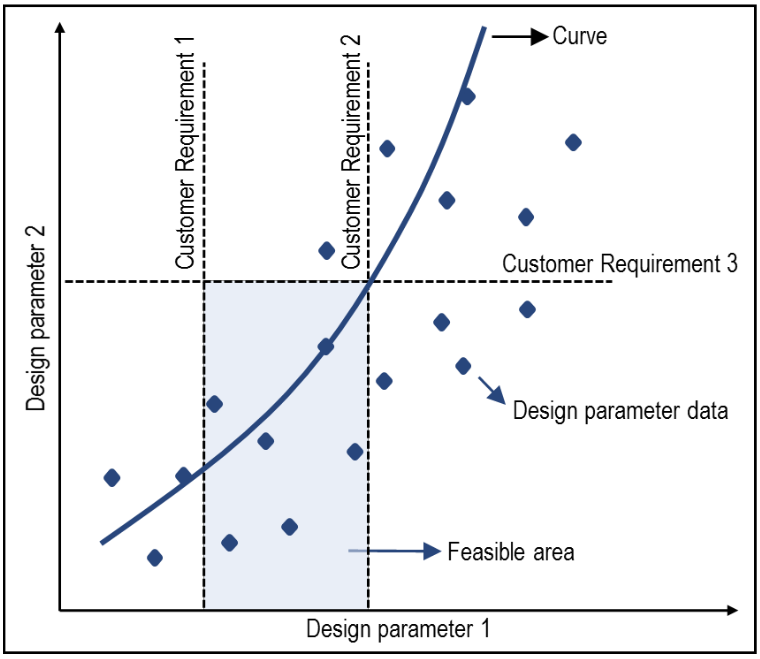


Figure 3-3: An example of a trade-off curve illustrating the key elements

1. <u>Customer requirements:</u>

   These are the minimum product-related requirements necessary to satisfy the stakeholders' needs. Figure 3-3 illustrates how customer requirements are utilised in trade-off curves to identify the feasible area. In this example, there are three customer requirements, which are illustrated by the dashed lines.

2. <u>Decision criteria:</u>

   These are related to customer requirements that drive the key design decisions. These frequently include cost, complexity, durability and reliability of the product. Decision criteria are not illustrated on a trade-off curve, however, each ToC should address at least one decision criteria.

3. <u>Design parameters:</u>

   These represent the special characteristics of the product under development. The different design parameters often conflict with each other. Analysis is required to understand the relationship between the conflicting design parameters. In addition, the areas of conflicts and the reasons behind them must be determined. Visually displaying such relationships in trade-off curves facilitates the communication between different departments and stakeholders, thereby knowledge creation. Examples of design parameters and how they may conflict with others are material cost (e.g. with the magnitude of production), noise level (e.g. with engine size), and fuel consumption (e.g. with pollution levels). Figure 3-3 shows how design parameters are represented on the X and Y axes.

4. Design parameter data:

   Ranges of data relating to the identified design parameters need to be captured from different sources, including previous projects, testing, and simulation. Figure 3-3 illustrates how design parameter data is plotted against the X and Y axes. This data represents the respective design solutions, and their relationship to the requirements, in a visual form.

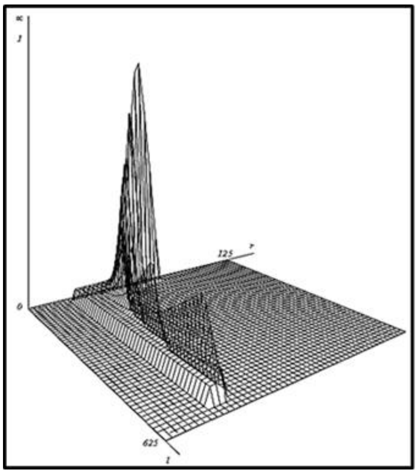
5. Feasible area:

   The feasible area is defined by plotting customer requirements against the design parameters. Thereby, possible conceptual design solutions that meet both the decision criteria and the customer requirements, for the related project, are identified. In the hypothetical example shown in Figure 3-3, six potential solutions are situated within the feasible area, which is defined by three customer requirements (dashed lines).

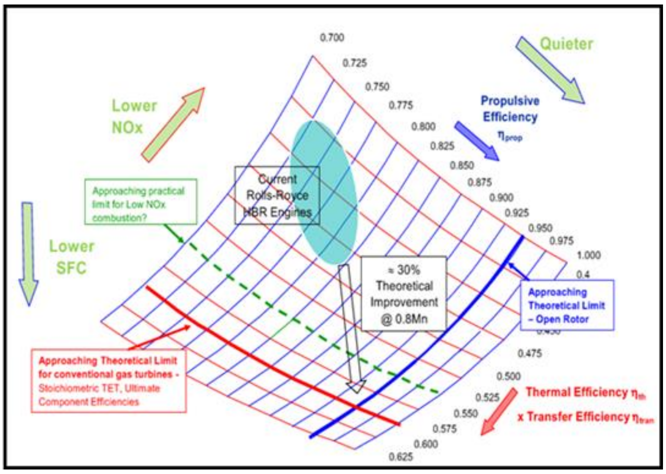
6. Curve:

   The curve in trade-off curves represents the trend of data and the form of the relationship between the design parameters. However, there are some cases where the plotted data on trade-off curves does not show a meaningful trend. In such cases, there may be no curve, only the design parameter data. Examples of trade-off curves without a plotted curve can be found in the literature (Burke *et al.*, 1988; Fine, Golany and Naseraldin, 2005; Vassilvitskii and Yannakakis, 2005; Raudberget, 2010; Michaelis, Levandowski and Johannesson, 2013).

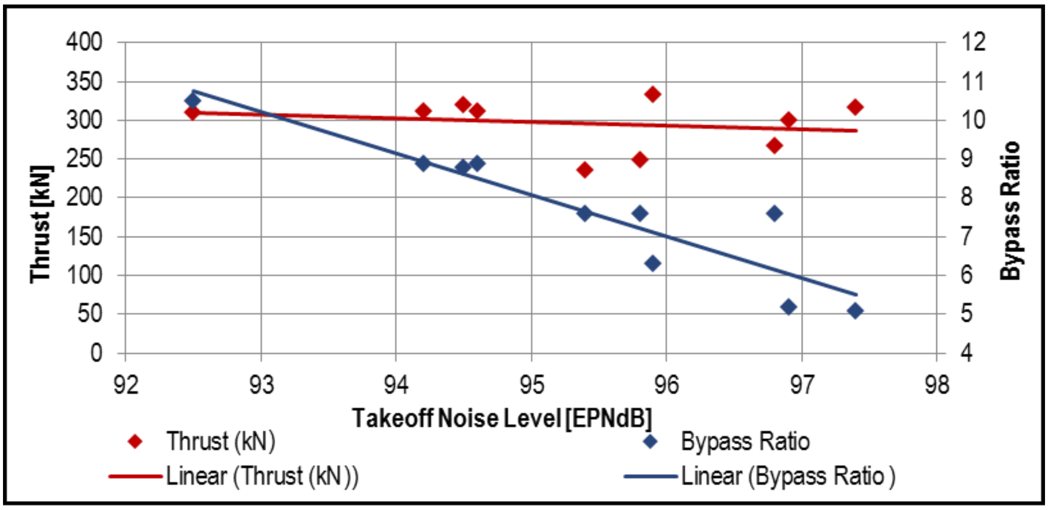
ToCs can be generated in two-dimensional, three-dimensional or multi-dimensional form depending on the analytic/analysis need or different types of products. If the design team would like to see relationships between more than two design parameters, in order to make a more accurate decision, these relationships can be visually projected on a three-dimensional trade-off curve (Otto and Antonsson, 1991; Browning and Eppinger, 2002; Wang and Terpenny, 2003; Fine, Golany and Naseraldin, 2005; Malak and Paredis, 2010; Raudberget, 2010; Richards and Valavanis, 2010) or multi-dimensional trade-off curve (Haselbach and Parker, 2012). Figure 3-4 illustrates examples of three-dimensional and multi-dimensional trade-off curves.



(a)
Three-dimensional ToC
(Otto and Antonsson, 1991)



(b)
Multi-dimensional ToC
(Haselbach and Parker, 2012)



(c) Three-axis ToC

Figure 3-4: Different trade-off curve examples

Trade-off curves can also be presented on multiple axes as shown in Figure 3-4 (c). Thus, the designer can see the relationships between three conflicting design parameters within one graph.

Trade-off curves have been widely referred to in the literature, especially from the 1960s onwards (Pershing, 1968), within a range of disciplines from finance and environmental science to engineering and computer science. Most of the studies in these disciplines have used trade-off curves to facilitate the solving of multi-objective optimisation problems. Multi-objective (or multi-criteria) optimisation problems are such that have more than one conflicting objective function to be satisfied in order to achieve the optimal solution (Askar and Tiwari, 2011). The most common areas that utilise trade-off curves to facilitate solutions of multi-objective optimisation problems are shown in Table 3-1.

Subjects that utilise ToCs as a multi-objective optimisation tool	**References**
Manufacturing networks optimisation	(Bitran and Morabito, 1999)
Scheduling	(Catalão *et al.*, 2008)
Capacity planning and resource allocation	(Bretthauer, Shetty and Syam, 2003)
Inventory management	(Grewal, Enns and Rogers, 2014)

Table 3-1: The subjects and the references that have utilised ToCs as a multi-objective optimisation tool

The role of trade-off curves within multi-objective optimisation problems is highlighted in Table 3-2. These trade-off curves are developed by using the data generated by algorithms and mathematical calculations rather than real data, experience, and knowledge. This issue will be discussed in more detail in sub-subsection 3.2.3.1.

The role of ToCs within multi-objective optimisation	References
Decision support	(Holtzman, 1984; Preetha Roselyn, Devaraj and Dash, 2014)
Data representation and visualisation	(Rhyu, and Clearance and Kwak, 1988; Abido, 2003)
Best solution compromise	(Avigad and Moshaiov, 2010; Zhou *et al.*, 2011; Mohagheghi, Kapat and Nagaiah, 2014)
Comparing conflicting parameters	(Dunning *et al.*, 2014; Kuo *et al.*, 2014)
Comparing solutions	(Gardner, Jr. and Everette, 1990; Suwanruji and Enns, 2007; Quirante, Sebastian and Ledoux, 2013)
Feasible/infeasible area definition	(Cao and Yang, 2004; Samarasinghe, Inaltekin and Evans, 2013)

Table 3-2: The role of ToCs within multi-objective optimisation problems

On the other hand, while it is possible to find many publications in aforementioned areas, the number of publications that mention trade-off curves within the PD context is very limited. Kennedy, Sobek and Kennedy (2014) reported that the earliest use of trade-off curves in PD was by the Wright Brothers in the late 1800s. They succeeded in the first manned and heavier-than-air flight, and did so in a very short time and with a lower budget than their rivals. It is believed that a part of this success was attributable to the use of trade-off curves in the early stages of their PD. Sobek, Ward and Liker (1999) reported that the utilisation of trade-off curves has appeared at Toyota as a knowledge visualisation tool which facilitates the key tasks of set-based design. At Toyota, “jidoka” refers to the visual management, a technique adapted from lean manufacturing to the PD area in order to simplify complex knowledge by using visual tools such as trade-off curves (Morgan and Liker, 2006). They visually display subsystem knowledge in a graph so that engineers are able to explore the design space (Ward and Sobek, 2014) and evaluate design alternatives (Kerga *et al.*, 2014). Moreover, in a lean product development context, trade-off curves avoid the reinvention of previously considered design solutions during prototyping (Womack, 2006). Hence, engineers save time that they can spend on new and innovative solutions.

3.2.3 Different types of trade-off curves depending on data source

There are different types of trade-off curves, these are math-based and knowledge-based ToCs which are generated by using data from different sources. The characteristics and data sources of each type of trade-off curve are explained in detail in the following sub-subsections.

3.2.3.1 The characteristics of math-based trade-off curves

Math-based ToCs are generated by using the data output from simulating engineering applications through mathematical modelling (Browning and Eppinger, 2002; Roemer and Ahmadi, 2004; Fine, Golany and Naseraldin, 2005; Panduro *et al.*, 2006; Richards and Valavanis, 2010). Math-based ToCs have been used for different purposes: To visualise and compare conflicting design parameters (Li et al., 2013) and to support the decision-making in multi-objective optimisation (Panduro *et al.*, 2006). However, the ToC data in these studies is generated in a mathematical manner (e.g. simulations, algorithms and mathematical programming) depending on assumptions (Malak and Paredis, 2010) rather than facts and knowledge. Assumptions, however, might be overestimated or underestimated which may lead designers to make an inaccurate decision. Moreover, due to the fact that uncertainty is an issue with math-based ToCs (Bitran and Morabito, 1999), there are risks and estimation errors (Roemer and Ahmadi, 2004). Additionally, math-based ToCs might not be reusable for future projects. They should be generated anew for every single project, since different projects have different assumptions and constraints (Fine, Golany and Naseraldin, 2005). Finally, while they are capable of generating thousands of solutions (Panduro *et al.*, 2006), it might take significant resources to compare and evaluate these solutions. Therefore, math-based trade-off curves do not provide the right environment to enable SBCE, which requires accuracy of data, the right reusable knowledge-environment and more precise data than is provided by math-based ToCs.

Table 3-3 demonstrates the use of math-based ToCs in different subjects. These trade-off curves are generated by the data that is obtained from algorithms, modelling, simulations and programming.

Data obtaining method	Subject areas using generated ToCs	Reference
Algorithm	Engineering design optimisation (Pareto Front algorithm)	(Richards and Valavanis, 2010)
	Linear antenna arrays (Genetic algorithm)	(Panduro *et al.*, 2006)
	Representing the variety of reasonable options in the design space (Genetic algorithm)	(Vassilvitskii and Yannakakis, 2005)
	Concurrent crashing and overlapping in product development (Overlapping crashing algorithm)	(Roemer and Ahmadi, 2004)
	Discrete manufacturing systems design (Genetic and heuristic algorithms)	(Bitran and Morabito, 1999)
	Gate sizing problems (Single-point optimisation algorithm)	(Berkelaar, Buurman and Jess, 1994)
Modelling and Simulation	Supply chain outsourcing risk management	(Wu *et al.*, 2013)
	Short-term scheduling of thermal unit problems	(Catalão *et al.*, 2008)
	Gate sizing problems	(Montiel-Nelson *et al.*, 2005)
	Cost and schedule risk in product development	(Browning and Eppinger, 2002)
	Demand planning, maintenance scheduling, transmission planning	(Burke *et al.*, 1988)
Programming	Quality of Service (QoS) routing and network design (Integer programming)	(Van Mieghem and Vandenberghe, 2006)
	Product and supply chain design (Goal programming)	(Fine, Golany and Naseraldin, 2005)

Table 3-3: Examples of subject areas using math-based ToCs

3.2.3.2 The characteristics of knowledge-based trade-off curves

Knowledge-based ToCs are generated by using data that is based on facts and knowledge obtained from material providers, previous projects (including failed or incomplete projects), R&D, prototyping and testing. Therefore, knowledge-based ToCs usually display the actual experiences from engineering activities, or the knowledge that companies already have. Table 3-4 illustrates the current practices of knowledge-based ToCs and their data sources that are mentioned in the literature.

Data obtaining method	Subject areas using generated ToCs	Reference
Material Providers	Knowledge visualisation to support engineering decision-making in SBCE	(Maksimovic *et al.*, 2012)
	Comparing different design concepts to support set-based convergence of integrated product and manufacturing system platforms	(Levandowski, Forslund and Johannesson, 2013) (Michaelis, Levandowski and Johannesson, 2013)
	Visualising the knowledge of technology and creating a set of design alternatives to enable SBCE	(Ward and Sobek, 2014)
Previous Projects	Selection of potential design solutions for SBCE	(Maksimovic *et al.*, 2012)
Prototyping and Testing	Hypothetical case of a muffler to identify feasible solutions to be used in SBCE	(Kennedy, Sobek and Kennedy, 2014)
R&D	Visualisation of several parameters to analyse and compare different aerothermal design concepts in early stages of product development process	(Haselbach and Parker, 2012)

Table 3-4: Current practices of using knowledge-based ToCs

The challenge is to provide a knowledge-environment that supports SBCE applications. The characteristics of such environments are as follows:

a. <u>Visual:</u>

Data to be used during the early design stage should be in a visual form so that the designers are able to quickly understand the trends among the design parameters (Maksimovic *et al.*, 2012; Correia, Stokic and Faltus, 2014; Levandowski, Michaelis and Johannesson, 2014).

b. Easy to communicate:

Captured knowledge should be clearly understood and communicated between different departments in the company (Hong, Nahm and Doll, 2004; Al-Ashaab *et al.*, 2013; Correia, Stokic and Faltus, 2014; Ward and Sobek, 2014).

c. Data type:

Design parameter data should be real and based on facts and knowledge, rather than algorithms and mathematical calculations (Sobek, Ward and Liker, 1999; Maksimovic *et al.*, 2012; Kennedy, Sobek and Kennedy, 2014). This creates knowledge in parts of the business where it was not previously available.

d. Minimum uncertainty:

The uncertainty during the early design stage should be decreased to a minimum level for the designers to make precise decisions. This is possible especially by using real data and experience rather than generating data with algorithms (Hong, Nahm and Doll, 2004; Kennedy, Sobek and Kennedy, 2014; Ward and Sobek, 2014).

e. The amount of generated conceptual design solutions:

Generating high amounts of design solutions (e.g. thousands) will require resources to evaluate the sets and eliminate those solutions with low performance (Al-Ashaab *et al.*, 2013; Khan *et al.*, 2013). It is thus preferable to have fewer design solutions, but base these in reality rather than theory.

f. Reusable:

Usable knowledge created during the early design stage should be stored rather than discarded, in order to reuse it for future projects. Thus, the designers will save resources by not generating the same design solutions repeatedly (Maksimovic *et al.*, 2012; Kennedy, Sobek and Kennedy, 2014).

It is imperative to clarify that "fuzzy set-based trade-offs" (Wang and Terpenny, 2003; Hernández-Luna, Moreno-Grandas and Wood, 2010) might cause confusion with set-based concurrent engineering. Zadeh (1965), who introduced the "fuzzy set theory", described it as a class of objects with a range of grades of characteristics (e.g. a set that includes not only black and white but also all the possible tones of grey). Thus, if the relationships between conflicting requirements are built based on this theory, it would be referred to as fuzzy set-based trade-offs. Fuzzy sets have been established as a new way to solve problems that were not addressed previously by the standard multi-objective optimisation methods (for more information see Hernández-Luna, Moreno-Grandas and Wood (2010); Wang and Terpenny (2003); Zadeh (1965)). It is, however, understood that fuzzy set-based trade-offs are not part of SBCE applications, and are therefore outside the scope of this thesis.

Knowledge-based ToCs have been shown to represent the design limit by separating the feasible design area from the infeasible design area (Araci, Al-Ashaab and Maksimovic, 2016; Ward and Sobek, 2014). Thus, designers will be able to locate the solutions that meet the requirements of the product under development (Ward and Sobek, 2014). Furthermore, since the history of the product does not change and some knowledge-based ToCs use historical data, companies can reuse these ToCs for future projects (Levandowski, Michaelis and Johannesson, 2014). Naturally, they should be updated carefully in order to include new technologies. Thus, innovation could be achieved in new projects.

Table 3-5 summarises similarities and differences between knowledge-based and math-based ToCs. While both types of ToCs are used as an efficient tool for visualisation and decision support, the source of data emerges as a significant difference between them. Since the aim of this thesis is to create and visualise the knowledge-environment for SBCE applications, knowledge-based ToCs are the focus of this research.

Features	Math-based ToCs	Knowledge-based ToCs
Visualisation	Yes	Yes
Decision Support	Yes	Yes
Source of data	Mathematical Calculations	Facts and knowledge
Accuracy	Based on assumptions	Based on reality
Updateable	No	Yes
Reusable	No	Yes
Amount of solutions	Many	Few
Evaluating generated solutions	Resource-intensive	Efficient

Table 3-5: Comparison between math-based and knowledge based ToCs

3.3 The Role of Trade-off Curves within the Set-Based Concurrent Engineering Environment

This section explains the role of trade-off curves within the SBCE context. The SBCE concept was first described by Dr. Allen Ward, who was a pioneer in lean product development (LeanPD) (Ward et al., 1995). LeanPD is an effective approach to performing new product development by eliminating the waste throughout the PD process (Al-Ashaab *et al.*, 2013). The lean product and process development (LeanPPD) model has been developed as shown in Figure 3-5.

The LeanPPD model consists of five enablers, namely: value-focused planning and development, the existence of a knowledge-based environment, the existence of a culture of continuous improvement, technical leadership by the chief-engineer, and the set-based concurrent engineering process. These enablers are applied in the early stages of a PD process (Khan *et al.*, 2013).

The SBCE process is the core enabler of the LeanPPD model. Unlike conventional PD processes, the SBCE approach deliberately delays the critical design decisions until the last possible moment to ensure that the customer expectations are fully understood and that the achieved design solution meets the requirements (Al-Ashaab *et al.*, 2013).

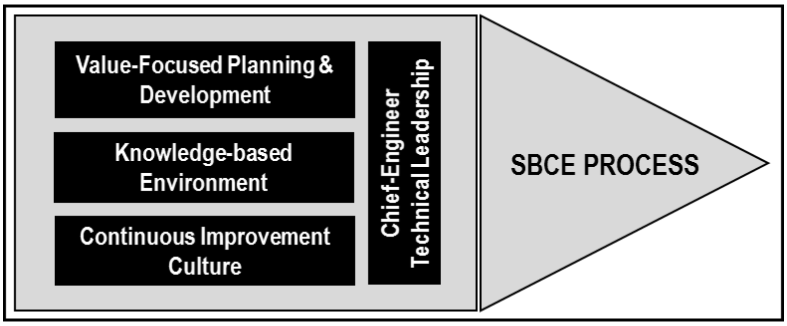


Figure 3-5: The LeanPPD model (Khan et al., 2011)

As it is illustrated in Figure 3-6, SBCE is a PD process within which products are developed by breaking them down into subsystems and designing sets of solutions for these subsystems in parallel. SBCE evaluates this set of designs concurrently and then gradually narrows the set by testing and communicating with other participants until the final solution is obtained (Al-Ashaab and Sobek, 2013; Raudberget, 2010; Sobek, Ward and Liker, 1999).

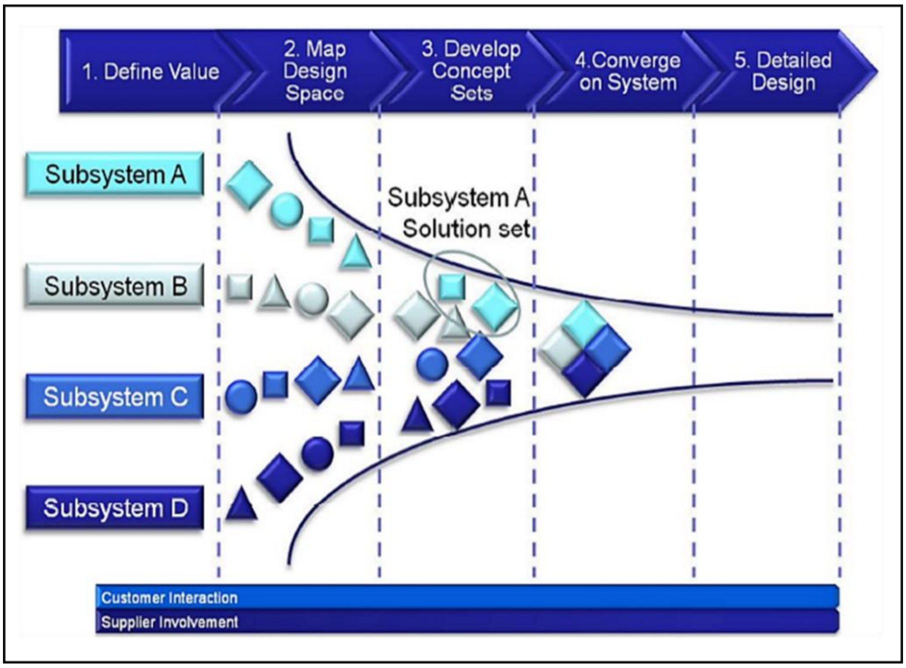


Figure 3-6: The SBCE process model (Khan et al., 2011)

The SBCE process ensures that designs are feasible and compatible with their environment (Sobek, Ward and Liker, 1999). SBCE has several benefits for the new product development. It significantly reduces the need for engineering changes (Khan *et al.*, 2011). Additionally, the set-based philosophy helps to identify and resolve problems as early as possible, and ensures that product attributes, including crucial trade-offs, are clearly understood (Sobek, Liker and Ward, 1998; Morgan and Liker, 2006; Al-Ashaab and Sobek, 2013).

Scholars, academics and practitioners studied the principles of the set-based concurrent engineering concept. However, SBCE was not well-established in a systematic process model until Khan et al. (2011) compiled the principles of the Toyota Product Development system and developed the SBCE process model as shown in Figure 3-7. Therefore, the SBCE process model, which is guiding designers step-by-step throughout their product development activities, has been employed in this thesis in order to demonstrate the processes for generating ToCs. The SBCE process model has five phases and several activities within each phase, as shown in Figure 3-7. The main outcomes of these phases are outlined as follows (Khan, 2012; Al-Ashaab *et al.*, 2013):

1. Value research:

   Customer value and innovation level of the product are identified and the project is aligned with the company strategy.

2. Map design space:

   The design team identifies the scope of the design as well as the feasible design area.

3. Concept set development**:**

   A set of possible conceptual design solutions is developed and tested at the subsystem level. In the meantime, the design team captures the created knowledge and utilises this knowledge for the evaluation of different sets of design solutions. These solutions are communicated within teams to receive feedback and understand constraints.

4. Concept convergence:

   Intersections of the subsystems are explored, and integrated systems are tested. The weak solutions are eliminated allowing the optimal design solution to reach the final phase.

5. Detailed design:

The final set is concluded and final detailed specifications are released.

1. DEFINE VALUE	2. MAP DESIGN SPACE	3. DEVELOP CONCEPT SETS	4. CONVERGE ON SYSTEM	5. DETAILED DESIGN
1.1 Classify project type	2.1 Identify sub-system targets	3.1 Pull design concepts	4.1 Determine set intersections	5.1 Release final specification
1.2 Explore customer value	2.2 Decide on level of innovation to sub-systems	3.2 Create sets for each sub-system	4.2 Explore system sets	5.2 Manufacturing provides tolerances
1.3 Align with company strategy	2.3 Define feasible regions of design space	3.3 Explore sub-system sets: Prototype and Test	4.3 Seek conceptual robustness	5.3 Full system definition
1.4 Translate customer value to designers		3.4 Capture knowledge and evaluate	4.4 Evaluate sets for lean production	
		3.5 Communicate set to others	4.5 Process planning for manufacturing	
			4.6 Converge on final set of sub-system concepts	

Figure 3-7: Activity view of the SBCE process model (Khan et al., 2011)

The knowledge-environment has a vital role throughout the SBCE process (Morgan and Liker, 2006; Al-Ashaab *et al.*, 2013; Khan *et al.*, 2013; Ward and Sobek, 2014). There are several knowledge sources that provide this knowledge-environment for SBCE applications. Trade-off curves are one of these knowledge sources (Maksimovic, 2013) since they have the ability of representing the design data in a visual format. During the SBCE process, evaluation of the design-set and learning effectively from several alternative designs can be challenging (Morgan and Liker, 2006). Trade-off curves are powerful tools to address these challenges. Moreover, trade-off curves facilitate the communication between different teams, departments and stakeholders in a company as well as supporting the decision-making of designers (Correia, Stokic and Faltus, 2014; Araci, Al-Ashaab and Maksimovic, 2016). Although trade-off curves are considered to be useful knowledge tools, the role of trade-off curves is not defined thoroughly (Oosterwal, 2010). However, the current literature shows initial insights on how to use ToCs in enabling key activities of the SBCE process model. These activities are illustrated in Table 3-6.

Key SBCE activities	**References**
Identifying the feasible design solutions area	(Maksimovic *et al.*, 2012; Khan *et al.*, 2013; Kennedy, Sobek and Kennedy, 2014; Kerga *et al.*, 2014)
Generating a set of conceptual designs	(Oosterwal, 2010; Ward and Sobek, 2014)
Communicating a set of designs to others	(Levandowski, Forslund and Johannesson, 2013; Correia, Stokic and Faltus, 2014)
Comparing alternative design solutions	(Sobek, Ward and Liker, 1999; Raudberget, 2010)
Trading-off and narrowing down the set of design solutions	(Sobek, Ward and Liker, 1999; Raudberget, 2010; Khan *et al.*, 2013)

Table 3-6: The key SBCE activities that can be enabled by using knowledge-based trade-off curves

3.4 How to Generate Trade-off Curves that Enable SBCE

Knowledge-based trade-off curves are important tools in supporting PD, and particularly in enabling SBCE applications. However, there is a lack of a systematic approach to generating knowledge-based ToCs (Oosterwal, 2010). For instance, Morgan and Liker (2006) propose that in a trade-off curve, a subsystem's performance in one characteristic is mapped on the Y-axis while another is mapped on the X-axis. A curve is then plotted to illustrate the subsystem's performance relative to the two characteristics. On the other hand, Ward and Sobek (2014) recommend the design team to execute three workshops of developing and using trade-off curve sheets. An example of this is depicted in Figure 3-8.

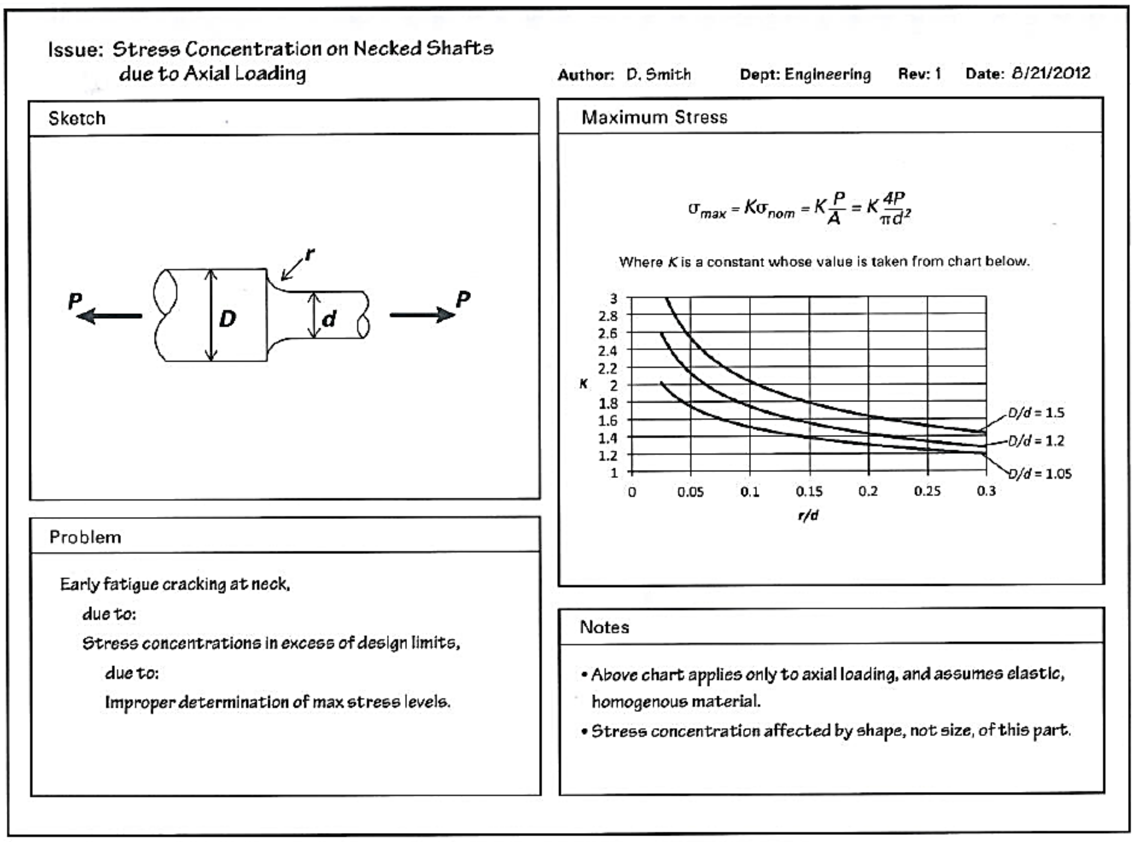


Figure 3-8: A sample of a trade-off curve sheet (Ward and Sobek, 2014)

The first workshop is intended for problem definition. They advise designers to focus on only one problem as a starting point and to identify the success measures for the progress of problem solving. The second workshop is recommended for drawing a causal diagram that identifies the possible causes of the problem and countermeasures, and then assigning a person to obtain the data required to generate trade-off curves. While data is being collected, the design team should seek a plausible combination of the parameters. This eventually enables them to generate ToCs. The third workshop is meant for the discussion of the ToCs. These are presented and used to evaluate the problem and find solutions. While generating the trade-off curve sheets, Ward and Sobek (2014) recommend designers to implement these sheets for the current problem, and then preserve them for future use. However, this model does not include the customer requirements and decision criteria, and also does not demonstrate any known solutions from previous projects.

3.5 Research Gaps

The research on creating a knowledge-environment that enables SBCE has been evolving and growing in volume, during the last few decades. However, knowledge creation and visualisation have not been addressed thoroughly. Therefore, the research gaps presented in Table 3-7 have been defined. This research attempts to address these gaps.

No.	Identified research gaps	Literature review section that the gap applies to	Related thesis section that the gap has been addressed
1	There is a lack of definition of the role of ToCs within the SBCE context.	Section 3.3: The Role of Trade-off Curves within the SBCE Environment	Section 5.2: The Approach to Developing Processes for Knowledge Creation and Visualisation to enable SBCE
2	There is no clear approach to assisting in the creation and visualisation of a knowledge-environment that enables SBCE applications.	Section 3.2.3: Different Types of ToCs Depending on the Data Source Section 3.4: How to generate ToCs that Enable SBCE	Section 5.3: The Process for Generating Knowledge-based ToCs: Based on Historical Data
3	There is no clear approach to generating ToCs based on the understanding of the physics and functions of the product under development.	Section 3.2.3: Different Types of ToCs Depending on the Data Source Section 3.4: How to generate ToCs that Enable SBCE	Section 5.4: The Process for Generating Physics-based ToCs: Based on Physics Knowledge of the Product
4	There is no clear explanation of how to analyse generated ToCs in order to enable SBCE.	Section 3.3: The Role of Trade-off Curves within the SBCE Environment	Chapter 6: Industrial Case Studies and Expert Judgements for Validation

Table 3-7: Research Gaps

3.6 Summary of Chapter 3

A comprehensive definition and an overview of ToCs were presented in this chapter. Two different types of ToCs were identified in the literature. These are knowledge-based and math-based ToCs. It was found that math-based ToCs are commonly used in multi-objective optimisation applications. On the other hand, characteristics of a knowledge-environment for the SBCE process were defined. Knowledge-based ToCs are considered to have the capability of creating and representing this knowledge-environment. Furthermore, SBCE activities that are supported by the use of ToCs were described and the current practices of generating ToCs were highlighted. Finally, research gaps were identified as a result of the extensive literature review.

4 INDUSTRIAL FIELD STUDY

4.1 Introduction

An industrial field study was performed in order to capture the real-life applications of trade-off curves during the practitioners' product development activities. This chapter, as illustrated in Figure 4-1, presents the industrial perspective of knowledge creation and visualisation by using ToCs. Section 4.2 describes the interactions with industrial collaborators. Section 4.3 presents the analyses of the results of the interviews with a semi-structured questionnaire.

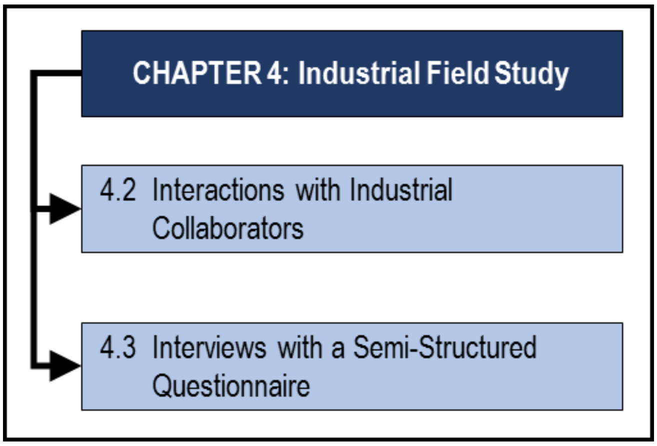


Figure 4-1: Structure of chapter 4

4.2 Interactions with Industrial Collaborators

Interactions with industry stakeholders consisted of discussions with industrial collaborators through virtual web-based meetings, as well as face-to-face meetings. These collaborators each have initiatives to apply the SBCE process model within their companies. The collaboration involved both observations of their product development process and discussions with engineers and managers. Meetings, observations and workshops were used in order to understand the industrial needs of generating and using ToCs that enable SBCE applications in their businesses.

Feedback and comments were received from senior managers in four collaborating companies. The details of these industrial collaborators are presented in Table 4-1. This collaboration helped the author, throughout the PhD research, to develop and improve the proposed processes for generating ToCs, which are described in chapter 5.

Collaborating company	Position of the industrial collaborator in the company
Rolls-Royce	Systems Design Integration Manager
	Knowledge Management Specialist
SiTech	Director of Product Strategy, Research and Development
Paxton	Development Director
	Process Improvement Engineer
	Senior Engineer - System Test
Caltec	Technology Director
	Process Engineer

Table 4-1: Portfolio of the industrial collaborators

4.3 Interviews with a Semi-Structured Questionnaire

Interviews were performed to capture the current practices of using trade-off curves during product development processes in the industry. A semi-structured questionnaire was developed to capture the most relevant information from the participants. Appendix A contains the relevant part of the "Best Practices in Product Development" questionnaire. This questionnaire originally consists of three parts:

1. Product Development Process
2. Trade-off Curves
3. Collaboration between Commercial and Engineering teams

Since part 1 and 3 are out of the scope of this thesis, only results of part "2. Trade-off Curves" are discussed in this section. The numbering of the questions is maintained in line within the original questionnaire.

The semi-structured questionnaire was completed by five participants from five different companies, as presented in Table 4-2. These companies either have initiatives to apply SBCE or are interested in using SBCE to support their product development processes. This section is presenting the results about how to use ToCs in supporting product development activities, and what key activities are to be carried out while generating ToCs. Participants were intentionally selected from managerial positions with more than fifteen years of experience. As shown in Table 4-2, interviewees were mainly from the automotive industry in the UK. Interviewing this strong profile of experts has facilitated the collection of reliable and trustworthy information about the practices, regarding trade-off curves, in product development activities of the industry.

No.	Company	Position	Years of Experience	Industry	Country
1	Ford	Senior Program Manager	15	Automotive	UK
2	GKN	Continuous Improvement Manager	23	Automotive and Aerospace	UK
3	Paxton	Process Improvement Engineer	15	Security & Access Control	UK
4	Ricardo	Program Manager	28	Automotive	UK
5	Visteon	Engineering Quality Senior Manager	15	Automotive	UK

Table 4-2: Profiles of the Interviewees

Question 1: *How would you describe the use of trade-off curves (ToCs) in the current product development (PD) process within your company?*

The aim of this question was to discover whether trade-off curves are currently being used within the company's product development process. Three participants indicated that they had initiatives to create and introduce ToCs. One of the interviewees said that ToCs were loosely used in some projects, while only one company uses ToCs formally throughout the PD process and in most of the projects. All participant companies are aware of the importance of using ToCs, however most of them have not established the formal use of ToCs. This might be due to the lack of a systematic approach for generating ToCs, and for using the generated ToCs in the PD process.

Question 2: *Which of the following descriptions is the closest to your company's interpretation of trade-off curves in the early stages of the product development?*

Participants were asked to define trade-off curves, in a product development context, from their perspective. Interviewees were able to select more than one definition from the available options. As shown in Figure 4-2, according to two respondents ToCs are tools to understand the relationships between various design characteristics as well as to characterise the relationship between two or more key parameters that represent the customer requirements. Additionally, most of the participants agree that ToCs are a source of knowledge which enables the identification, capture, comparison, and reuse of knowledge for new projects. Another application of ToCs was also acknowledged by the majority, with ToCs being seen as a simple form of visualising the limits of design performance of the product under development.

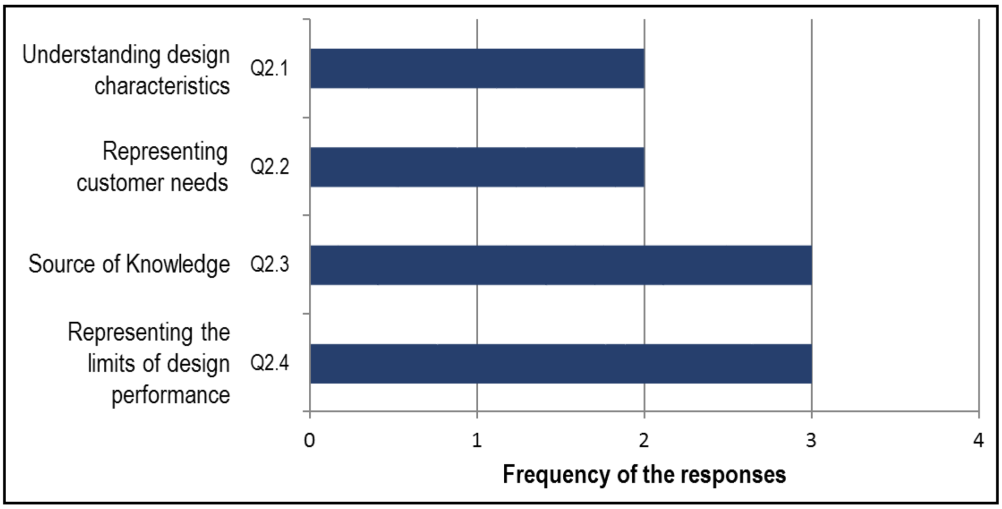


Figure 4-2: Definition of ToCs from the participants' perspective

Therefore, ToCs are perceived as helpful and simple tools to be used throughout the product development processes.

The importance of using ToCs in PD was obvious from the related literature review, and was supported by the evidence from the first two questions. Therefore, it became necessary to ask participants how to generate ToCs. Possible activities were listed to provide a guidance for the respondents, however, an option was provided to specify their own opinions.

Question 3: *How important do you find the following activities in generating trade-off curves, and how efficient do you implement these activities throughout the early stages of the new product development process?*

This question has two parts to answer. The first part questions the importance of each activity while the second part asks participants to understand how efficiently they implement the relevant activity. Figure 4-3 illustrates a graph representing the responses of both parts as importance and efficiency.

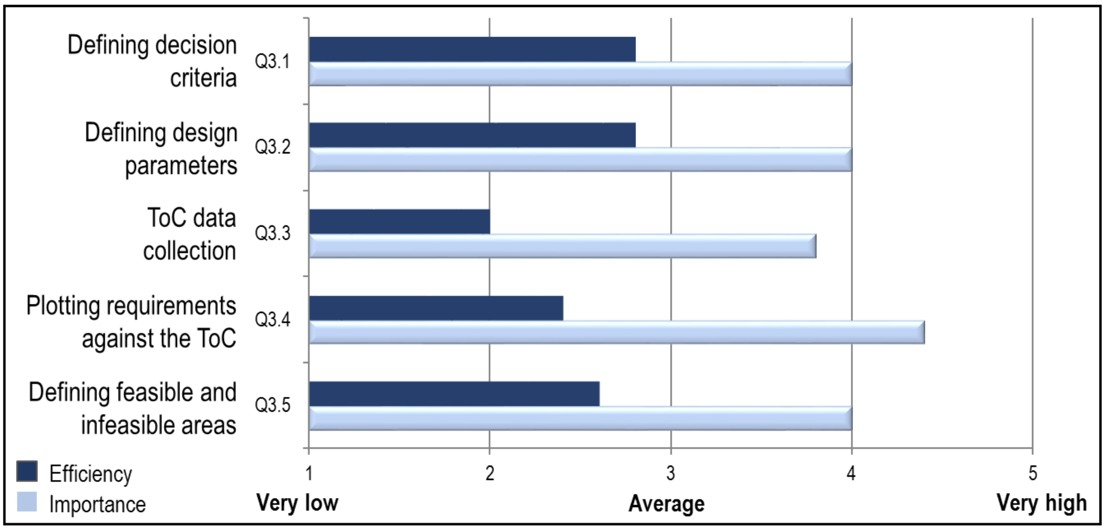


Figure 4-3: Key activities to generate trade-off curves

Participants indicated that, in order to generate ToCs, identifying decision criteria, design parameters, and customer requirements are as important as collecting data from previous projects and defining the feasible and infeasible area. One of the participants indicated that investigating and understanding the physical characteristics and functions of the product properly also has a significant contribution to generating trade-off curves.

Although the interviewees were aware that these activities are essential to generate ToCs, they expressed that they do not implement these activities efficiently. This could be due to the fact that there is no systematic approach for generating ToCs in product development which clearly explains how to implement these activities.

Question 4: *How do you define decision criteria for the generation of trade-off curves?*

Defining decision criteria has a significant role in ToC generation, since they affect the key decision-making throughout the PD process. The aim of this question was to capture the best practices of identifying decision criteria. As shown in Figure 4-4, participants appreciate the use of experiences from previous projects, such as conflicting issues and problems they encountered. Additionally, extracting from customer requirements was another means of defining decision criteria that was frequently stated. One of the participants also suggested that it was very important to define decision criteria by understanding the customer's need.

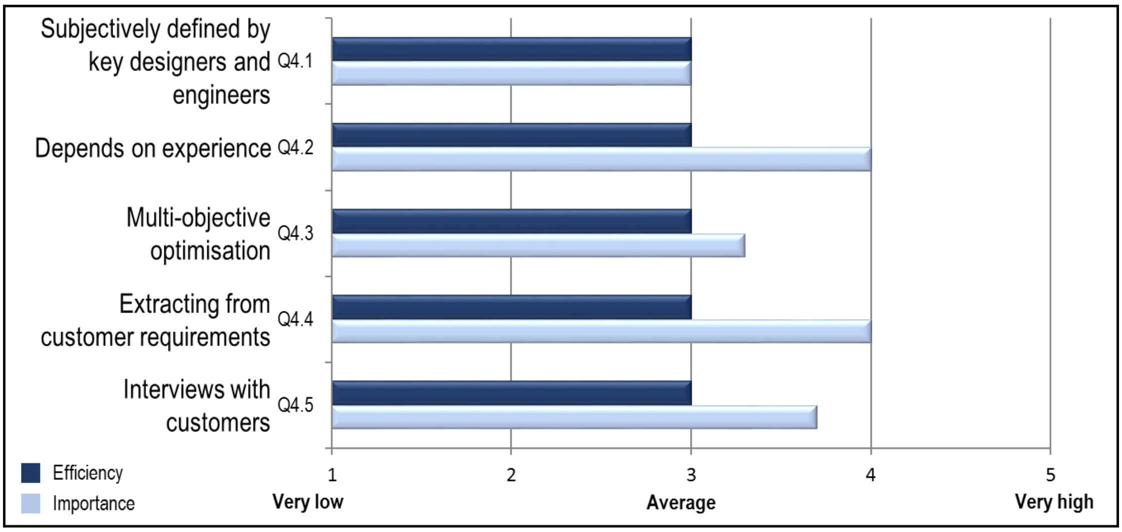


Figure 4-4: Methods of identifying decision criteria for generating ToCs

Question 5: *How do you obtain the required data to generate trade-off curves?*

Data collection is one of the most important activities of generating ToCs. Interviewees were asked to express their thoughts about several means of data collection. Responses show that collecting data from previous projects has a high importance, however, efficiency of their practice is low as shown in Figure 4-5 (option 5.1). On the other hand, it is understood that dedicating people to collect data has a high importance, however most participant companies do not practice this method (low importance). The reason might be that this method is rather resource-intensive, and that no systematic approach is defined for it.

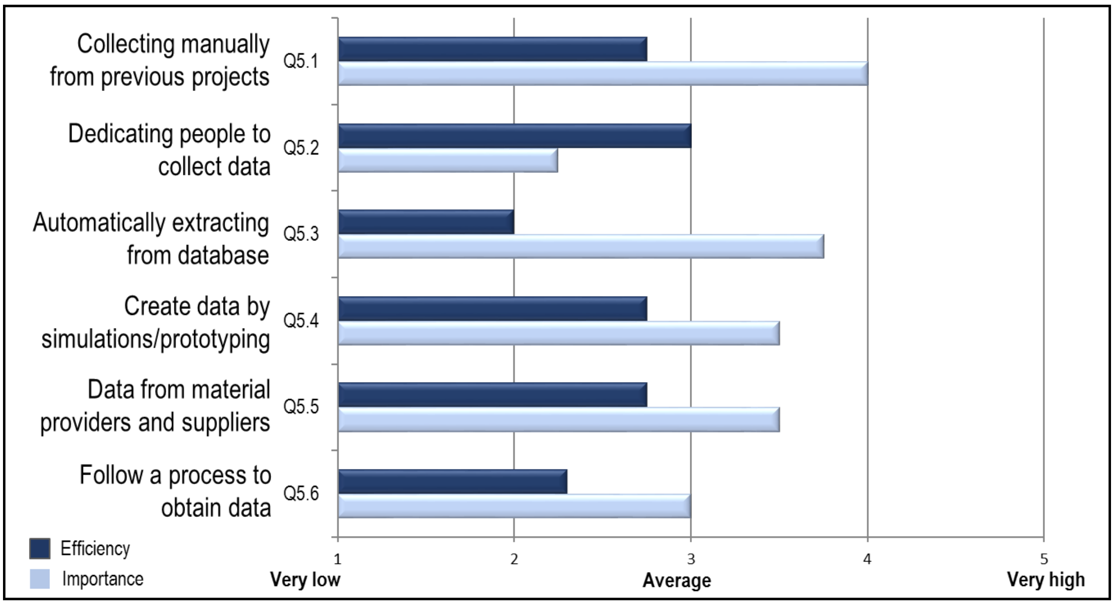


Figure 4-5: Tools and methods for data collection to generate ToCs

A process for data collection, as presented in Figure 4-6, was recommended to the respondents as an alternative method. Participants appreciated the importance of having such a process to collect data for generating ToCs.

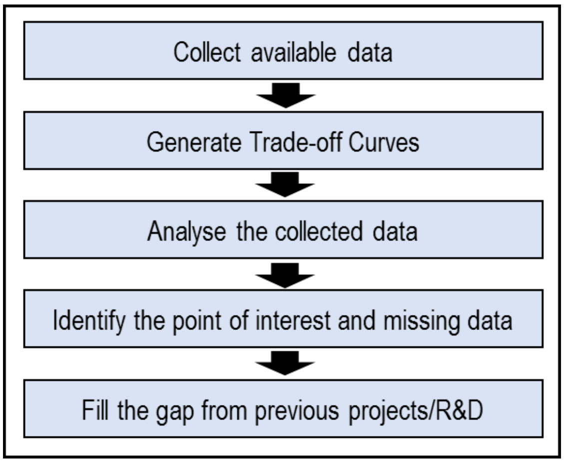


Figure 4-6: A recommended process to collect data for generating ToCs

Question 6: *In which steps/tasks/activities of your current product development process would you use trade-off curves?*

This question was asked to capture the best practices of using ToCs throughout the product development activities of companies. Figure 4-7 shows that it is very important to use ToCs to enable the PD activities listed in the figure. However, ToCs are not used efficiently in these activities. The reason is likely the lack of understanding about how and where to use ToCs effectively in product development processes. These results support the authors' proposal that a process is needed for how to use ToCs that enable SBCE, as is presented in chapter 5.

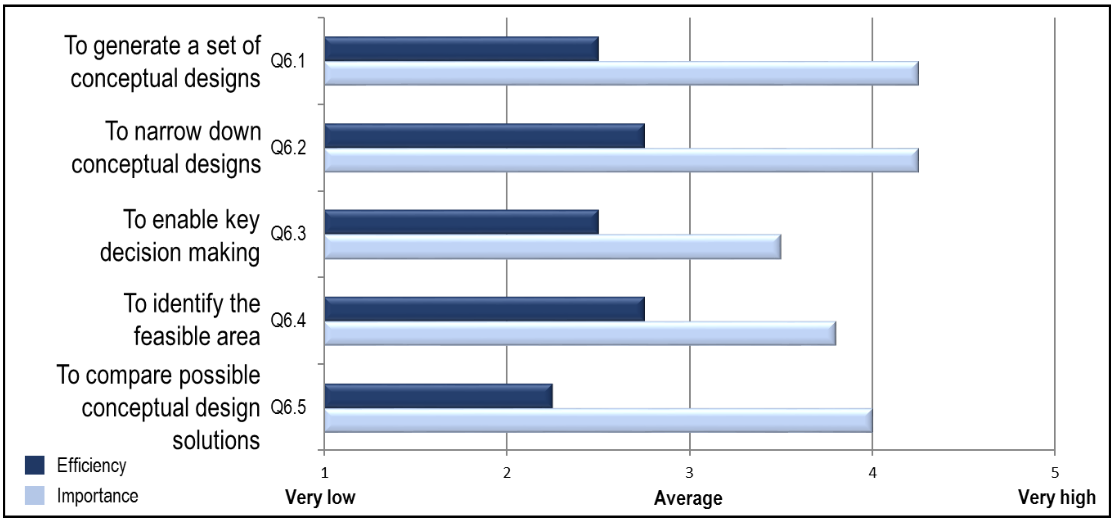


Figure 4-7: PD activities to be enabled by the use of generated ToCs

4.4 Summary of Chapter 4

An industrial field study was carried out to obtain a better understanding of the industrial perspective for this research. The field study includes interactions with industrial collaborators and interviews. Feedback and comments from the industrial collaborators as well as the findings from interviews contributed to the research by providing a direction for the development of processes for knowledge creation and visualisation that enable SBCE applications.

5 PROCESSES FOR KNOWLEDGE CREATION AND VISUALISATION THAT ENABLE SBCE

5.1 Introduction

The analysis of the extensive literature review in chapter 3, and the industrial field study in chapter 4, demonstrated that a systematic approach is needed in order to create a knowledge-environment for SBCE applications. This chapter, as is illustrated in Figure 5-1, presents three processes that were developed in order to address this need. Section 5.2 describes how the author developed these three processes. Section 5.3 presents the process for generating knowledge-based ToCs by using historical data. Section 5.4 presents the processes for generating physics-based ToCs by using knowledge obtained from the understanding the physics and functionality of the product. Section 5.5 presents how to utilise generated knowledge-based and physics-based ToCs throughout the SBCE process model.

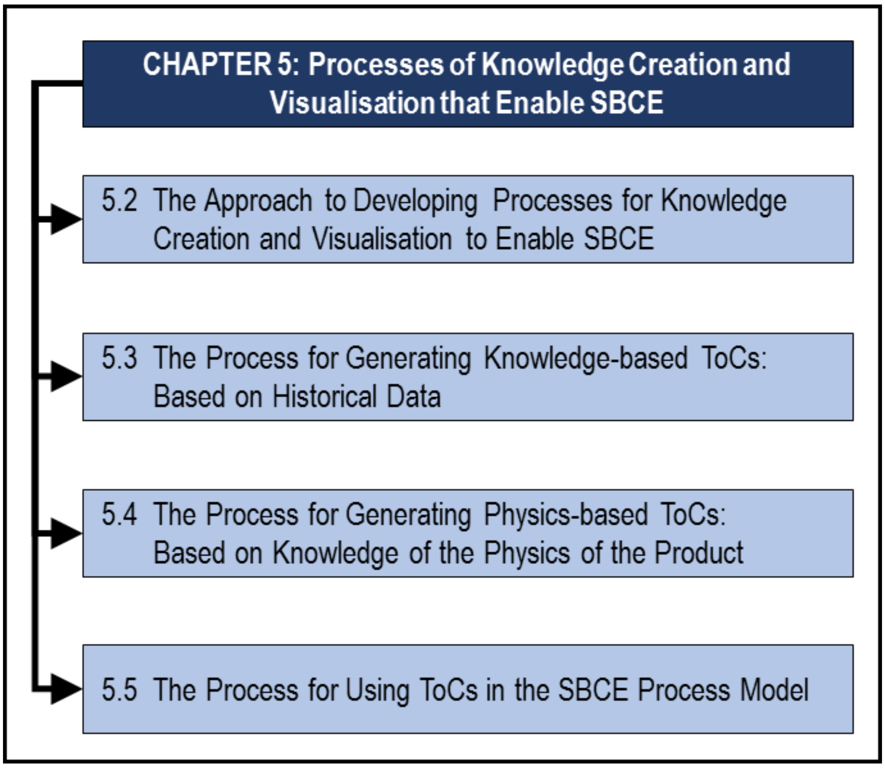


Figure 5-1: Structure of chapter 5

5.2 The Approach to Developing Processes for Knowledge Creation and Visualisation to Enable SBCE

This section presents the approach taken to develop three processes, which are for generating ToCs that create and visualise a knowledge-environment for SBCE applications. These three processes are listed in section 5.1.

Among the key driving elements that helped the author to develop these three processes were an understanding of the information gained from the related literature and analysis of the research gaps as presented in section 3.5. They suggest that there is a need of a visually displayed knowledge-environment throughout the SBCE application. Data obtained from the field study, as is presented in section 4.3, supported the notion that industrial companies are also in need for such an environment. Therefore, an initial process for generating knowledge-based ToCs was developed as shown in Figure 5-2. This process was implemented in a research-based aerospace case study and is demonstrated in section 6.3.

Step 1: Define decision criteria for the product under development

Step 2: Get the data related to each of the decision criteria.

a) Data from material providers.
b) Data from previous projects, incomplete projects, R&D.
c) Data from simulations and engineering calculations.

Step 3: Generate different trade-off curves.

Step 4: Get the requirements (customer) and plot these against the ToCs.

Step 5: Define feasible/infeasible design area.

Step 6: Extract/locate the design solution.

Step 7: Develop a set of potential solution that might be useful for the project under consideration.

Step 8: Convert these potential solutions to a viable solution.

Figure 5-2: Initial process for generating ToCs

Comments and constructive feedback helped the author to improve the initial process, as is shown in Figure 5-3, and implement it in an automotive case study for a car seat structure design. This case study is described in detail in section

6.4, and has also been published in an open access electronic journal (Araci, Al-Ashaab and Maksimovic, 2016).

STEPS	ACTIVITIES
1. Decision Criteria	1.1. Get customer requirements 1.2. Define decision criteria 1.3. Define design parameters 1.4. Define the relations between defined design parameters
2. Data Collection	2.1. Collect the data of the defined design parameters 2.2. Filter and refine the data 2.3. Prepare the final filtered data
3. ToC Generation	3.1. Plot the data of the corresponding design parameters 3.2. Plot the customer requirements against generated ToCs
4. Feasible Solutions	4.1. Define the feasible and infeasible area 4.2. Identify the design solutions within the feasible area 4.3. Develop a set of potential design solutions
5. Optimal Solution	5.1. Generate new ToCs 5.2. Compare and trade-off developed design set 5.3. Narrow down the design solutions 5.4. Select the optimal design solution

Figure 5-3: Improved version of the process for generating ToCs

Through the experiences from the industrial case studies, which are presented in sections 6.3 and 6.4, the process for generating knowledge-based ToCs was evolved to its final version as presented in Figure 5-4. This process was validated with an industrial case study for a new access card reader in electronics industry, which is explained in section 6.5. The main change was made in step 5 of the process shown in Figure 5-3, where it became apparent that this step should be explained in more detail in order to accurately compare the possible design solutions until achieving the optimal design.

Additionally, applying the process for generating knowledge-based ToCs and feedback from one of the interviewees showed that it is essential to understand the physical characteristics of the product, especially in the conceptual design stage. Physics-knowledge supports the creation of new design solutions and assists in improving, comparing and narrowing down the design-set while proceeding through the SBCE process. However, the literature does not reveal applications, information or research to address this issue. It has thus been identified as a research gap in section 3.5. Analysing the industrial case study results and collaborating with different industries helped the author to develop a new process for generating physics-based ToCs, as shown in Figure 5-6, to provide physics-knowledge for SBCE applications. This process was also validated by an industrial case study, which is presented in section 6.6. Both processes provide a systematic approach. The sequential steps and activities within each process enable an ordered flow of tasks required in order to generate ToCs.

Information gained from the literature review and implementing the processes in different industrial case studies clarified the need for a systematic approach for use of the generated ToCs in enabling the SBCE process model, which is presented in detail in section 5.5 and validated by a case study with oil and gas industry.

In the following sections and chapters, reference will be made to “the design team”. This term refers to the designers, engineers, managers or other stakeholders who are involved in the development of a new product in the related project.

5.3 The Process for Generating Knowledge-based Trade-off Curves: Based on Historical Data

This section describes the process for generating knowledge-based ToCs that enable SBCE applications. As mentioned in sub-subsection 3.2.3.2, knowledge-based ToCs are generated by using historical data that is collected from material providers, previous projects (complete or incomplete), R&D, testing and prototyping. Figure 5-4 illustrates the process for generating knowledge-based

ToCs including five main steps, which are further broken down into different activities. Although a sequential approach has been suggested here, the chronological position of some activities within the process may be interchangeable. The activities within each step are described in detail below.

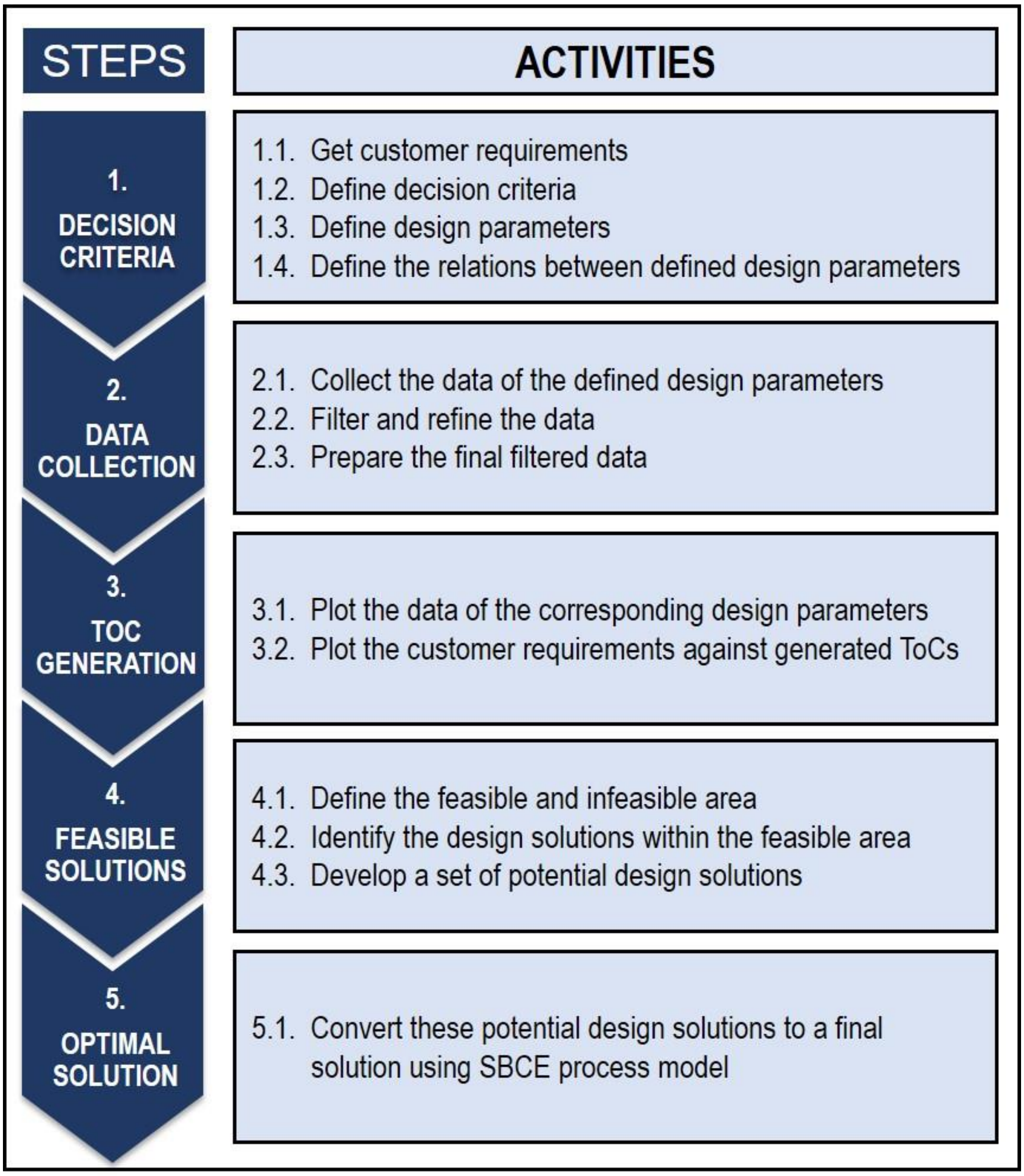


Figure 5-4: The process for generating knowledge-based ToCs that enable SBCE

5.3.1 Step 1: Decision criteria

<u>Activity 1.1: Get customer requirements</u>

Objective: Customer requirements are the characteristics, specifications and features of a product that are determined by a customer. Customer requirements should be thoroughly understood in order to identify both the decision criteria and the key design parameters.

Method: Customer requirements are obtained by using customer request documentation and requirements, market research methods, and meetings with customer representatives.

Activity 1.2: Define decision criteria

Objective: Decision criteria that drive the key design decisions should be identified by the design team. With them, they will be able to make a final decision about the product design which they believe fulfils the customer requirements. Additionally, decision criteria will support the team in identifying the design parameters for the next activity of the process for generating knowledge-based ToCs.

Method: Decision criteria are identified by extracting them from customer requirements, benchmarking and using experiences from previous projects. Among such experiences may be information about conflicting issues and problems that were encountered.

Activity 1.3: Define design parameters

Objective: Design parameters represent the special characteristics of the product under development. They are measurable indicators of the decision criteria identified in the previous activity. Design parameters are vital elements of ToCs and essential for the data collection activity. They facilitate the collection of the appropriate data, thereby minimising resource wastage. Therefore, all identified design parameters should relate to the decision criteria.

Method: Each design parameter should represent at least one decision criteria. One parameter might be related to more than one decision criteria. As the parameters are identified, they should be listed in preparation for the data collection in “Activity 2.1. Collect the data of the defined parameters”. Eventually, parameters should be classified according to the respective decision criteria. They can then be used, in the next activity, for defining the relationships between the design parameters. While identifying design parameters, environmental matters can also be considered in order to reduce negative impacts.

<u>Activity 1.4: Define the relations between defined design parameters</u>

Objective: ToCs are knowledge visualisation tools that display the relationship between various design parameters, each of which have an impact on design decisions. This activity provides insights for the design team to understand the conflicting relations and make an accurate decision accordingly.

Method: The design team should associate the defined design parameters to each other and define plausible relationships that represent meaningful knowledge, as well as conflicts between the individual parameters. Two conflicting design parameters should be related to each other in order to represent at least one decision criteria. The design team decides which parameters are compared. If the product is a complex system, the design team might require more than two relations within one pair of parameters. In addition, defined relationships are classified according to the related decision criteria. Thus, it is easily understood which possible design solutions meet which decision criteria, and decision-making is facilitated.

5.3.2 Step 2: Data collection

<u>Activity 2.1: Collect the data of the defined design parameters</u>

Objective: Design parameter data is the primitive form of the knowledge that is required in order to present the design performance of the product on trade-off curves.

Method: Data of the design parameters is collected from previous projects, testing and prototyping, material providers, suppliers, and R&D

projects. Collected data is made available in a data processing software (e.g. Excel).

Activity 2.2: Filter and refine the data

Objective: After data collection, instances might be found where there is unavailable data which has not previously been recorded, does not exist in the data source or cannot be generated at the present time. The data set should be amended in order to avoid generating ToCs based on inaccurate data.

Method: Design parameters that do not have data, or where data integrity is questionable (e.g. outliers), should be removed from the data set.

Activity 2.3: Prepare the final filtered data

Objective: Design parameters data might not be found in the required format. The data may require transformation into a form that the design team can work with.

Method: The design team should check the data set to see if there is a need for converting the unit of data (e.g. converting cm^2 to mm^2) or for derivations from the collected data. The data set should be organised in a way that the design team can easily select and use the data when generating ToCs.

5.3.3 Step 3: ToC generation

Activity 3.1: Plot the data of the corresponding design parameters

Objective: This activity will lead to the generation of a trade-off curve which turns the data into a visual form. It will then be available for the design team and assist them in identifying the feasible and infeasible design solutions, which are explained in detail in the activity 4.1.

Method: Design parameter data is plotted on the related axes of the ToC diagram according to the relationships defined in activity 1.4. The design team should be able to generate as many ToCs as there are defined relationships between the parameters. However, if any parameters have been removed in activity 2.2, the number of generated ToCs may decrease. In some cases, it is difficult to discern a clear relationship between the data points. Reasons for the unclear relationship should be analysed and understood by the design team. For example, one reason might be that changes in the regulations for a product might have resulted in new restrictions or requirements, when compared to previous products.

Activity 3.2: Plot the customer requirements against generated ToCs

Objective: Customer requirements represent the limits, specifications and numeric values of the product that the design team desire to achieve. This activity is the first step needed to identify the feasible area, which is explained in activity 4.1.

Method: After generating ToCs, the customer requirements, which are obtained in activity 1.1, should be plotted against the related ToCs. It should be noted that not every generated ToC must necessarily present customer requirements or show a trend. In such cases, the design team should analyse these ToCs in order to support decision-making.

5.3.4 Step 4: Feasible solutions

Activity 4.1: Define the feasible and infeasible area

Objective: The feasible area is the region that includes the data of possible design solutions from previous projects, or new solutions, which either fulfil or are very close to meeting new customer requirements. The infeasible area is the region that features the data of design solutions which do not meet the customer requirements.

Method: After plotting the customer requirements against the generated ToCs, the area surrounded by these customer requirements should be highlighted. Thus, the feasible area will be differentiated from the infeasible area.

Activity 4.2: Identify the design solutions within the feasible area

Objective: Design solutions located within the feasible area are named as “feasible” design solutions. These designs are reused for the current project in order to develop a design-set.

Method: Highlighting the feasible area facilitates pointing out the possible feasible designs. They stem from complete/incomplete previous projects, R&D projects, testing and prototyping. Detailed information about all these solutions can be obtained from a shared folder of the previous solutions and company database, for example PLM or PDM. The design team should note down the feasible solutions in a table by indicating the related decision criteria. This activity, then, is repeated for each ToC that is generated.

Activity 4.3: Develop a set of potential design solutions

Objective: This activity aims to develop a set of possible design solutions to be utilised and narrowed down in the early stages of the SBCE process.

Method: Activities 4.1 and 4.2 are performed for all generated ToCs. The design solutions and the curve within the feasible area are analysed by considering the customer requirements and decision criteria that are explained in activities 1.1 and 1.2. Thus, companies do not need to employ resources only to redesign already existing solutions. Rather, they reuse those which fall in the feasible area, as explained in activity 4.1. One or a combination of the following activities can be carried out to this end:

i. Reusing the existing proven design solution: If the feasible design solution shows a suitable solution, or nearly does so, this solution can be reused as a part of the set of possible design solutions. In addition, in some cases, some of the components or subsystems of the proven existing product design within the feasible area can be reused.

ii. Minor changes: ToCs will help the design team to identify several existing design solutions within the feasible area. However, because requirements for the product under development may have changed compared to earlier work, these identified feasible design solutions may only be reused after applying minor modifications. For example, the quantitative value of the design parameters (e.g. physical principles, shape variations, tolerances) can be modified and tested in order to turn the existing solution into a suitable solution.

iii. Major changes: Existing design solutions may have been classified as feasible. However, these design solutions can only be reused after applying major modifications. For example, the performance of the product on the subsystem or component level (e.g. material properties, geometry) may require modification, without re-thinking all of it.

iv. Create new conceptual design solutions: The design team may make a decision not to reuse the existing design solutions for the current project. However, the approach, knowledge and experience from these existing solutions might inspire the design team while creating new, innovative solutions. After identifying the feasible area and the curves within this area, the design team chooses a point on the curve from each ToC. This point will be representing the design parameters (X and Y axes / X, Y1, Y2) of a suitable solution for the examined ToC. This suitable solution should be addressing the customer requirements and decision criteria of the project under development. Thus, the design team will understand the accurate design parameters which will support the creation of new conceptual designs for the set of possible design solutions.

5.3.5 Step 5: Optimal solution

Activity 5.1: Convert these potential solutions to a final optimal solution by using the SBCE process model:

Objective: The optimal solution is a design which fully meets the identified customer requirements and decision criteria as defined in activities 1.1 and 1.2, and is therefore ready for detailed design. The aim of this activity is to enable SBCE applications by providing a design-set which is to be used throughout the SBCE process, until eventually achieving the optimal design solution.

Method: The generated design-set is analysed in order to evaluate and compare the possible solutions. Solutions should be aggressively narrowed down, by using the SBCE process model, until an optimal solution is identified.

Since each step has been explained in detail, the proposed process might be perceived as tiresome work. However, in real life this process proceeds quite smoothly, especially after gaining experience in using it. Figure 5-5 illustrates an overview of the process.

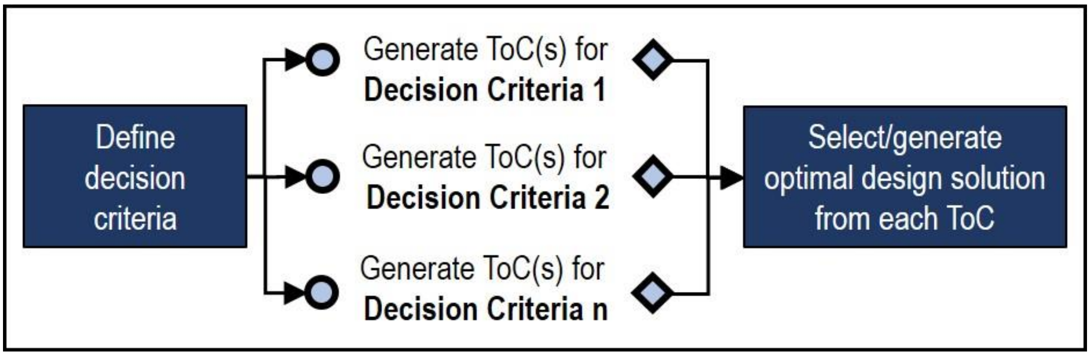


Figure 5-5: Overview of the process for generating knowledge-based ToCs

5.4 The Process for Generating Physics-based Trade-off Curves: Based on Knowledge about the Physics of the Product

This section presents the process for generating physics-based trade-off curves that enable SBCE applications, as illustrated in Figure 5-6.

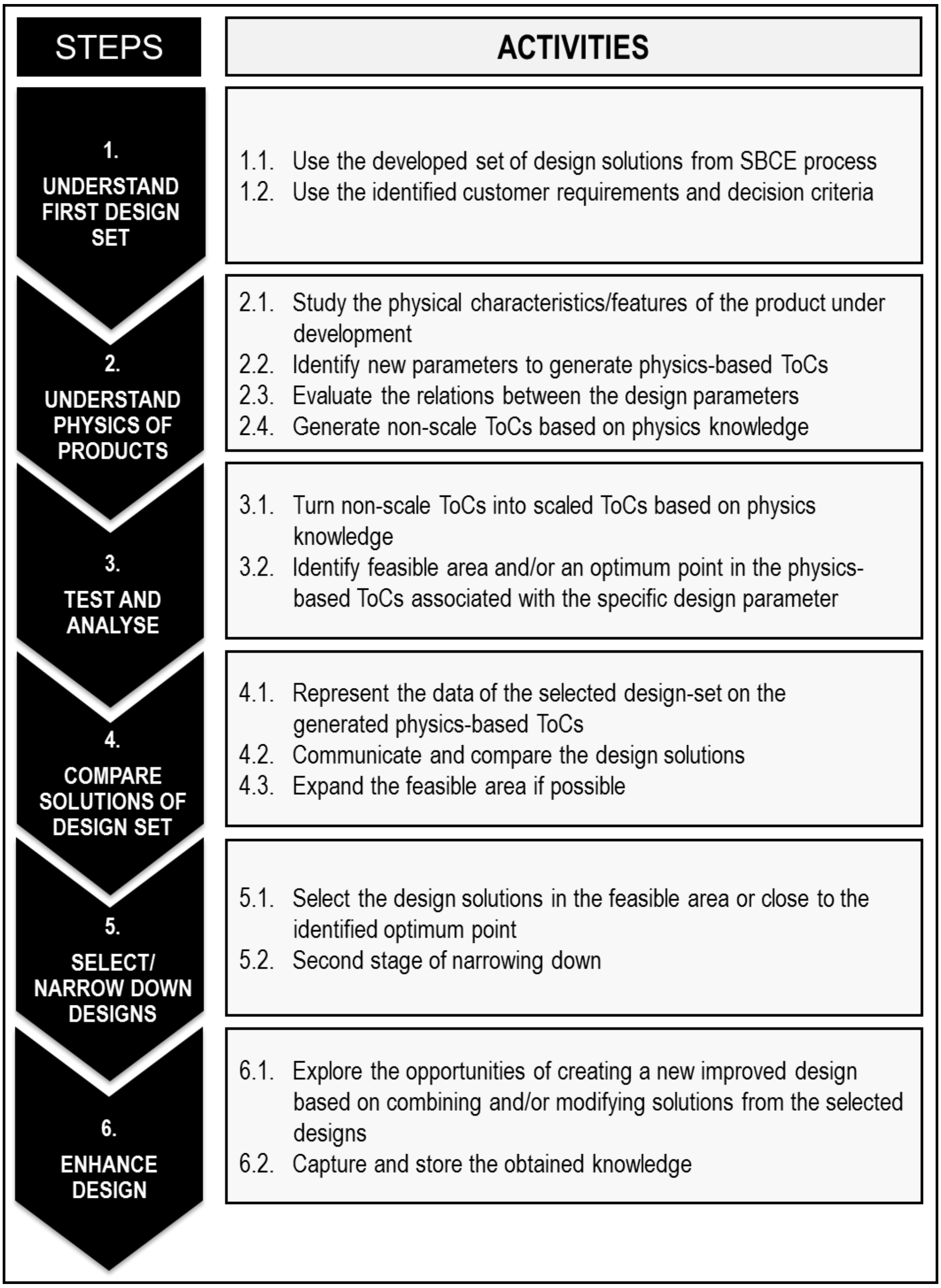


Figure 5-6: The process for generating physics-based ToCs that enable SBCE

Physics-based trade-off curves are generated by using data that is obtained by understanding the physical characteristics of the product under development. A key requirement for this process is the existence of a design-set, which can be evaluated and narrowed down further throughout the SBCE process. Thus, the need for a detailed work could be eliminated. The activities within each step of the process for generating physics-based ToCs are described in detail in this section.

5.4.1 Step 1: Understand the first design-set

<u>Activity 1.1: Use the developed set of design solutions from the SBCE process</u>

Objective: In order to evaluate the design-set and narrow it down, the design team must ensure that it is available in the correct format.

Method: The design team should obtain the identified design-set to use during the SBCE process. This set is obtained from the designs that were developed by using one or a combination of the generated knowledge-based ToCs, from R&D, from simulations, and from prototyping and testing. Should no such ToCs exist, the design team can generate designs by using the knowledge obtained from understanding the physical characteristics and functionality of the product.

<u>Activity 1.2: Use the identified customer requirements and decision criteria</u>

Objective: In order to achieve an optimal design solution that addresses the needs of the customer(s), the customer requirements and decision criteria must be understood by the design team.

Method: The design team obtains the identified customer requirements and decision criteria identified for knowledge-based ToCs for the same project. If such records are unavailable, the design team refers back to the customer requirements and decision criteria that were identified at the start of the SBCE project. Should no such data exist, the design team should follow the process laid out in subsection

5.3.1, step 1, to identify customer requirements and decision criteria.

5.4.2 Step 2: Understand physics of the product

Activity 2.1: Understand the physical characteristics/features of the product under development:

Objective: This activity provides confidence for the design team to evaluate different design solutions. It is essential to understand the purposes, functions, and working environments of the product.

Method: Fundamental features and the physical characteristics of the product under development should be investigated by referring to the laws of physics, and considering the identified customer requirements and decision criteria. Required information can be obtained from literature, industrial practices, and physics applications. A new set of ToCs, based on the obtained physics knowledge, could then be generated.

Activity 2.2: Identify new design parameters to generate physics-based ToCs

Objective: As mentioned in section 5.3 in activity 1.3, design parameters are essential elements of trade-off curves. This activity identifies new design parameters that are representing the physical features and characteristics of the product.

Method: Conflicting new design parameters should be identified based on an understanding of the physics of the product, and by considering the identified customer requirements and decision criteria.

Activity 2.3: Evaluate the relations between the design parameters

Objective: This activity is to provide designers with sufficient confidence for decision-making while comparing and narrowing down the design-set. Thus, designers will be able to eliminate those solutions that are not meeting the customer requirements and decision criteria.

Method: The design parameters should be reviewed and understood in relation to the product physics. The type of relationship between design parameters should be identified.

Activity 2.4: Generate non-scale ToCs based on the obtained physics knowledge:

Objective: This activity generates non-scale physics-based ToCs that are presenting only the relationships between design parameters identified in activity 2.3, without numeric values. These ToCs facilitate communication among stakeholders, even without requiring a detailed engineering background, which enables decision-making, especially on the management level.

Method: The design team should project the relations evaluated in activity 2.3 against the non-scale ToCs. These relations could depict several forms of trend such as increasing, decreasing, linear, exponential, etc.

5.4.3 Step 3: Test and analyse

Activity 3.1: Turn non-scale ToCs into scaled ToCs based on physics knowledge

Objective: In order to evaluate the design solutions within the developed design-set and make an accurate selection of the feasible designs, the non-scale ToCs must be turned into scaled physics-based ToCs that are representing real data based on physics knowledge.

Method: The design team should collect real data of the identified design parameters from the individual solutions in the design-set, as well as from the simulations and testing that have been carried out.

Activity 3.2: Identify the feasible area and/or an optimal point in the physics-based ToCs associated with the specific design parameter

Objective: This activity identifies the area of design solutions that are meeting customer requirements and decision criteria, or are close to being an optimal design.

Method: The design team should analyse the effects of changing design parameters on the performance of the product. As a result of understanding the product's physics, designers can identify the optimal point in the physics-based ToCs associated with the specific design parameter, and/or the feasible area on each ToC.

5.4.4 Step 4: Compare the solutions of the design-set

Activity 4.1: Represent the data of the selected design-set on the generated physics-based ToCs

Objective: This activity prepares the physics-based ToCs for the design team to start evaluating and comparing the design-set.

Method: The values of the design parameters of each solution in the selected design-set are plotted against the generated physics-based ToCs. Thus, the design team identifies the differences between the physical features of the developed design solutions and the identified feasible solutions.

Activity 4.2: Communicate and compare the design solutions

Objective: A comparison is required to distinguish the high-quality designs from the low-quality solutions, in order to achieve/obtain a robust optimal solution.

Method: The projection of the design parameter values of every solution in the physics-based ToCs will provide visualisation of each solution. This helps to compare each solution with the identified customer requirements and decision criteria. The design team can then make a decision and narrow down solutions. Moreover, the design team will understand the differences and similarities between generated design solutions by using the physics-based ToCs generated in "Step 3: Test and Analyse".

Activity 4.3: Expand the feasible area if possible

Objective: This activity is to increase the possibility of achieving the optimal design and thereby to improve the design performance and innovation level of the product.

Method: In order to explore all possible design solutions as an alternative to the optimal design, the feasible area could be expanded. At this stage, the thorough understanding of the physical and product constraints will help to expand the feasible area that was defined in activity 3.2. However, the feasible area expansion is not a parametric extension, which would mean an equal expansion of all directions of the feasible area. Instead, expansions are undertaken on a case by case basis, according to the project under consideration.

5.4.5 Step 5: Select and narrow down designs

Activity 5.1: Select the design solutions in the feasible area or close to the identified optimal point

Objective: The intention of this activity is to select quality designs for further narrowing down, since the design team intends to trade-off and narrow down the set of design solutions through the SBCE process. ToCs provide an objective tool to accomplish this task.

Method: Those design solutions that fall in the feasible area should be selected. In addition, those designs that do not fall in the feasible area but meet the requirements partly and show relatively satisfying performance should also be selected to understand whether it is possible to improve these designs.

Activity 5.2: Second stage of narrowing down

Objective: This activity helps to further narrow down the selected design solutions resulting from activity 5.1.

Method: Design solutions are evaluated and compared to each other in order to obtain more optimised values of the design parameters that were identified in activity 2.2. From the selected design solutions, design(s) performing below the desired optimal point should be discarded. Discarded solutions are not compatible with the company benefits or have constraints at any stage of the product lifecycle. Designs should be selected for further development through the SBCE process if they perform at or above the customer requirements and meet the decision criteria. Thereby, the design team will be able to further narrow down the design solutions.

5.4.6 Step 6: Enhance design

Activity 6.1: Explore the opportunities for creating a new, improved design based on combining and/or modifying solutions from the selected designs

Objective: This activity explores the generation of a new, enhanced design.

Method: The design team should explore the opportunities for enhancing the design solution by combining the best performances of different design solutions that are included within the narrowed down design-set. This enables the selection of complimentary features of the selected design solutions, and to generate a new design that takes advantage of each solution's strengths.

Activity 6.2: Capture and store the obtained knowledge

Objective: The knowledge obtained throughout this process should be captured and stored for future reuse. In order to complete this activity, a software is required for organising and storing the knowledge in a systematic manner. Developing this software is out of the scope of this PhD research, however, it is being developed under the name of "knowledge-shelf" concept by a member of the LeanPPD research team at Cranfield University (Suwanda, no date).

Figure 5-7 illustrates an overview of the process for generating physics-based ToCs.

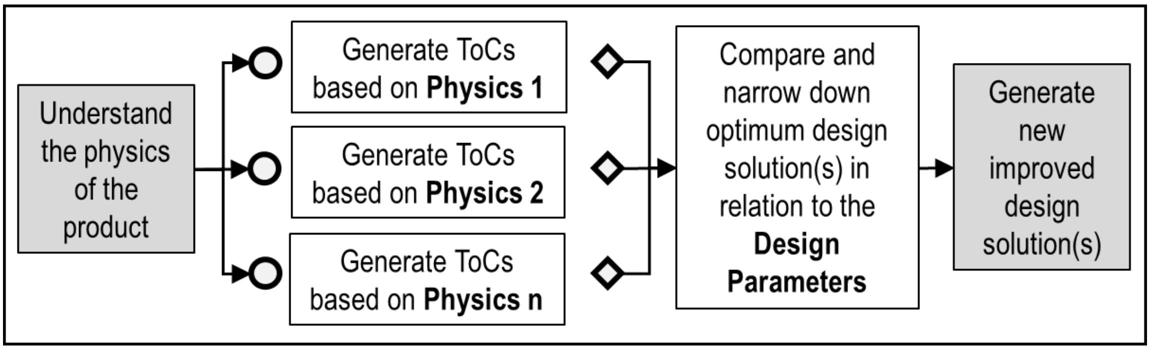


Figure 5-7: Overall view of the process for generating physics-based ToCs

As shown in Figure 5-7, the physical characteristics of the product are explored and understood to generate ToCs representing each physical characteristic. The design team then evaluates and compares the possible design solutions in order to narrow down the design-set considering the related design parameters. Then, optimal design solution(s) from each ToC are selected for further use within the SBCE process. Selected design solutions are improved and enhanced in order to achieve a final optimal design.

5.5 The Process for Using ToCs in the SBCE Process Model

The two processes presented in sections 5.3 and 5.4 focus on generating trade-off curves by using different sources of data. Implementing these two processes in industrial case studies raised the following questions by the industrial collaborators, practitioners and academics:

1. How to use knowledge-based ToCs within the SBCE process model,
2. How to use physics-based ToCs within the SBCE process model,
3. Is it possible to combine knowledge-based and physics-based ToCs within one trade-off curve?

In order to address these questions, this section presents a process for the use of ToCs that enable the key SBCE activities, as shown in Figure 5-8. Review of the related literature (Chapter 3), industrial field study results (Chapter 4) and experience gained from the applications in industrial case studies (Chapter 6) showed that the following key activities of the SBCE process model are enabled by using ToCs.

1. Identify feasible design area,
2. Generate a set of design solutions,
3. Compare possible design solutions,
4. Narrow down the design-set,
5. Achieve the optimal design solution.

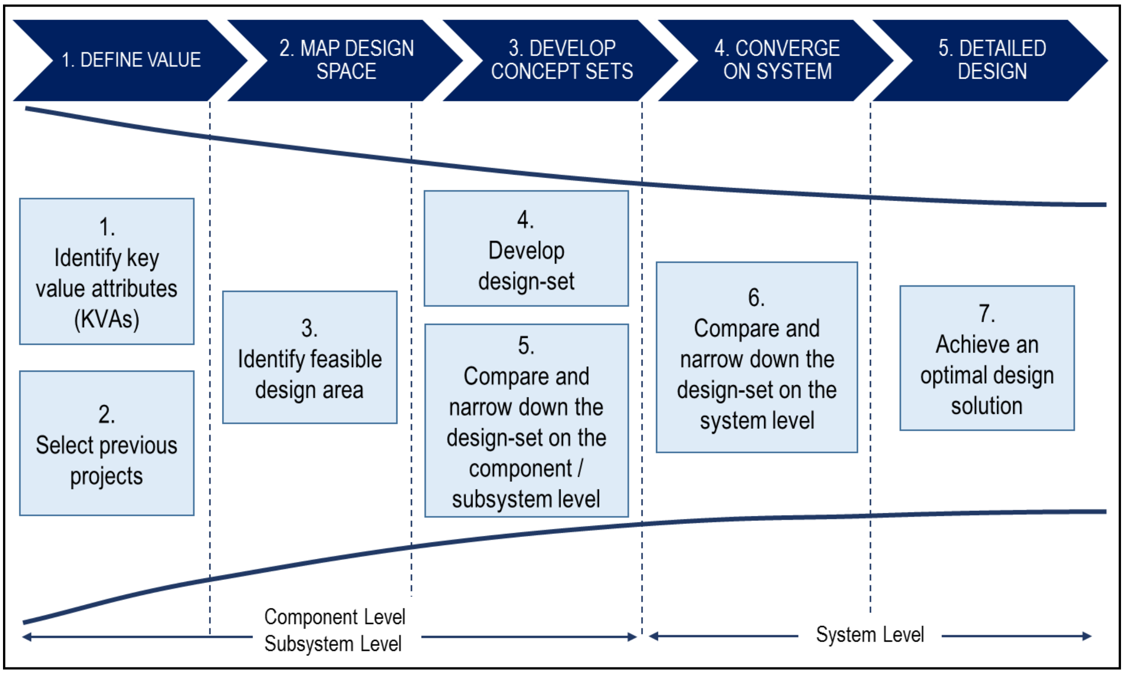


Figure 5-8: The process for using ToCs in the SBCE process model

Table 5-1 shows interactions and relations between the two processes. It describes how to use ToCs, and which type of ToCs should be applied in which activities of the SBCE process. The first column presents the sequential steps of the process for the use of ToCs, which is shown in Figure 5-8. The second column presents the associated activities of the SBCE process model as shown in Figure 3-7, which can be effectively supported by using ToCs. The third column presents the types of trade-off curves to be used in order to enable the SBCE activities.

Each step of Figure 5-8 is explained in detail in the following subsections. The sequence of the process may change depending on the complexity of the product, detail, level of innovation, and requirements of the designers during the product development process.

Table 5-1: Interactions and relations between activities of ToCs and the SBCE process

Steps of the process for using ToCs in SBCE (Figure 5-8)	SBCE activities to be supported by ToCs (Figure 3-7)	Type(s) of ToCs to be used
1. Identify key value attributes	1.2. Explore customer value 1.4. Translate value to designers	
2. Select previous projects		
3. Identify the feasible design area	2.3. Define feasible regions of design space	Knowledge-based ToCs
4. Develop the design-set	3.1. Pull design concepts 3.2. Create sets for each subsystem	Knowledge-based ToCs
5. Compare and narrow down the design-set on the component/ subsystem level	3.4. Capture knowledge and evaluate 3.5. Communicate set to others	Physics-based ToCs
6. Compare and narrow down design-set on the system level	4.2. Explore system sets 4.6. Converge on final set of sub-system concepts	Knowledge-based and physics-based ToCs
7. Achieve the optimal design solution		Combined knowledge-based and physics-based ToCs

5.5.1 Step 1: Identify key value attributes

Objective: Customer value should be defined so that the final optimal design solution can represent the required performance and meet the customer needs. The term “key value attributes (KVAs)” is a representation of customer requirements and decision criteria, both of which are important to generate trade-off curves as explained in subsections 5.3.1 and 5.4.1. This activity uses the terminology of KVAs in the ToC context in order to relate to the SBCE process model.

Method: The design team explores, understands and identifies the key value attributes of the product. These KVAs are used to generate knowledge-based and physics-based ToCs, which in turn identify the feasible design area that is described in subsection 3.2.1.

5.5.2 Step 2: Select previous projects

Objective: The aim of this activity is to provide the design team with the existing designs from previous projects, which may have been successful, failed, complete or incomplete. Thus, the design team can generate knowledge-based ToCs, which represent the historical data of previous projects, in a more resource-efficient manner.

Method: Considering the KVAs of the current project, the design team identifies the similar previous projects that are stored in the company's database. The similarity could be related to the duration, cost or size of the project. A member of the team should be dedicated to retrieving data from the company's database. Previous projects identified during this activity can be reused for the current project.

5.5.3 Step 3: Identify feasible design area

Objective: The aim of this activity is to identify the feasible design area and to develop a design-set by using the data of previous projects. As explained in subsection 3.2.1, the identification of feasible design area is the first step in generating the design-set. This activity explores the alternative design solutions on the component or subsystem level of the product.

Method: The design team generates knowledge-based ToCs considering the KVAs identified in step 1. They then use these generated knowledge-based ToCs to define feasible regions of the design space, as described in subsection 5.3.4, and to create design-sets for each subsystem.

5.5.4 Step 4: Develop design-set:

Objective: The aim of this activity is to develop a set of design solutions to be used in the early stages of the SBCE process model.

Method: The design team uses the generated knowledge-based ToCs to create design-sets for each component/subsystem. In order to complete this step, subsection 5.3.5 can be referred to. If lacking knowledge from previous projects, the design team can refer to the process for generating physics-based ToCs.

5.5.5 Step 5: Compare and narrow down the design-set on the component/subsystem level

Objective: The aim of this activity is to compare possible design solutions and to narrow down the design-set by using the knowledge of the physical characteristics of the product. This activity evaluates and compares alternative design solutions on the component or subsystem level.

Method: The design team generates physics-based ToCs considering the KVAs identified in step 1. They then proceed to use these generated physics-based ToCs in order to capture knowledge and evaluate the design-set, as well as to communicate the set to stakeholders of the current project.

5.5.6 Step 6: Compare and narrow down the design-set on the system level

Objective: The aim of this activity is to evaluate and compare alternative design solutions on the system level. The system is developed as a result of using the SBCE process model.

Method: Initially, the design team is required to apply the SBCE process model in an effort to converge on a system that combines the components/sub-systems of the product. After developing the design-set on the system level, the design team generates knowledge-based and physics-based ToCs – or reuses the generated ToCs – in order to evaluate, compare and narrow down the converged design-sets. In this step, the design team can refer to the processes for generating knowledge-based and physics-based ToCs as described in sections 5.3 and 5.4, respectively.

5.5.7 Step 7: Achieve an optimal design solution

Objective: The aim of this activity is to achieve an optimal design solution that meets all KVAs.

Method: By employing the SBCE process model, the design team reuses the generated ToCs and continues comparing and narrowing down the design-sets until achieving the best design solution. If required, new ToCs may also be generated as a combination of historical data and physics data. In this step, ToCs can be generated by using the data from both existing knowledge and understanding the physics of the product. Thus, a combined trade-off curve can represent the historical data and the physical functionality of the product in the same graph.

5.6 Summary of Chapter 5

This chapter described how to create and visualise a knowledge-environment systematically by using trade-off curves. Knowledge-environments are key enablers of the SBCE process model. Three processes were developed and described in detail, in order to create the knowledge-environment. It was explained how to collect historical data and physics data that is then represented on ToCs. Finally, the utilisation of ToCs in enabling key activities of the SBCE process model was presented.

6 INDUSTRIAL CASE STUDIES AND EXPERT JUDGEMENTS FOR VALIDATION

6.1 Introduction

This chapter presents the application and the validation of the processes developed and presented in chapter 5. Figure 6-1 illustrates the structure of this chapter.

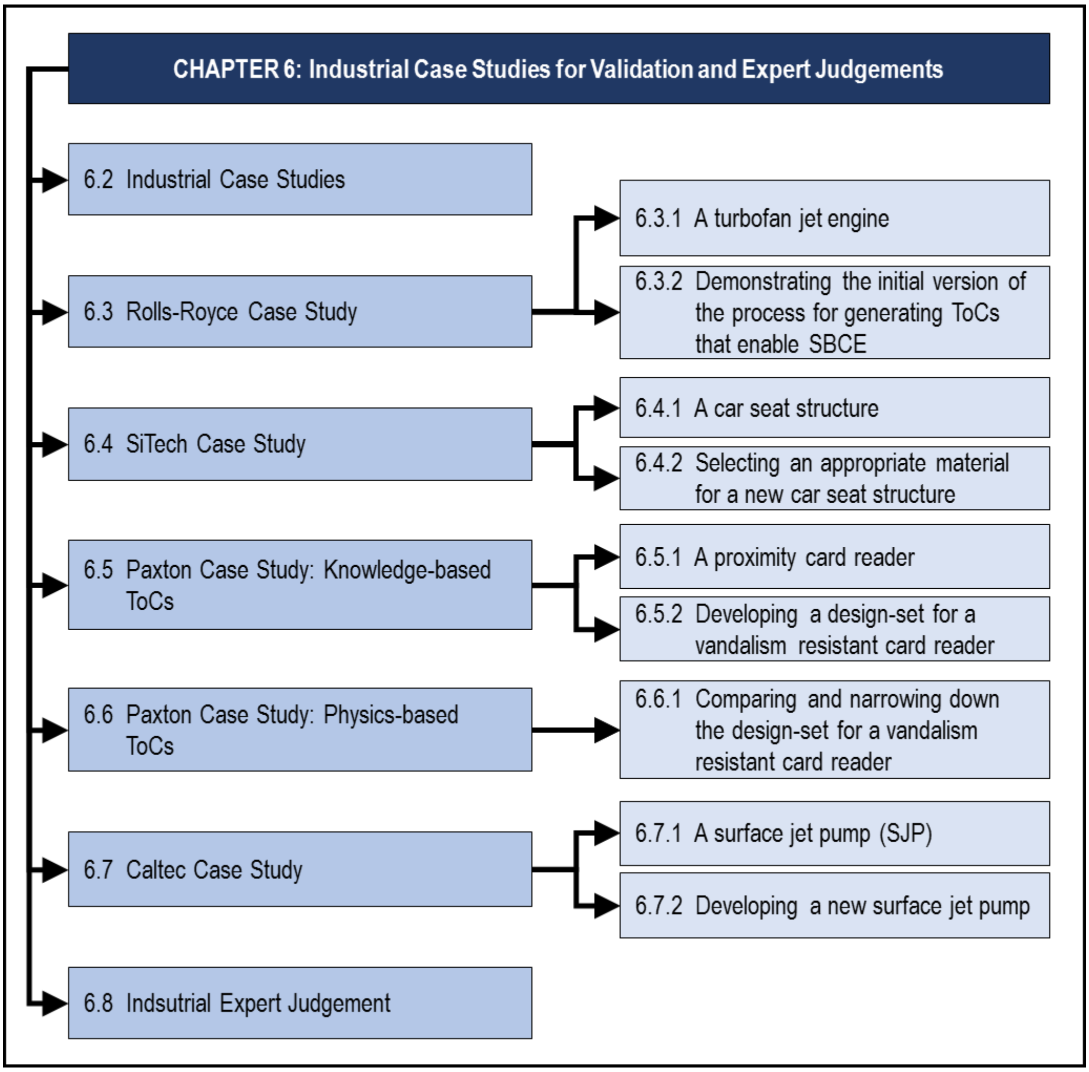


Figure 6-1: Structure of chapter 6

Section 6.2 provides an outline for each of the case studies that were used to develop and validate the processes. Section 6.3 presents the application of the initial version of the process for generating ToCs, which is shown in Figure 5-2, with an aerospace case study. Section 6.4 explains an application of the improved version of the process for generating knowledge-based ToCs, as shown in Figure 5-3, through an automotive case study. Section 6.5 describes the validation of the finalised version of the process for generating knowledge-based ToCs, as shown in Figure 5-4. The process for generating physics-based ToCs is validated by an electronics case study in section 6.6. Section 6.7 shows how to use generated knowledge-based and physics-based ToCs in an SBCE application in oil and gas industry. Finally, experts' judgements are presented in section 6.8.

6.2 Industrial case studies

This section presents a brief outline of each case study, as they are shown in Table 6-1. There are five case studies in total. The first two industrial case studies, with Rolls-Royce and SiTech, helped the author to improve the proposed process in the early stages of this PhD research. In addition, three industrial case studies have then been conducted in order to validate the proposed processes for knowledge creation and visualisation that enable SBCE activities, which were presented in chapter 5.

1. <u>Rolls-Royce Case Study:</u>

   This hypothetical case study was completed in order to observe the potential benefits of generating and using knowledge-based trade-off curve practices in an industrial environment, as well as to identify the gaps within the process for further improvement. Rolls-Royce was the collaborating company, and the case study was part of the CONGA project (refer section 1.4). As mentioned in section 1.4, the aim of CONGA was to develop set based design and collaborative tools and methods, with example data to show how a noise requirement could be met. Although CONGA was not a project "to reduce the noise level of the engine", this case study considered a turbofan engine in order to demonstrate the initial version of the proposed process for generating knowledge-based ToCs, as shown in Figure 5-2. Observations and obtained knowledge helped the author to improve the process. Detailed explanations on this case study are provided in section 6.3.

No.	Case Study	Complexity	Design level	ToC Types	Process used	Aim of the Case Study
1	**Rolls-Royce** Turbofan jet engine	High	System	Knowledge-based ToCs	Initial process for generating ToCs	• To demonstrate and to improve the proposed initial process for generating ToCs
2	**SiTech** Car seat structure	Medium	Subsystem	Knowledge-based ToCs	Improved version of the process for generating ToCs	• To visualise a knowledge-environment using ToCs • To support decision-making through the SBCE process
3	**Paxton** Proximity Card Reader	Simple	Component	Knowledge-based ToCs	The process for generating knowledge-based ToCs that enable SBCE	• To identify the feasible design area • To generate a design-set
4	**Paxton** Proximity Card Reader	Simple	Component	Physics-based ToCs	The process for generating physics-based ToCs that enable SBCE	• To compare the possible design solutions of the design-set • To narrow down the design-set
5	**Caltec** Surface Jet Pump	Medium	System	Knowledge-based ToCs Physics-based ToCs Combined knowledge-based and physics-based ToCs	The process for using generated ToCs within the SBCE process model	• To achieve an optimal design using knowledge-based and physics-based ToCs within the SBCE process model

Table 6-1: Outline of the content of case studies

2. SiTech Case Study:

This case study aimed to demonstrate an application of knowledge-based ToCs that enable SBCE activities in a research environment, by using real data. The requirement in this case study was to select an appropriate material for a new car seat structure as well as to achieve a hypothetical optimal design. Following this case study, it was understood that knowledge-based ToCs support the design decision-making, although the process as it is shown in Figure 5-3 needed further improvement. Detailed explanations on this case study are provided in section 6.4.

3. Paxton Case Study: Knowledge-based ToCs:

This case study demonstrated the generation and the use of knowledge-based ToCs that enable the below key activities of SBCE:

- Identifying the feasible design area,
- Developing a design-set from previous projects.

The product under development was a proximity card reader, which is considered to be a simple product. This case study was focused on only one component of this product, the front cover. It demonstrates the application and the validation of the proposed process for generating knowledge-based ToCs, as it is shown in Figure 5-4. Detailed explanations on this case study are provided in section 6.5.

4. Paxton Case Study: Physics-based ToCs:

This case study demonstrated the generation and the use of physics-based ToCs, as it is shown in Figure 5-6, that enable further key activities of SBCE:

- Comparing possible design solutions,
- Narrowing down the design-set.

This case study was conducted as a continuation of the Paxton case study: Knowledge-based ToCs. The product, as well as the requirements for the product, remained the same. Detailed explanations on this case study are provided in section 6.6.

5. Caltec Case Study:

This case study demonstrated the validation of the process for using ToCs in the SBCE process model, as it is shown in Figure 5-8. The main objective of this case study was to achieve the optimal design solution by using both knowledge-based and physics-based ToCs throughout the SBCE application. The product under development was a surface jet pump used in the oil and gas industry. As the functional principles of a surface jet pump are highly complex, but the device itself has only few components, it was classified as a product of medium complexity. This case study is unique in that it shows the application of knowledge-based and physics-based ToCs on both the component and the system level. Detailed explanations on this case study are provided in section 6.7.

The following sections describe and explain these industrial case studies in more detail. Confidential data and information have been removed or modified.

6.3 Rolls-Royce Case Study

This is a research-based case study carried out in order to understand the initial process, which is presented in Figure 5-2, to generate useful ToCs to support SBCE. This hypothetical case study demonstrates example data to show how to generate trade-off curves based on the knowledge obtained from historical data.

Rolls-Royce Plc. is a British company headquartered in London. The company provides power systems and services for aviation and other industries. The Bristol branch builds on the history of the aircraft industry in Bristol. Rolls-Royce Bristol was engaged with during the initial stages of the research. Feedback and comments from the senior managers in the company helped the researcher with developing the process for generating knowledge-based trade-off curves. However, although Rolls-Royce provided support in developing a process, this case study is research-based and does not necessarily reflect Rolls-Royce's view on the choice of parameters being compared, or on the conclusions being drawn from the generated ToCs. The developed process was implemented in a hypothetical case study of a turbofan jet engine. Members of the research team who contributed to and were involved in conducting this case study are presented in Appendix B. An overview and the characteristics of a turbofan jet engine, which is the product under consideration in this case study, is presented in the following subsection.

6.3.1 Overview and characteristics of a turbofan jet engine

A jet engine is an integral part of an aircraft, as it generates thrust by jet propulsion. The jet engine's most common form, in commercial aircraft, is the turbofan engine. Figure 6-2 illustrates an example of a turbofan jet engine and its components. In a turbofan engine, the forward force is generated by accelerating the entering gas (air) between the entrance and the exit of the engine, thereby creating a forward force.

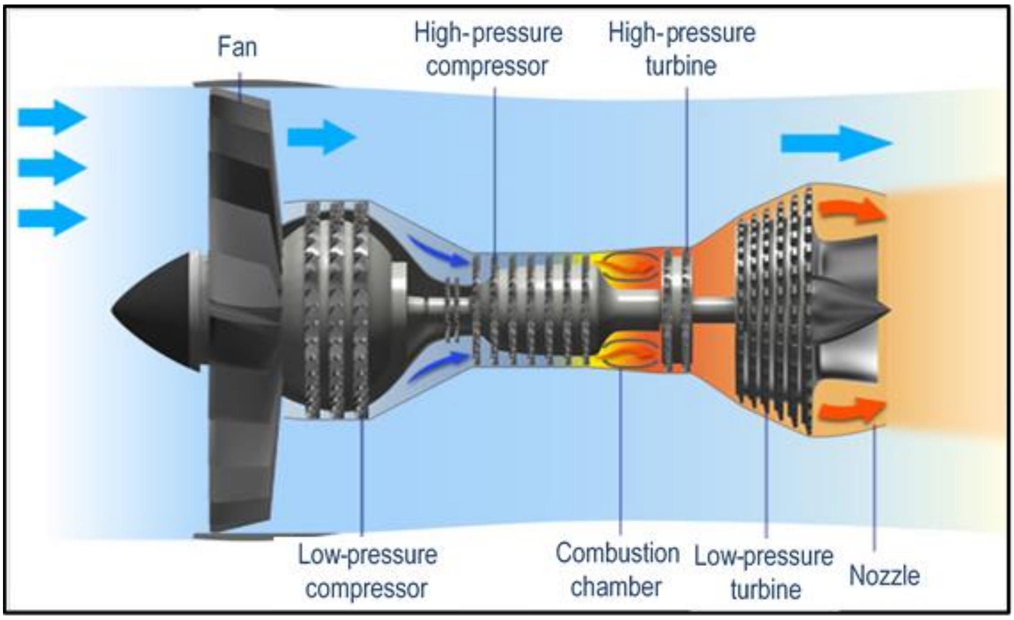


Figure 6-2: An illustration of a turbofan jet engine and its key components (Olympus, no date)

The acceleration of the gas within the engine requires combustion, and therefore fuel. In order to reduce fuel burn but maintain thrust, designers have devised engines in which only a small amount of gas passes through the engine core and is accelerated. A much larger amount of gas bypasses the engine core and is combined with the exhaust gas behind the engine. The bypass ratio is defined as the ratio between the air passing outside and the air passing through the engine core. Behind the engine, a small amount of high-velocity gas (from the engine core) combines with a large amount of low-velocity gas (from the bypass).

The combination of the gases results in a velocity transfer from the high-velocity gas to the low-velocity gas. The combined velocity, however, is larger than the common velocity at the entrance of the engine.

Thus, turbofan engines use a small amount of fuel to affect a moderate velocity change of a large amount of gas, thereby creating thrust reasonably efficiently.

6.3.2 Demonstrating the initial version of the process for generating ToCs that enable SBCE

The main objective of this hypothetical research-based case study was to reduce the engine noise level, in order to meet the night operations regulations of London Heathrow Airport. In this research-based exercise, the initial version of the process for generating ToCs, as shown in Figure 5-2, was followed step-by-step and is presented below. This case study was established based on the author's observations, understanding and judgement according to the knowledge obtained from several CONGA project meetings.

6.3.2.1 Step 1: Define decision criteria for a low noise jet engine

The author hypothetically identified the following decision criteria, in order to demonstrate the process for generating ToCs:

1. **Low noise:**

   The take-off noise level of the new product should be lower than the noise levels of existing products.

2. **Reliability:**

   The new product should operate 24/7 without significant downtime.

3. **Durability:**

   The new product should be durable enough to be able to operate on an aircraft capable of carrying 150 passengers. As all aircraft must be able to fly with only half their engines operating, each engine on a twin-engine aircraft must be capable of carrying all passengers.

4. **Cost:**

   Fuel consumption should not be higher than the consumption of existing turbofan jet engine solutions.

It became apparent during the case study that only identifying the decision criteria was not sufficient in order to start generating trade-off curves. The need for the representation of each decision criteria also emerged. That was a contribution of this case study to improving the initial process. In this research-based case study, the analysis of decision criteria helped the author to identify design parameters and possible conflicting relations between these design parameters as shown in Table 6-2. Knowledge-based ToCs were generated in order to visualise these conflicts and identify the best balance compromise between the design parameters.

No.	Relationships	Conflicts between the design parameters
1	Thrust vs. Take-off Noise Level	Engine noise was defined as 100% of the aircraft take-off noise. As aircraft take off with full power, thrust and fuel consumption are at a maximum. It was surmised that the noise level is related to the amount of thrust generated.
2	Bypass Ratio vs. Take-off Noise Level	In order to achieve high thrust but low noise, the bypass ratio of the engine can be increased. A higher bypass ratio produces higher thrust at lower noise levels.
3	Fan Diameter vs. Take-off Noise Level	In order to increase the bypass ratio, the fan diameter can be increased. This increases air intake. However, a larger fan results in the engine being heavier.
4	Engine Weight vs. Take-off Noise Level	In general, larger and heavier aircraft engines produce more noise than lighter engines. Through increasing the bypass ratio by increasing the fan diameter, the engine weight will also increase.
5	Engine Weight vs. Fuel consumption	A bigger fan means a heavier engine, and a heavier engine results in more fuel consumption. This increases operating cost.

Table 6-2: Conflicting relationships between the design parameters of a low noise jet engine

6.3.2.2 Step 2: Get the data related to each of the decision criteria of the low noise engine

Data was collected from publicly available data sources. Due to confidentiality issues, the collaborating company was not in a position to provide data from their previous projects. Table 6-3 shows the data collected from previous projects, which were released to market as successful commercial products and for which data is available for public use.

Engine	Take-off noise [EPNdB]	Thrust [kN]	Bypass Ratio	Engine Weight [lb]	Fan diameter [in]	Fuel consumption [lb/lbf thrust/hr]
Trent 1000-G	90.6	297.8	10.5	11,924	112	Not publicly available
Trent 553-61	95.4	235.8	7.6	10,400	97.4	
Trent 556-61	95.8	249.1	7.6	10,400	97.4	
Trent 560-61	96.8	266.9	7.6	10,400	97.4	
Trent 768-60	96.9	300.3	5.2	10550	97.4	
Trent 772-60	97.4	316.3	5.1	10550	97.4	
Trent 875	95.8	333.6	6.3	13,100	110	
Trent 877	96.1	342.5	6.2	13,100	110	
Trent 884	95.9	373.6	6	13,100	110	
Trent 890	91.5	400.33	6.4	13,100	110	
Trent 892	98.1	400.3	6.4	13,100	110	
Trent 895	98.4	415.4	5.8	13,100	110	
Trent 970	94.2	311.4	8.8	13,842	116	
Trent 972	94.5	320.3	8.8	13,842	116	
Trent XWB-84	91.5	374.5	9.1	16,043	118	

Table 6-3: Data collected from successful previous projects (ICAO, 2016)

6.3.2.3 Step 3: Generate different trade-off curves for the low noise turbofan jet engine

The author plotted the data against ToCs, as illustrated in Figure 6-3. Only four trade-off curves were generated, instead of the five defined in the previous step in Table 6-2, as data for the fuel consumption was not publicly available in the required detail. In Table 6-2, relationship 5 features fuel consumption as a design parameter, and was thus not generated in a ToC. Figure 6-3 illustrates the available four trade-off curves, which were generated based on the available data:

1. **ToC 1** – Thrust vs. Take-off Noise Level
2. **ToC 2** – Bypass Ratio vs. Take-off Noise Level
3. **ToC 3** – Fan Diameter vs. Take-off Noise Level
4. **ToC 4** – Engine Weight vs. Take-off Noise Level

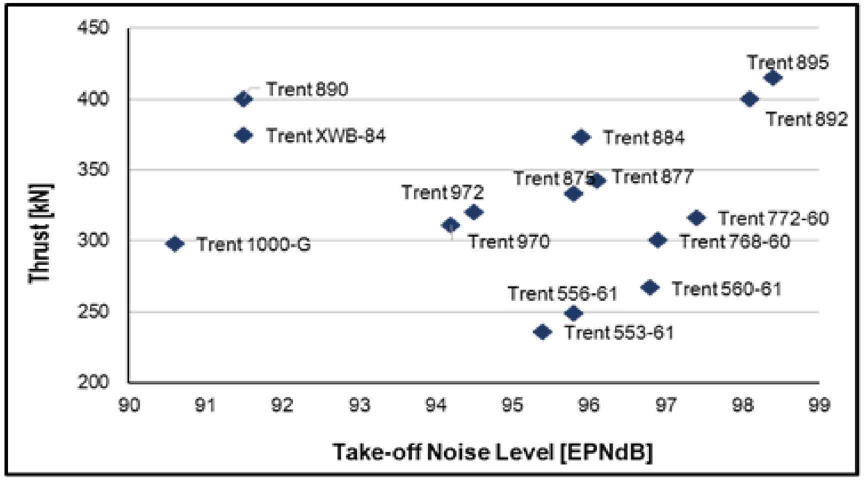
After generating ToCs, a trendline was added to each ToC except for ToC 1 in Figure 6-3(a), as it did not show a plausible trend between the design parameters of thrust and take-off noise level. ToC 1 should be analysed among different departments in order to identify the reason for such a scattered relation. Due to resource constraints, this task could not be completed in this case study.

6.3.2.4 Step 4: Get the requirements (customer) and plot these against the ToCs

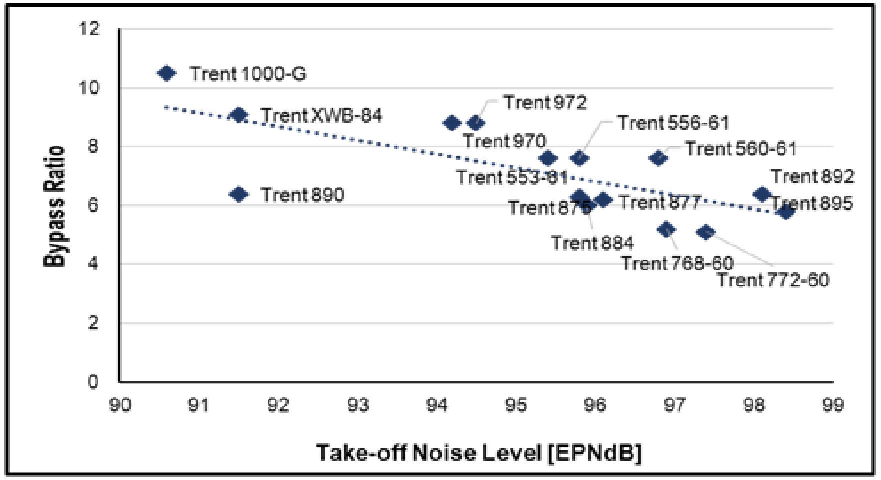
The requirement for a low noise turbofan jet engine was identified as it having to be lower than 84 EPNdB. The author noticed that the customer requirements were obtained very late throughout the case study when the initial version of the process was followed. Consequently, the author modified the process for ToC generation to ensure that customer requirements are identified as the first step of the process, before identifying the decision criteria. As shown in Figure 6-3, all turbofan engines considered in this case study have take-off noise levels above the customer requirement of 84 EPNdB.

6.3.2.5 Step 5: Define feasible/infeasible design area

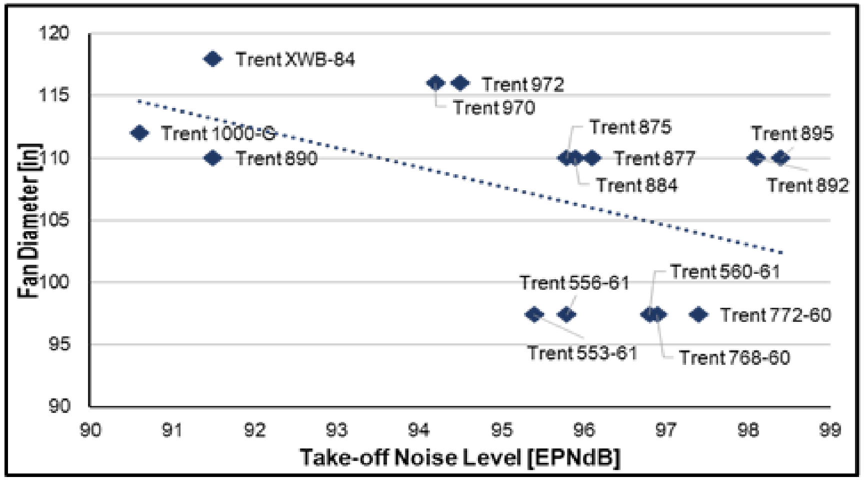
In order to define the feasible and infeasible design areas, the value of the customer requirement of 84 EPNdB was plotted against the generated knowledge-based ToCs. In Figure 6-4, straight lines at the value of 84 EPNdB on the X axis of each trade-off curve represent the customer requirement. The area to the left of the line represents the feasible area, since the take-off noise level is required to be below 84 EPNdB. The area to the right of the line shows the infeasible area, which means that the designs with their data in this area do not meet the current customer requirement.



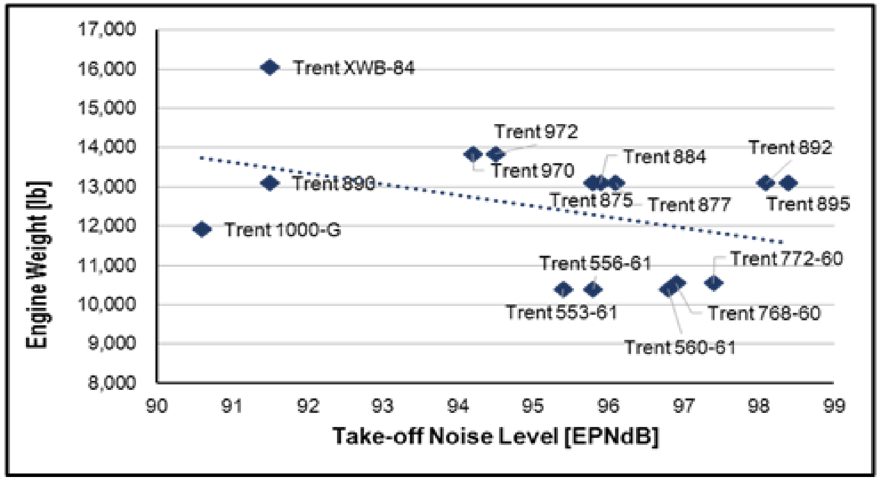
(a) *ToC 1 – Thrust vs. Take-off Noise Level*



(b) *ToC 2 – Bypass Ratio vs. Take-off Noise Level*

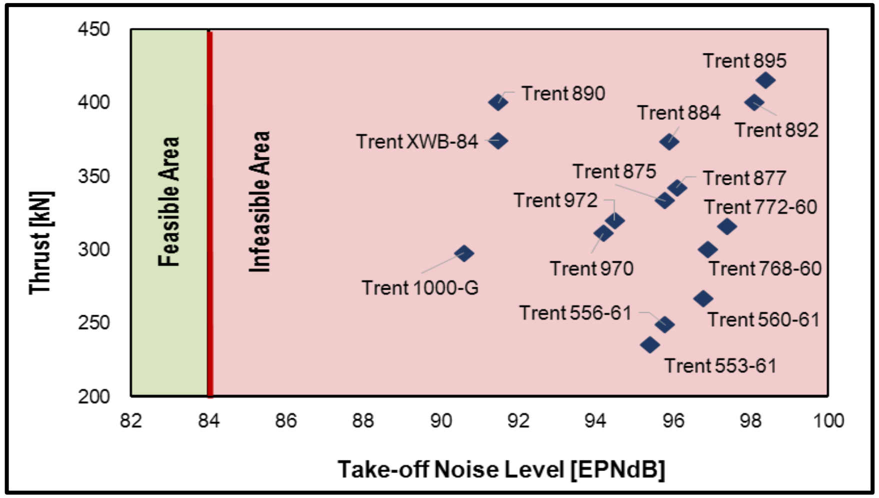


(c) *ToC 3 – Fan Diameter vs. Take-off Noise Level*

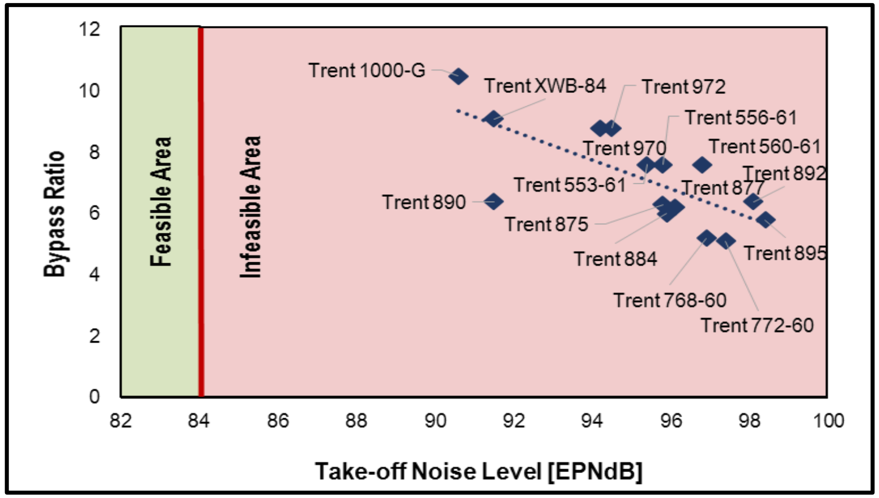


(d) *ToC 4 – Engine Weight vs. Take-off Noise Level*

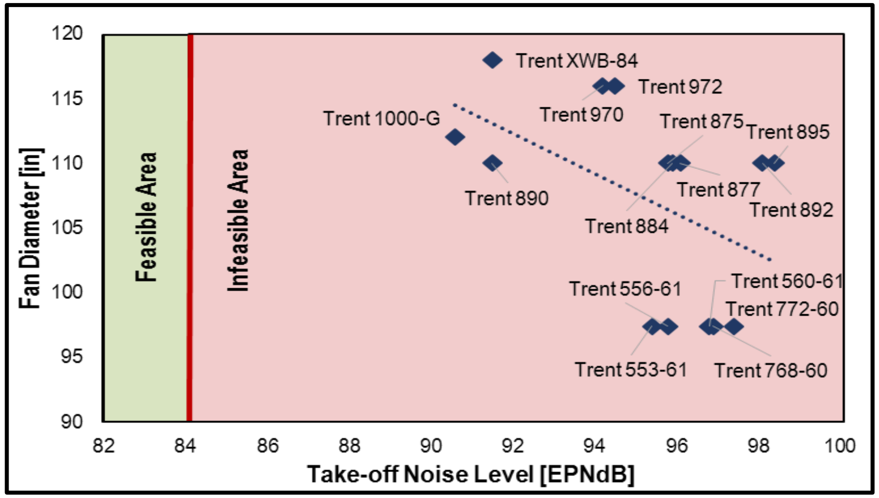
Figure 6-3: Knowledge-based ToCs generated for the low noise turbofan jet engine



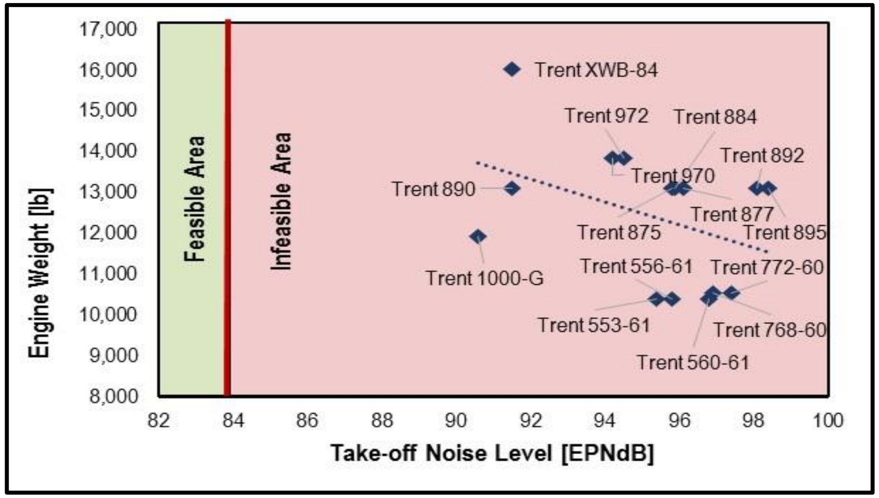
(a) Feasible/Infeasible areas for Thrust vs. Take-off Noise Level



(b) Feasible/Infeasible areas for Bypass Ratio vs. Take-off Noise



(c) Feasible/Infeasible areas for Fan Diameter vs. Take-off Noise



(d) Feasible/Infeasible areas for Engine Weight vs. Take-off Noise

Figure 6-4: Feasible and infeasible areas of knowledge-based ToCs for the low noise turbofan jet engine

6.3.2.6 Step 6: Extract/locate the design solution

After plotting the customer requirements against the generated trade-off curves, it was seen that there was no design solution within the feasible area. However, the author suggests that design solutions out of the feasible design area might be helpful for developing a new design, if the reasons are explored and understood by the designers and engineers. The author made her own justification and presented her own conclusions in order to demonstrate how ToCs can be analysed, and how the comparison can be executed by using ToCs.

Obtaining publicly available information helped the author to select following designs from each ToC in Figure 6-4:

1. Trent 1000-G from all trade-off curves in Figure 6-4, since it has the lowest noise level and highest bypass ratio when compared to other designs.
2. Trent 553-61 from the ToC in Figure 6-4(d), since it is the lightest engine when compared to other designs. However, it has the lowest thrust, which should be taken into account regarding the durability and reliability decision criteria.

6.3.2.7 Step 7: Develop a set of potential solutions that might be helpful for the product under consideration

Selected design solutions were investigated, and the data of these designs was analysed by using the ToCs in Figure 6-4. It was determined that some designs might be used to create new, potentially feasible designs by combining a number of characteristics from several existing designs. In order to be a potentially feasible solution, existing designs might need to undergo one of the following (see 5.3.4):

1. Minor modifications
2. Major modifications
3. Complete re-design

This analysis was performed for the selected designs in step 6 above, and the results are presented below:

a) Take-off Noise Level:

The author focused on the data that shows the lowest take-off noise level, which is 90.6 EPNdB for the design Trent 1000-G. Then, the author understood the key features and characteristics of the Trent 1000-G design, related to noise. Characteristic features of the Trent 1000 series are:

- Ultra-efficient, swept fan blades enable a quieter operation and optimal engine core protection.
- A Trent 1000 powered Boeing 787 at full take off power is 3 dB quieter than the previous generation engine.

While it was understood from the ToCs that the Trent 1000-G cannot be used as a whole system concept, the Trent 1000 fan design might be an inspiring idea for a new design.

b) Engine Weight:

The author focused on the data that shows the lightest engine in Figure 6-4(d). This design solution is the Trent 553-61, with an engine weight of 10,400 lbs. A characteristic feature of the Trent 500 series is:

- Lightweight, hollow titanium wide chord fan for low noise and high efficiency.

If the same material as used in the Trent 553-61 can also be used in a new design, this might decrease the engine weight of the new product design. In fact, Trent 500 series engines power the Airbus A340 aircraft. This aircraft is configured with four engines. It is apparent that four engines will be noisier than two engines. In addition, the total weight of an aircraft with four engines would be higher than an aircraft with two engines. Heavier aircraft also emit more noise. Therefore, the design of the Trent 553-61 could be reused if the fan diameter is increased (which reduces engine noise), and the number of engines is reduced from four to two. Furthermore, the passenger capacity of the Trent 553-61 is more than 300 passengers, which is more than the customer requirement for passenger capacity in this study (150 passengers). Hence, it can be investigated if noise decreases when the design of Trent 553-61 engines is simulated for 150 passenger capacity.

This step proves that knowledge-based ToCs provide an environment to create knowledge by using the data and features of existing products.

6.3.2.8 Step 8: Convert these potential solutions to a viable solution

Two design solutions, Trent 1000-G and Trent 553-61, can be considered as the basis of future designs. As explained above, a combination of their characteristics may lead to the emergence of a viable solution that meets the customer requirements. Converting these designs to a useful solution requires the use of the SBCE process model. Due to resource limits and data availability restrictions, this step was not applied in this case study.

6.3.3 Debriefing of the Rolls-Royce case study

The existing design solutions Trent 1000-G and Trent 553-61 can be considered hypothetically to be reused, after modifications, in order to develop a design-set for the SBCE application of a low noise turbofan jet engine. Feedback received from the industrial collaborators helped the author to identify the gaps in the initial process for generating ToCs, and to improve this process. The next section applies the revised process in an industrial case study of a car seat structure.

6.4 SiTech Case Study

This section demonstrates the application of the improved version of the process for generating knowledge-based ToCs, as presented in Figure 5-3. This case study aims to visualise a knowledge-environment using ToCs, and to support decision-making through the SBCE process. An overview and characteristics of the car seat structure is presented in the following subsection. The term for “design or design solution” refers to a hypothetical design which does not have all technical details, but the design data to be used in order to develop a new design.

SiTech Sp. z o.o., the collaborating company, is a car seat manufacturer with production plants in Poland, Germany and China. The company is a supplier of Volkswagen AG. The researcher was able to reuse collected real data in order to validate the proposed process for generating knowledge-based trade-off curves that enable key activities of SBCE. Members of the research team who contributed to and were involved in conducting this case study are presented in Appendix B.

6.4.1 Overview and characteristics of a car seat structure

Recently, the automotive industry has focused on manufacturing more fuel efficient and lightweight cars due to the carbon emission reduction regulations. Several components are impacting the vehicle weight, one of which is the seat structure. The seat structure is the ‘*skeleton*’ of the seat system, which is assembled to later fit into the body of the car. Figure 6-5 illustrates an example for a car seat structure. Regarding the contribution to weight, the material type is the most essential part of the seat structure. Using a lightweight material can reduce the weight, however, durability constraints might apply. On the other hand, using a material that is both lightweight and strong might increase the material and manufacturing costs. In order to find a balance between these conflicting issues, ToCs are used in this case study for selecting an appropriate material.

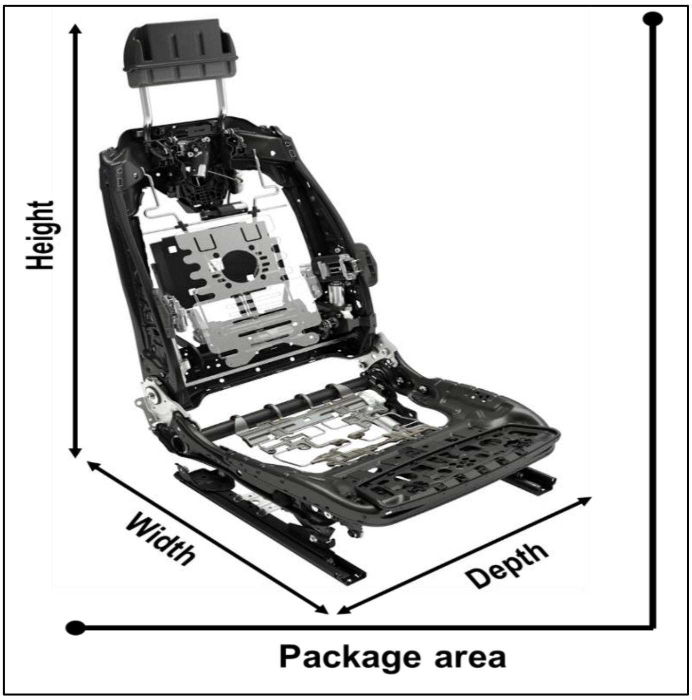


Figure 6-5: An example of a car seat structure

6.4.2 Selecting an appropriate material for a new car seat structure

The main objective of this case study was to develop a new design solution for a passenger car seat that is both strong and light weight. The process implemented in this case study was the improved version of the process for generating ToCs that enable SBCE applications, as it is shown in Figure 5-2. The systematic application of the process steps for generating ToCs in this case study is described below, with the car seat structure being referred to as the "final product".

6.4.2.1 Step 1: Decision criteria for the new car seat structure

<u>1.1. Get customer requirements:</u>

The following are the given customer requirements for the car seat:

1. Light and strong metal material
2. Durability
3. Low manufacturing cost
4. Small seat size

1.2. Define decision criteria:

The analysis of the customer requirements helped to identify the following decision criteria:

1. **High durability:** The final product should be durable with regards to regular operational load as well as in crash events.
2. **Low cost:** This is the cost of the final product, which includes the material cost and the manufacturing cost.
3. **Low weight:** The final product should be as light as possible, while still providing the required strength.
4. **Small package area:** Dimensions of the final product should not exceed the determined area within the car.

1.3. Define design parameters:

The design parameters were identified by breaking down the final product into parts: material type, joining process and shape of the product. For example, material type and joining process affect the durability, cost and weight of the product while the shape would have an impact on package size. In this case study, the main focus was on defining design parameters that were related to the material type.

1. **Maximum tensile strength:** Durability is related to the maximum tensile strength: A higher tensile strength results in a stronger and more durable material.
2. **Material cost:** Product cost is related to material cost: Different types of material affect the cost, depending on the elements they include or their production method.

1.4. Define the relations between defined design parameters:

In this case study, the following pairs of parameters provide the knowledge for plausible relationships to be presented in trade-off curves:

ToC 1 – Material cost vs. maximum tensile strength:

The relationship between the material cost and maximum tensile strength will show the conflicts between the durability and cost decision criteria.

6.4.2.2 Step 2: Data Collection for the new car seat structure

2.1. Collect the data of the defined design parameters:

Data was collected from material providers. Table 6-4 presents the collected metal data, which includes different material types. However, the data for the material cost was not available in the required format. The following activity explains how data was obtained in order to represent the material cost.

2.2. Filter and refine the data:

Due to data for the material cost being unavailable, an alternative design parameter was considered to represent the cost decision criteria. “Price increase on identical dimension in percentage” was identified as the new design parameter. It is related to the price increase when the volume of the material is stable but the maximum tensile strength and density of the material vary. Data is presented in Table 6-4.

2.3. Prepare the final filtered data:

In this case study, activity 2.3 was not required as the data was made available in the required format in activities 2.1 and 2.2.

No.	Sheet Metal	Max Tensile Strength [N/mm^2]	Density [Kg/dm^3]	Price increase on identical dim. in %
1	Material 1	270	2.7	0
2	Material 2	380	7.85	2
3	Material 3	545	7.85	12
4	Material 4	580	7.85	16
5	Material 5	615	7.85	22

Table 6-4: Metal data for the car seat structure collected from material providers

6.4.2.3 Step 3: ToCs generation for the new car seat structure

3.1. Plot the data of the corresponding design parameters:

A trade-off curve, as mentioned in activity 1.4, was generated by using the corresponding data in Table 6-4 according to the defined relationship between the related design parameters. Generated knowledge-based ToC is presented in Figure 6-6.

3.2. Plot the customer requirements against generated ToCs:

Customer requirements were not provided as numeric values in this case study. They can therefore not be plotted against the axes of the ToC. In the absence of predetermined requirements, in order to demonstrate the improved version of the process, an achievable realistic system target was identified. This target is based on the product and market knowledge, assuming that it is a good approximation of an implicit customer requirement. This implicit customer requirement is quantified as below:

- Maximum tensile strength should be between 350 and 550 N/mm^2.

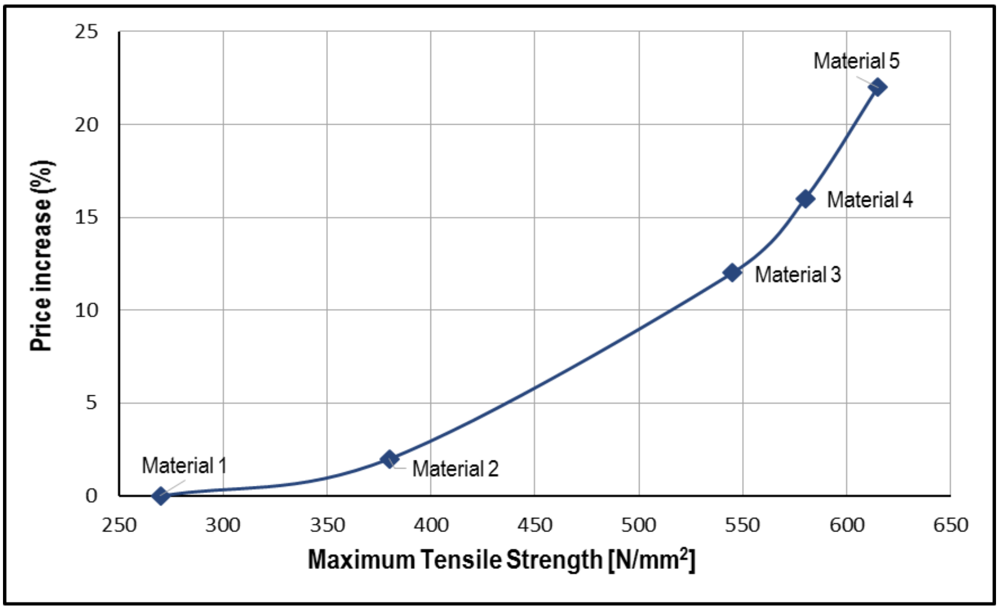


Figure 6-6: ToC 1 – Knowledge-based ToC representing the data for the durability and cost decision criteria

6.4.2.4 Step 4: Feasible solutions for the new car seat structure

4.1. Define the feasible and infeasible area:

The implicit customer requirement identified in the previous activity was plotted against the generated ToC, and the feasible area is highlighted in Figure 6-7.

4.2. Identify the design solutions within the feasible area:

After identifying the feasible area, feasible solutions could be located. It was found that out of five material types in total, there were two viable materials extracted from the generated ToC. These are Material 2 and Material 3, which meet durability and cost decision criteria.

4.3. Develop a set of potential design solutions:

Ideally, a design-set should be developed by using the data of Material 2 and Material 3. Due to limited resources, the author reused the data that was previously captured based on 15 previous design solutions as shown in Table 6-5, so that weight and package area decision criteria could also be addressed.

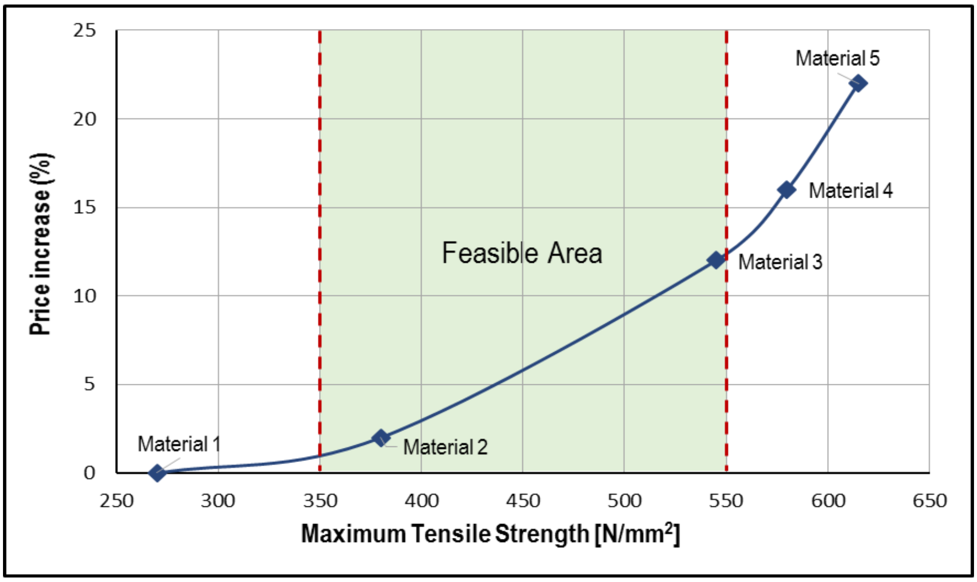


Figure 6-7: ToC 1 – Knowledge-based ToC representing the feasible area for the durability and cost decision criteria

6.4.2.5 Step 5: Optimal solution for the new car seat structure

5.1. Generate new ToCs:

New design parameters were identified related to the weight and package area decision criteria. These design parameters are:

1. **Sheet metal thickness:** Increasing the sheet metal thickness increases the strength of the material, and thus the durability of the product. On the other hand, thicker sheet metal causes additional material cost and increases the weight of the final product.
2. **Weight/package area ratio:** This is the amount of the sheet metal that falls into an identified package area. Due to weight considerations of the final product, this ratio is required to be low.

After identifying new design parameters, the following relationship between them was defined as below:

ToC 2 – Sheet metal thickness vs. weight/package area ratio:

These design parameters have an impact on weight and package size of the car seat structure. The author aimed for a low weight/ package area ratio, while simultaneously achieving sufficient sheet metal thickness. The ToC which was created based on this relationship was used to narrow down the set of possible design solutions.

Table 6-5 presents the data of weight/package area ratio with different sheet metal thicknesses that is reused from previous design solutions. Data in Table 6-5 is plotted in ToC 2, as shown in Figure 6-8.

Previous Design Solutions	Sheet Metal Thickness [mm]	Total Design Weight to Package Area Ratio [Kg/m^2]
Design 1	0.5	4.51
Design 2	0.9	2.65
Design 3	0.6	5.33
Design 4	0.6	5.06
Design 5	0.5	4.2
Design 6	0.6	5.05
Design 7	0.6	4.59
Design 8	0.5	3.81
Design 9	0.9	2.29
Design 10	0.5	3.81
Design 11	0.6	4.89
Design 12	0.8	7.34
Design 13	0.8	6.21
Design 14	0.8	7.2
Design 15	0.8	6.15

Table 6-5: Data reused from previous design solutions

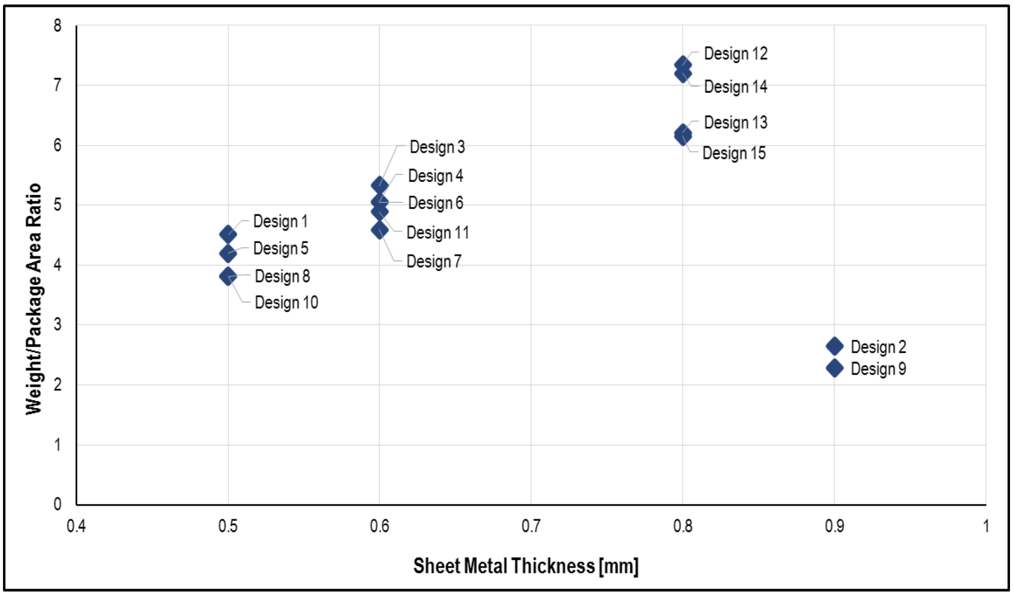


Figure 6-8: ToC 2 – Comparison of 15 design solutions for weight and package area decision criteria

5.2. Compare and trade-off developed design-set:

This activity was completed in parallel with the next activity, 5.3.

5.3. Narrow down the design solutions:

ToC 2, shown in Figure 6-8, was generated to be able to compare and narrow down the possible design solutions. A lower ratio of weight/package area provides a better solution. On the other hand, increasing the sheet metal thickness may increase the durability, however, the material cost also increases accordingly. Based on this knowledge, the following conclusions were made by the author:

- Design 2 and Design 9 should be eliminated from the design-set, since they have the highest sheet metal thickness compared to other designs, which may cause an increase in material cost.
- Design 12, 13, 14 and 15 should be eliminated since they have very high sheet metal thickness (0.8mm), and also the highest weight/package area ratio. This leads to the consideration of final product weight. The optimal design should be lightweight.
- Design 3, 4, 6, 7 and 11 should also be eliminated since they show lower performance than Design 1, 5, 8 and 10 considering the weight/package area ratio and sheet metal thickness.

As a result of comparing the possible design solutions to each other, and narrowing down the design-set, there were four selectedr designs:

1. Design 1
2. Design 5
3. Design 8
4. Design 10

5.4 Select the optimal design solution:

In order to select the best design solution among these four designs in the design-set, a new ToC can be generated. The author identified the following possible relationship between the design parameters for a new ToC:

ToC 3 – Crash Performance vs. Weight:

These design parameters have an impact on durability and weight of the car seat structure. The author aimed for a lightweight final product, while simultaneously achieving sufficient strength against any crash incidents.

Due to limited resources, this relationship is hypothetically represented in ToC 3 as shown in Figure 6-9, in order to demonstrate the improved version of the process for generating ToCs that enable SBCE applications. Thus, the remainder of this case study includes hypothetical conclusions by the author, which do not necessarily reflect SiTech's view on the selection of designs.

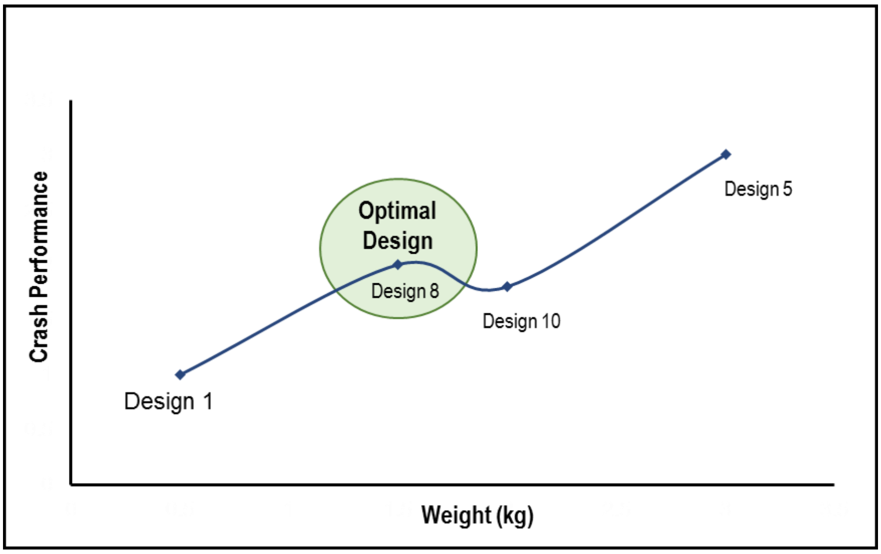


Figure 6-9: ToC 3 - Crash performance analysis for achieving optimal design solution

As shown in Figure 6-9, data of four different design showed different weight and crash performance results. It can be approximated that the relationship between weight and crash performance was roughly linear. A heavier product is expected to show better crash performance (a trend which was observed in three out of four designs). Ideally, the decision would be to select the highest crash performance, which was Design 5.

However, Design 5 was too heavy to meet the decision criteria of weight. On the other hand, Design 1 was the lightest design solution (with low weight being a customer requirement), but its crash performance did not meet the durability decision criteria. Since the data of Design 8 met all the identified decision criteria and customer requirements for the current project, it was hypothetically selected as an optimal design.

6.4.3 Debriefing of the SiTech case study

Material 2 was selected as an appropriate material type for the new car seat structure, and data of Design 8 was selected from the developed design-set to be used in developing an optimal design. This case study provided a better understanding of the industrial applications of using ToCs that enable SBCE activities. Moreover, decision-making was supported by ToCs representing a knowledge-environment. The process for generating knowledge-based ToCs was also further refined to its final form, as it is depicted in Figure 5-4.

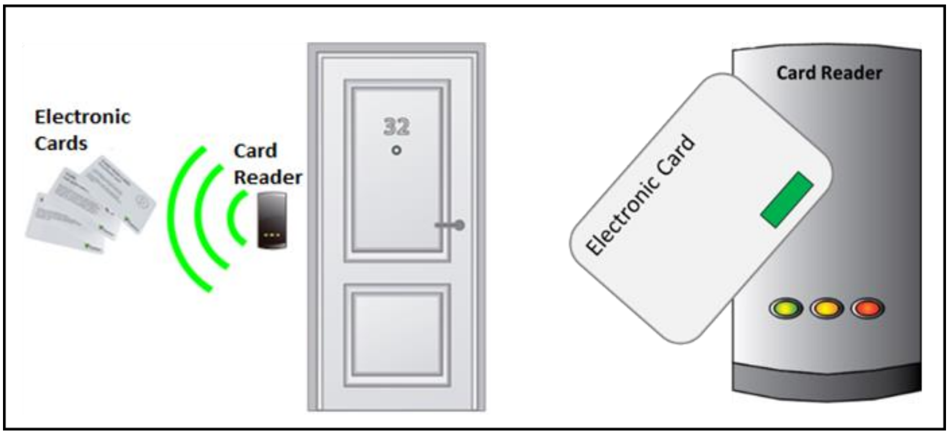
6.5 Paxton Case Study: Knowledge-based ToCs

This section presents the application and the validation of the process for generating knowledge-based ToCs that enable SBCE, as presented in Figure 5-4. This case study aims to present the utilisation of knowledge-based ToCs to identify the feasible design area and to develop a set of design solutions, which are the key activities of SBCE.

Paxton designs and manufactures market leading IP access control, door entry and building intelligence systems for smart buildings. The company develops systems for the mid-market (such as education, healthcare, retail, leisure, commercial and public sector) and provides solutions suitable for a wide range of sites and requirements. The members of “the research team” that took part in this case study, and their contributions to it, are defined in Appendix B. An overview and characteristics of the card reader, which is the subject of this case study, is presented in the following subsection.

6.5.1 Overview and characteristics of the proximity card reader

Access control is the selective restriction of access to a place or other resource. An example of an access control system is illustrated in Figure 6-10. The specific product for this case study is commonly known as a “proximity card reader”, which is referred to as “card reader” in this case study. It is an important part of an electronic access control system. The card reader identifies the different users trying to access the system and sends this information to another device, which verifies if the users are allowed to have access. Thus, the customer company will be able to gather information about the entries into the system (e.g. the number and identity of people accessing the system within a specific time-period, and also the number of people within the system for fire, life, safety considerations).



(a) Electronic access control system diagram *(b) The card reader*

Figure 6-10: An example of a card reader within the electronic access control system

A card reader consists of seven components, as illustrated in Figure 6-11. The front cover protects the electronic part of the product, while the back-plate facilitates the installation of the product on a wall or door. The remaining five components – the reader's module, the coil, the main PCB, the exciter, the power connection – are internal components that provide a magnetic area and facilitate the recognition of the credentials of the users.

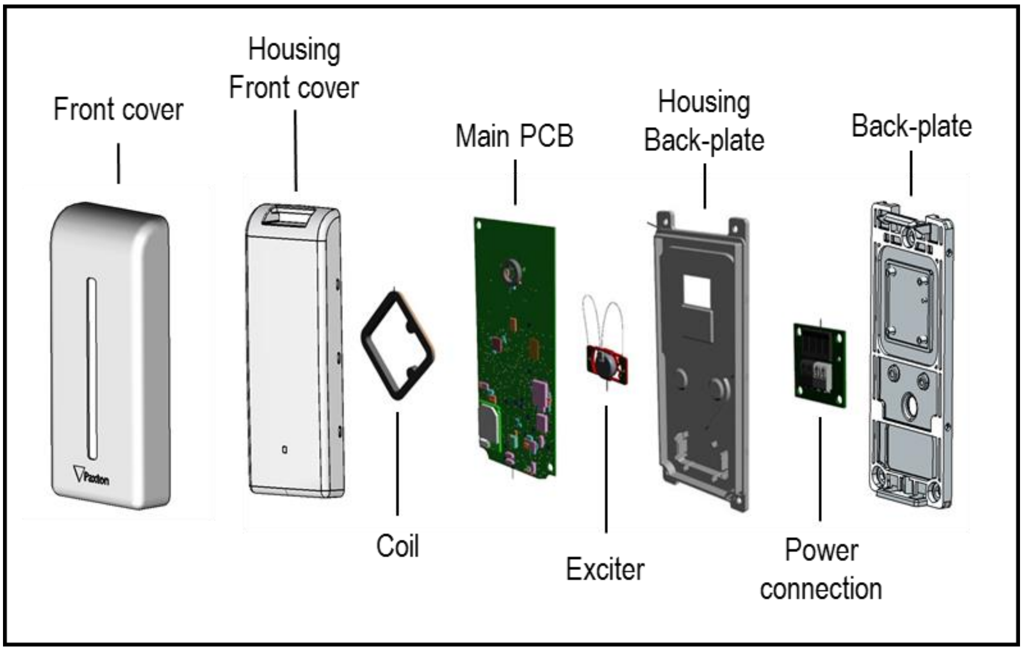


Figure 6-11: Components of an electronic access card reader

6.5.2 Developing a design-set for a vandalism resistant card reader

The main objective of this case study is to present and validate the application of the process to generate several ToCs based on historical data. This enables the identification of the feasible design area and the generation of a design-set for the SBCE application. The aim is to design a card reader that is resistant to vandalism. Vandalism is defined as deliberate damage being inflicted on the product, for instance a removal of the card reader by hand, blows to the card reader with any object, intentional fire damage, and damage resulting from liquids, sand or stones. The process for generating knowledge-based ToCs, as shown in Figure 5-4**,** was followed. Its application is presented below.

6.5.2.1 Step 1: Decision criteria for the new card reader

<u>1.1. Get customer requirements:</u>

The following customer requirements have been identified by examining the customer feedback about the current products of the company, as well as by brainstorming and interacting with designers and engineers in Paxton:

1. **Resistant to vandalism**.
2. **250,000 activations** during the product life (5 years): The card reader must work for a minimum of 250,000 times within five years.
3. **Minimum operational distance of 10 mm**: The card reader must be activated by the electronic cards at a minimum of 10mm distance.
4. **Maximum operational distance of 50 mm:** The card reader must be activated by the electronic cards at a maximum of 50mm distance.
5. The new card reader's **manufacturing cost** must not exceed the amount that the customer identified (due to confidentiality issues, the required amount could not be provided in this thesis).

<u>1.2. Define decision criteria:</u>

The following decision criteria were identified by analysing the customer requirements and brainstorming with designers and engineers in Paxton:

1. **Durability:**

   The new card reader must be durable against vandalism, violation, burning, and breaking.

2. **Reliability:**

   The new card reader should work as intended, and with the required read operational distance of 10-50mm, for at least 250,000 times during the product life of 5 years.

3. **Cost Efficiency:**

   The manufacturing cost of the new card reader is identified as a percentage of the retail price of the product as per company policy (due to confidentiality issues, the percentage could not be provided in this thesis).

1.3. Define design parameters:

The following design parameters have been identified by analysing the features and characteristics of the card reader in order to identify relationships with each of the decision criteria defined in activity 1.2:

1. Coil size
2. Coil shape
3. Coil wire length
4. Coil magnetic area
5. Operation distance
6. Front cover material type
7. Manufacturing cost
8. Front cover material cost

1.4. Define the relations between defined design parameters:

The research team conducted a brainstorming meeting to determine the conflicting relationships between the characteristics of the design solutions, which will support the creation of a design-set to provide a knowledge-environment for the SBCE application. These relationships are based on the understanding of the product's characteristics to create meaningful knowledge, as well as an overview of potential conflicts between them. As a result of the brainstorming meeting, it was understood that shape and wire length of the coil have an influence on the magnetic area created by the coil, which affects the operation distance of the product. The operation distance is also affected by the size of the coil. Regarding the cost efficiency and durability aspects of the new product, the research team was interested in the relationships between the material type of the front cover and the manufacturing cost, as well as the material cost. Table 6-6 illustrates the identified relationships by showing the related decision criteria.

No.	Parameters for X axis	Parameters for Y axis	Related Decision Criteria
1	Coil shape	Coil magnetic area	Reliability
2	Coil wire length	Coil magnetic area	Reliability
3	Operation distance	Coil magnetic area	Reliability
4	Operation distance	Coil size	Reliability
5	Front cover material type	Manufacturing cost	Durability and Cost
6	Front cover material type	Front cover material cost	Durability and Cost

Table 6-6: Plausible and conflicting relationships between identified design parameters

6.5.2.2 Step 2: Data collection for the new card reader

2.1. <u>Collect the data of the defined design parameters:</u>

Once the design parameters were identified, the required data was collected by the research team from previous, successful commercial projects. The sources for the data included final detailed designs, product installations and operations manuals, among others. Figure 6-12 illustrates the previous products for a card reader, namely P38, P50, P75, P200, Metal reader, Architect reader, Backbox reader, and the Marine reader. Table 6-7 shows the design parameter data collected of these previous products. In Table 6-7, the design parameters defined in activity 1.3 are listed in the left column, and confidential data has been labelled with “X”.

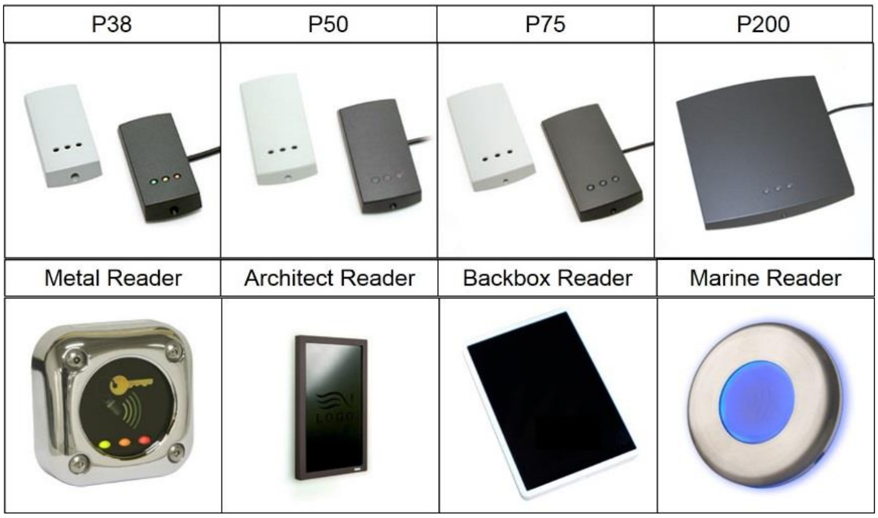


Figure 6-12: Images of previous products that were used for data collection (Paxton, 2017)

		Previous Projects							
No.	**Design Parameters**	**P38**	**P50**	**P75**	**P200**	**Metal reader**	**Architect reader**	**Backbox reader**	**Marine reader**
1	Coil size	X	X	X	X	X	X	X	X
2	Coil shape	X	X	X	X	X	X	X	X
3	Coil wire length	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
4	Coil magnetic area	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
5	Operation distance	60	80	110	200	50	50	125	40
6	Front cover material type	ABS Plastic	ABS Plastic	ABS Plastic	ABS Plastic	Zamak3 and PC window	ABS Plastic	ABS Plastic	Steel and PC window
7	Product retail price [£]	110	110	110	110	165	220	150	220
8	Front cover material cost	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Note:	Product retail prices are for reference only and may not represent the actual retail prices. X: Confidential Data								

Table 6-7: Design parameter data collected from previous projects

2.2. Filter and refine the data:

It was noticed that some of the identified design parameters had no data, since it was not recorded for the previous projects. The data that could not be sourced was defined as “unknown”. The parameters with unknown data were removed. Design parameters with unknown data are the coil wire length, the coil magnetic area and the front cover material cost. Table 6-8 shows the filtered and refined data of the design parameters.

		Previous Projects							
No	Design Parameters	P38	P50	P75	P200	Metal reader	Architect reader	Backbox reader	Marine reader
1	Coil size	X	X	X	X	X	X	X	X
2	Coil shape	X	X	X	X	X	X	X	X
3	Operation distance	60	80	110	200	50	50	125	40
4	Front cover material type	ABS Plastic	ABS Plastic	ABS Plastic	ABS Plastic	Zamak3 and PC window	ABS Plastic	ABS Plastic	Steel and PC window
5	Product retail price [£]	110	110	110	110	165	220	150	220

Note: Product retail prices are for reference only and may not represent the actual retail prices.

X: Confidential Data

Table 6-8: Filtered and refined design parameters data from the previous projects of the card reader

2.3. Prepare the final filtered data:

During the data collection activity, the research team was unable to obtain the data in the format that they required. For example, the required data of the coil size was captured in the form of coil dimensions (height*width*thickness) in millimetres [mm]. However, the research team needed the volume of the coil size in cubic centimetres [cm^3]. Therefore, the coil size was derived from the coil dimensions by multiplying the height, width and thickness and then converting into cm^3. Similarly, the material type and the coil shape did not have numeric values. In order to plot these design parameters on ToCs, the research team assigned numeric values for different material types and coil shapes (e.g. 1 for steel, 2 for Zamak3 and 3 for ABS Plastic). Furthermore, the manufacturing cost was derived from the product retail price as the required data was unavailable. Manufacturing cost was assumed as being a defined percentage of the product retail price, as per the collaborating company’s policy. This percentage is not presented in this thesis for reasons of confidentiality.

Finally, the data spreadsheet was reorganised in order to facilitate the generation of knowledge-based ToCs, as shown in Table 6-9. Highlighted rows are representing the derived data.

		Previous Projects							
No.	**Design Parameters**	**P38**	**P50**	**P75**	**P200**	**Metal reader**	**Architect reader**	**Backbox reader**	**Marine reader**
	Coil dimensions (height*width*thickness) [mm]	X	X	X	X	X	X	X	X
1	Coil size [cm3]	X	X	X	X	X	X	X	X
	Coil shape	X	X	X	X	X	X	X	X
2	Coil shape (numeric values: 1 to 3)	1	1	1	1	2	2	1	3
3	Operation distance [mm]	60	80	110	200	50	50	125	40
	Front cover material type	ABS Plastic	ABS Plastic	ABS Plastic	ABS Plastic	Zamak3 and PC window	ABS Plastic	ABS Plastic	Steel and PC window
4	Front cover material type (numeric values: 1 to 3)	3	3	3	3	2	3	3	1
	Product retail price [£]	110	110	110	110	165	220	150	220
5	Manufacturing cost [£]	X	X	X	X	X	X	X	X

Note: Product retail prices are for reference only and may not represent the actual retail prices.
X: Confidential Data

Table 6-9: Final filtered and reorganised design parameter data required to start generating knowledge-based ToCs

6.5.2.3 Step 3: ToCs generation for the new card reader

<u>3.1. Plot the data of the corresponding design parameters:</u>

In this activity, relations between the defined design parameters were referred to, which were developed in activity 1.4. Initially, there were six relationships before the commencement of data collection. However, due to unavailable data, only two relationships were available for generating knowledge-based ToCs. These are highlighted in Table 6-10 and listed below.

1. **ToC 1 –** Coil size vs. Operation distance
2. **ToC 2 –** Material type vs. Manufacturing cost

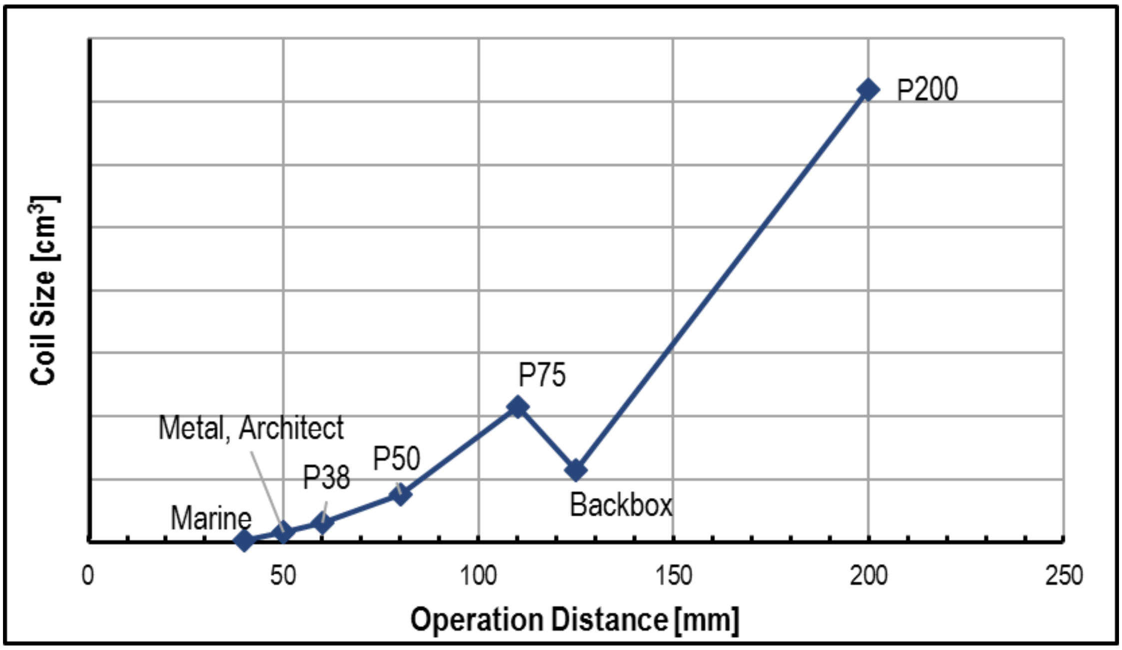
No.	Parameters for X Axis	Parameters for Y Axis	Related Decision Criteria
	~~Coil shape~~	~~Coil magnetic area~~	~~Reliability~~
	~~Coil wire length~~	~~Coil magnetic area~~	~~Reliability~~
	~~Operation distance~~	~~Coil magnetic area~~	~~Reliability~~
1	Operation distance	Coil size	Reliability
2	Front cover material type	Manufacturing cost	Durability and Cost
	~~Front cover material type~~	~~Front cover material cost~~	~~Durability and Cost~~

Table 6-10: Relationships to be used for generating knowledge-based ToCs for the new car reader

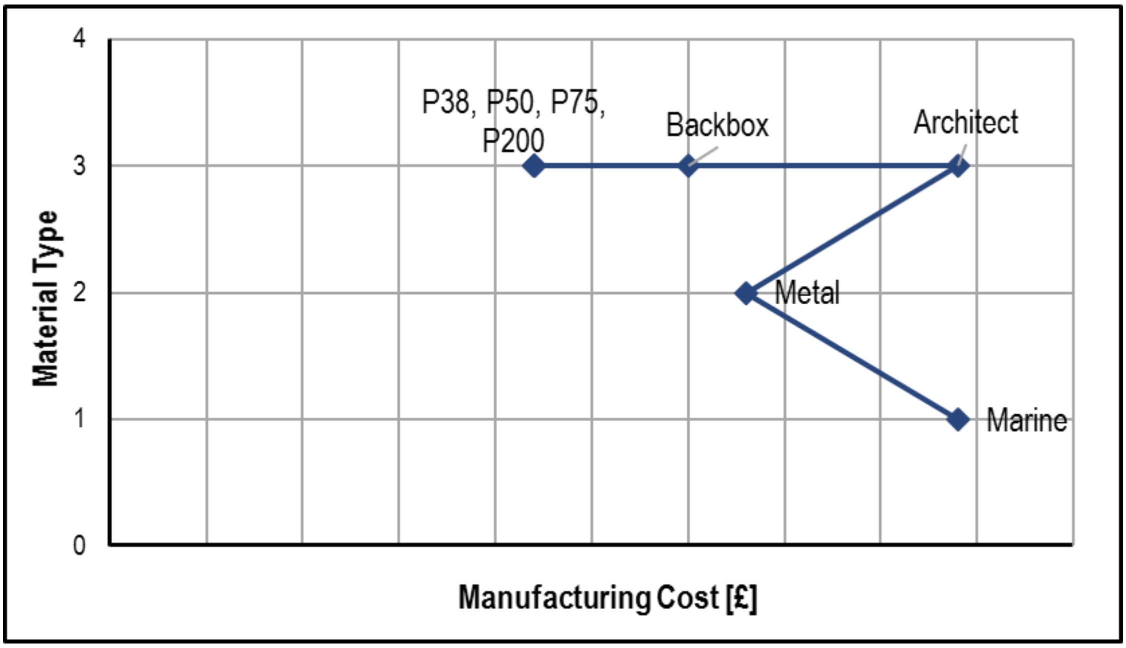
The data of the design parameters was plotted against two trade-off curves as shown in Figure 6-13. The relationship between operation distance and coil size is presented in ToC 1 in Figure 6-13(a), and the relationship between manufacturing cost and material type is shown in ToC 2 in Figure 6-13(b).

3.2. Plot the customer requirements against generated ToCs:

The customer requirements captured in activity 1.1 were plotted on the generated knowledge-based ToCs and presented in Figure 6-15. The dashed lines in Figure 6-14 illustrate the customer requirements. Figure 6-14(a) is related to the customer requirements of 10mm minimum and 50mm maximum operational distance. Similarly, Figure 6-14(b) is related to the customer requirement of the card reader's manufacturing cost.

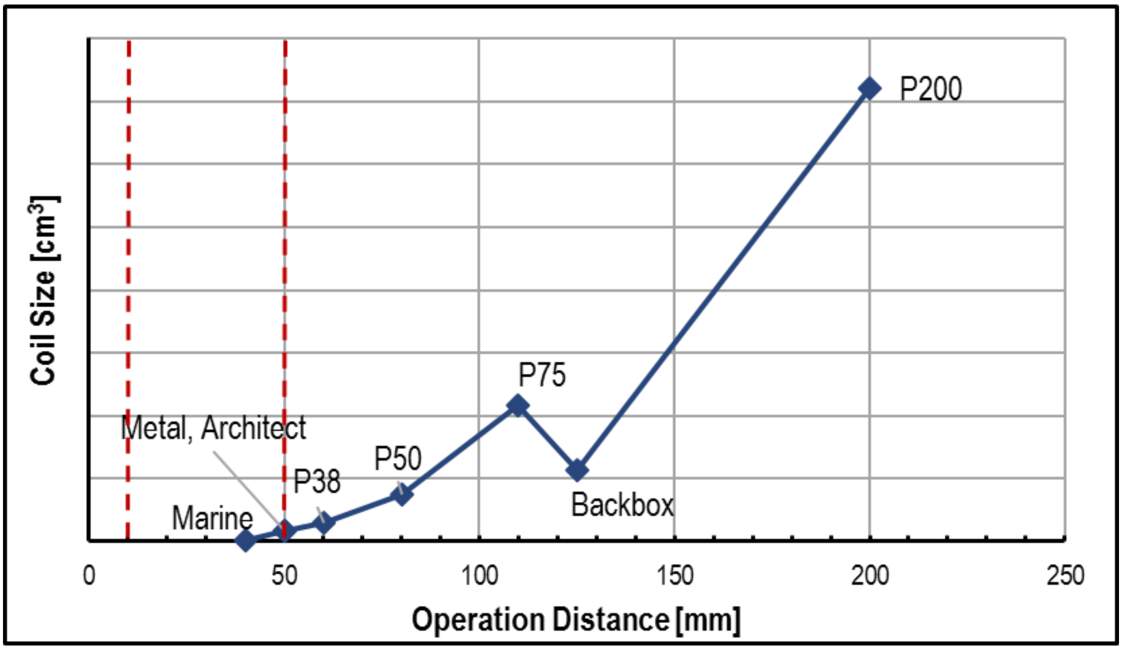


(a) ToC 1, depicting the reliability decision criteria by illustrating the relationship between coil size and operational distance

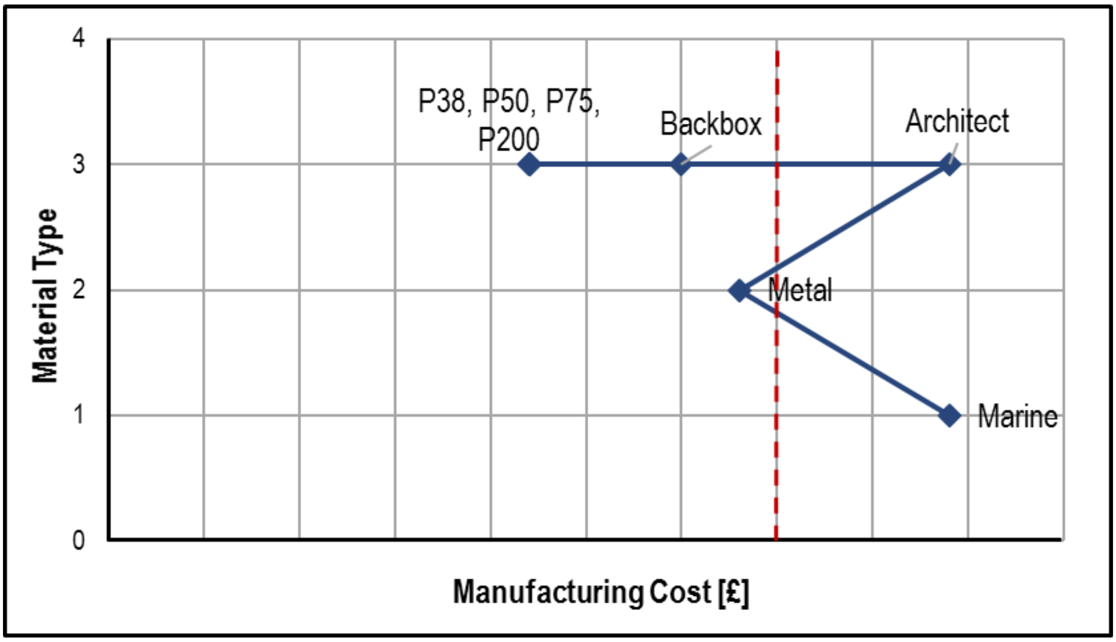


(b) ToC 2, depicting the durability and cost efficiency decision criteria by illustrating the relationship between material type and manufacturing cost

Figure 6-13: Generated knowledge-based ToCs related to the decision criteria of durability, reliability and cost efficiency



(a) Customer requirements mapped on ToC 1 for reliability



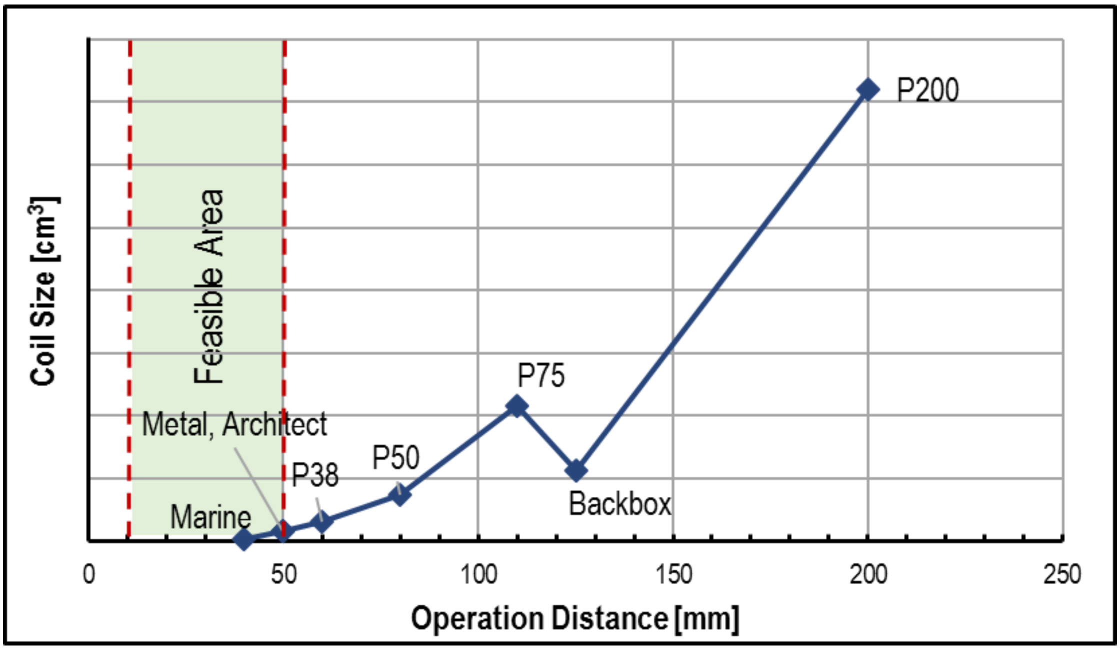
(b) Customer requirements mapped on ToC 2 for durability and cost

Figure 6-14: Generated knowledge-based ToCs presenting the customer requirements

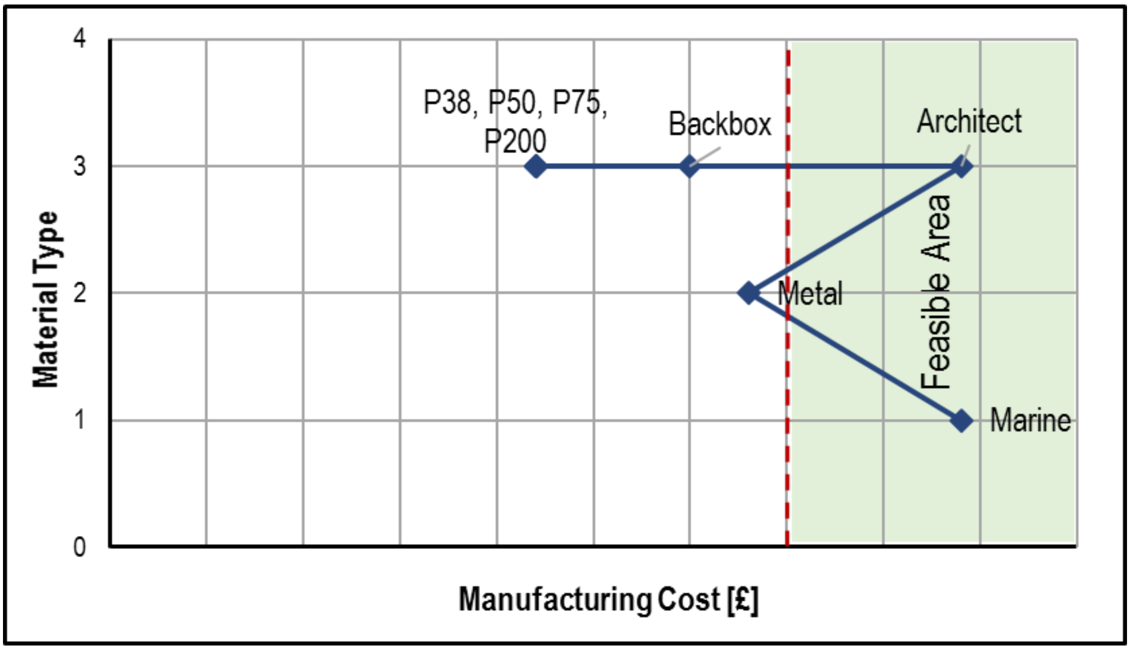
6.5.2.4 Step 4: Feasible solutions for the new card reader

4.1. Define the feasible and infeasible area:

After plotting the customer requirements, feasible areas were identified as highlighted in Figure 6-15. The feasible area in Figure 6-15(a) lies between the customer requirements of 10mm and 50mm operational distance. The feasible area in Figure 6-15(b) lies between the Y axis and customer requirement of the manufacturing cost.



(a) Feasible area of ToC 1 for reliability



(b) Feasible area of ToC 2 for durability and cost

Figure 6-15: Generated knowledge-based ToCs presenting the feasible design area

4.2. Identify the design solutions within the feasible area:

Identifying the feasible area revealed two feasible design solutions in ToC 1 related to reliability (Figure 6-15(a)), while there were six design solutions found in the feasible area of ToC 2 related to durability and cost efficiency (Figure 6-15(b)). Table 6-11 presents the selected design solutions from the generated ToCs. It is apparent that one design solution – the Metal reader – meets all customer requirements and decision criteria.

Related ToC that the design solutions were selected	Possible design solutions from previous projects	Related decision criteria that the design meets
ToC 1: Coil size vs. Operation Distance	Marine reader	Reliability
	Metal reader	
	Architect reader	
ToC 2: Front Cover Material type vs. Manufacturing Cost	Metal reader	Durability and Cost Efficiency
	P38	
	P50	
	P75	
	Backbox reader	
	P200	

Table 6-11: Feasible design solutions selected from each knowledge-based ToC

4.3. Develop a set of potential design solutions:

The research team generated a set of possible design solutions by using the feasible designs identified in activity 4.2. There were eight feasible designs, as the metal reader was a common design in both ToCs. Table 6-12 presents the evaluation of these eight feasible solutions and shows that a set of six conceptual designs could be put forward for consideration during further development in the SBCE environment. The table also presents the recommended action and the rationale behind it. For example, D1 is the "Marine reader" from the previous project, the design data of which meets requirements for reliability, and the material of the front cover component meets the durability criteria. However, it does not meet the cost requirement and therefore requires a major design change until the criteria is met. Another example is the design D2 - Metal reader – which meets all customer requirements and decision criteria. Therefore, the data of this design could be reused, as it is, to develop a new design-set. The rest of the feasible solutions follows the same logic, as shown in Table 6-12.

No.	Previous Projects	Recommended Action	Rationale
D1	Marine reader	Major changes	Meets the reliability decision criteria. The material type of the product meets the durability decision criteria, however fails to satisfy the cost requirement. Major design changes might help to reduce the cost, meet the decision criteria.
D2	Metal reader	Reuse the existing design solution	Meets all customer requirements and decision criteria.
D3	Architect reader	Used to inspire creating new conceptual design solutions	Meets the reliability criteria, however its material type is not resistant to vandalism. Thus, it meets neither the durability nor the cost criteria.
D4	P38	Minor changes	Very close to meeting the operational distance requirement. The shape of the product, with minor changes, is suitable for a vandalism-resistant design. These changes will increase the cost slightly, but the solution will remain within the feasible area.
D5	P50	Minor changes	Very close to meeting the operational distance requirement. The shape of the product, with minor changes, is suitable for a vandalism-resistant design. These changes will increase the cost slightly, but the solution will remain within the feasible area.
D6	P75	Used to inspire the creation of new conceptual design solutions	Meets the cost criteria, however its material type is not sufficiently resistant to vandalism. Thus, it meets neither the durability nor the reliability criteria.
D7	Backbox reader	Not to be considered	Far from meeting both decision criteria and requirements.
D8	P200	Not to be considered	Far from meeting both decision criteria and requirements.

Table 6-12: Potential design solutions identified from previous projects, and recommended actions for proposing a set of design for SBCE application

The research team took the recommended actions as shown in Table 6-12 and followed the SBCE process model. Thus, nine new design solutions were generated and are presented in Figure 6-16. Design A1 illustrates the existing design solution to be developed and improved throughout the SBCE application in order to meet the customer requirements and decision critera. Conceptual designs in the design-set, as depicted in Figure 6-16, are coded by using the letter "A" in order to differentiate them from the design solutions of previous projects, which are coded with "D".

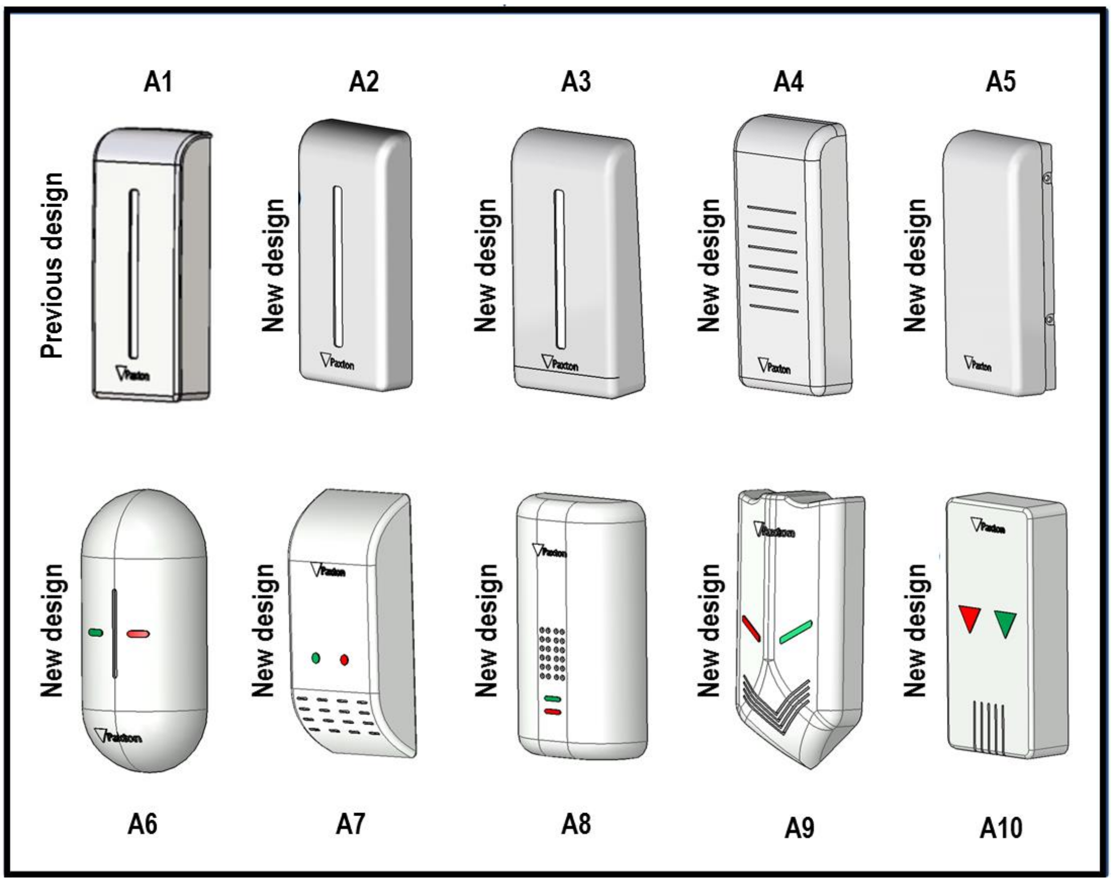


Figure 6-16: Design-set developed through the application of knowledge-based ToCs throughout the SBCE process

6.5.2.5 Step 5: Optimal solution for the new card reader

5.1. Convert these potential solutions to a final optimal solution using the SBCE process model:

The generated design-set was used to compare and narrow down throughout the further application of the SBCE process model, which is demonstrated in section 6.6.

6.5.3 Debriefing of the case study

Knowledge-based ToCs were generated by using data from previous projects. Knowledge-based ToCs were used throughout the SBCE process model and supported the development of a design-set consisting of nine new conceptual design solutions.

6.6 Paxton Case Study: Physics-based ToCs

This section describes the validation of the process shown in Figure 5-6. The process was developed in order to generate ToCs based on the physics of the product, and subsequently using these physics-based ToCs to compare the possible design solutions and narrow down the design-set, which are the key activities of SBCE. This case study is a research-based case study using realistic data. The product under development was a proximity card reader, the details of which are presented in subsection 6.5.1 above. Members of the research team who contributed to and were involved in conducting this case study are presented in Appendix B.

6.6.1 Comparing and narrowing down the design-set for a vandalism resistant card reader

This case study is a continuation of the case study presented in section 6.5. The difference between the two case studies is the process that is used for generating ToCs. The previous study implements the process for generating knowledge-based ToCs, while this case study uses the process for generating physics-based ToCs, as it is presented in Figure 5-6. The application of that process is demonstrated, step-by-step, below.

6.6.1.1 Step 1: Understand the first design-set of the new card reader

<u>1.1 Use the developed set of design solutions from SBCE process:</u>

The design-set taken into consideration in this case study was generated in the previous case study and is shown in Figure 6-16. The set consists of ten front covers, including one existing design and nine new conceptual designs. Since there is no change required in other components of the product, designs were created only for the front cover, which is mostly affected by vandalism.

<u>1.2 Use the identified customer requirements and decision criteria:</u>

Since the same product as in the previous case study was under consideration for this case study, the customer requirements and decision criteria were adopted from step 1 of subsection 6.5.2. Customer requirements and decision criteria will hereafter be referred to as “key value attributes (KVAs)”. As the process for identifying customer requirements and decision criteria has been demonstrated in subsection 6.5.2, the KVAs in this case study are as below:

1. Durability,
2. Reliability,
3. Cost efficiency.

6.6.1.2 Step 2: Understand physics of the card reader

2.1 Study the physical characteristics/features of the product under development:

The physical characteristics were studied to understand the parameters that affect the product’s features. The certainty about the KVAs (durability, reliability and cost efficiency) facilitated the identification of the design parameters. These design parameters are described below:

1. **Durability-related design parameters:**
   - Fire resistance:

     The product might be damaged when it is exposed to fire. The possible action with fire considered in this case study is an attempt to burn the product with a lighter.
   - Impact resistance:

     The product might be cracked or damaged by hitting, punching or kicking.
2. **Reliability-related design parameters:**
   - Read range:

     The read range is defined as the usable distance of the magnetic area created by the reader’s module. Once the electronic card reaches the read range, the electronic access system is activated by receiving magnetic signals.

3. **Cost efficiency-related design parameters:**
   - Cost:

     The manufacturing cost of the product is depending on the type and amount of the material used.

2.2. Identify new design parameters to generate physics-based ToCs:

Physics knowledge obtained in activity 2.1 was employed to identify new design parameters. As it is shown in Figure 6-17, the wall thickness, depth and geometry of the front cover have effects on fire resistance, impact resistance, read range and cost. Changing the numeric values of wall thickness and depth affects the performance of the design solution. Similarly, different front cover geometries, like some of the possible shapes shown in Figure 6-17, affect the design parameters identified during activity 2.1. Relationships between these design parameters are described in the next activity.

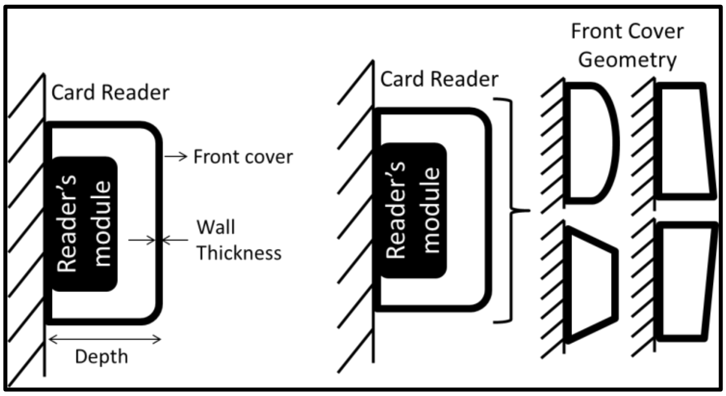


Figure 6-17: The new design parameters (wall thickness, depth, front cover geometry)

2.3. Evaluate the relations between the design parameters:

Information was captured and is presented below:

- Fire resistance:

  Increasing the wall thickness and depth will increase the fire resistance. A front cover with higher wall thickness and depth prolongs the time needed by the flame to damage the product and reach the reader's module, which improves the durability and reliability of the product.

- Impact resistance:

  Increasing the wall thickness and depth will increase the impact resistance. A thicker and wider front cover protects the product from being damaged easily by hitting, kicking or punching. Moreover, different angles of the front cover geometry will protect the product against the vandalism actions more effective than a flat geometry.

- Read range:

  Increasing the wall thickness and depth will affect the read range in a negative way. It will cause an increase in the distance between the reader's module and the surface of the front cover.

- Cost:

  A design solution with a thicker and wider front cover will require more material, which leads to an increase in cost.

2.4. Generate non-scale ToCs based on the obtained physics knowledge:

The relations identified in activity 2.3 helped the author to generate non-scale ToCs in order to see the relationships and interactions between the design parameters in a single diagram (Figure 6-18). Due to resource constraints, in this activity the focus was on the relationships between the wall thickness and fire resistance, impact resistance, read range and cost only.

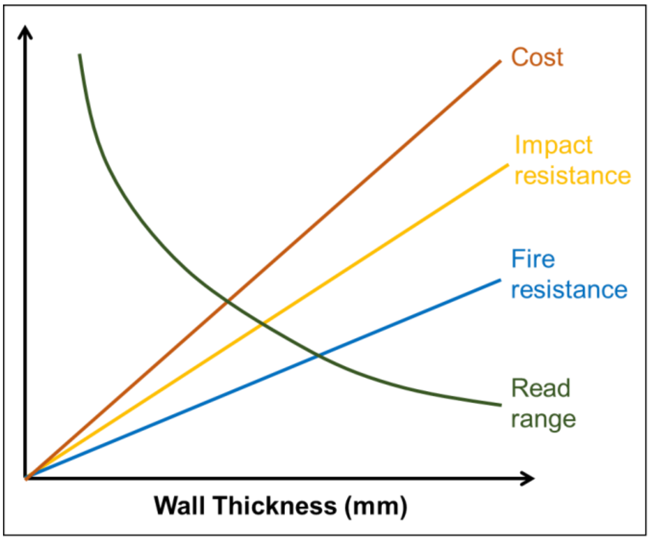


Figure 6-18: Non-scale ToC illustrating the relationships between design parameters

As depicted in Figure 6-18, increasing the wall thickness of the front cover will improve the resistance to impact and fire. However, these enhancements are achieved at the expense of rising device cost caused by increasing material requirements. Furthermore, the read range of the device will decrease as a thicker wall will weaken magnetic signals passing through the product.

6.6.1.3 Step 3: Test and analyse the possible designs of the new card reader

3.1. Turn non-scale ToCs into scaled ToCs based on physics knowledge:

As explained in step 2, wall thickness and depth have significant effects on the identified design parameters. Due to limited amount of data available, only impact and fire resistance of the designs were analysed further in this case study. The analysis was carried out by using structural and thermal simulations. The structural analysis was focused on simulating the impact of a hammer, while the thermal analysis was focused on simulating the impact of a lighter flame. “Ansys” software was used for the simulations. The input parameters of the simulations are shown in Table 6-13.

Input Parameters	Input Values
Applied temperature	1400°C
Area of hammer	0.000314 m^2
Mass of hammer + arm	7.4 kg
Approx. velocity of hammer coming down	5 m/s
Estimated bounce back	1m/s
Impact time	0.01s
Acceleration (V1-V2)/t	600m/s^2
Force	4500N

Table 6-13: Structural and thermal simulations inputs

In order to turn non-scale ToCs into scaled physics-based ToCs, the following indicators were used as result of the structural and thermal analyses.

1. Indicators for the structural analysis:
    - Highest stress level (MPa) (related to the impact resistance)
    - Deformation scale (related to the impact resistance)
2. Indicators for thermal analysis:
    - Highest temperature level (^{o}C) (related to the fire resistance)

Figure 6-19 illustrates the physics-based ToCs that were generated according to the knowledge gained from the non-scale ToCs as shown in Figure 6-18. These are:

1. **ToC 1** – Highest stress level vs. Wall thickness
2. **ToC 2** – Deformation scale vs. Highest stress level
3. **ToC 3** – Depth vs. Highest temperature level

3.2. Identify feasible area and/or an optimal point in the physics-based ToCs associated with the specific design parameter:

The optimal point for the thermal analysis was defined as 230^{o}C. The cover would be accepted as flame resistant if it was above this temperature. Therefore, the performance of the design solution was required to be higher than 230^{o}C.

Regarding the impact resistance, designs were expected to be durable up to at least 450MPa, which is a value that could reasonably be considered as a vandal action. In addition, a lower deformation scale represents a better impact resistance.

Feasible areas for the ToCs were identified according to these targets, and are illustrated in Figure 6-19.

6.6.1.4 Step 4: Compare the solutions of the design-set of the new card reader

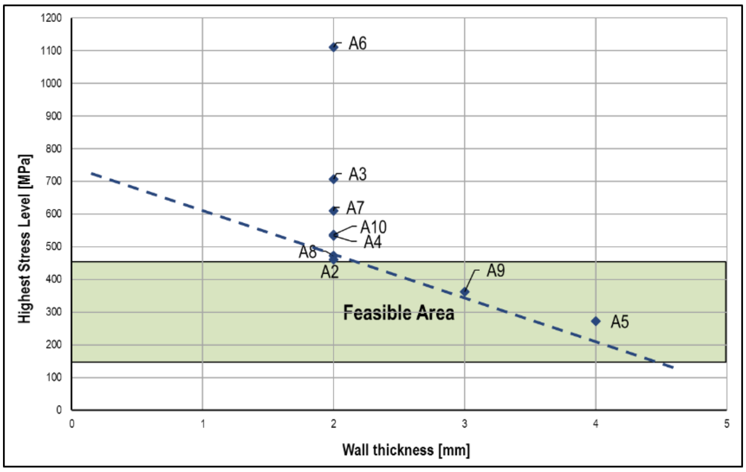
4.1. Represent the data of the selected design-set on the generated physics-based ToCs:

Data was collected from the structural and thermal simulations and presented in Table 6-14. This data was plotted against the generated physics-based ToCs, as shown in Figure 6-19 (Illustrations of the analyses are included in Appendix C). The front cover design A1 was excluded from the design-set, as it was the existing design that required improvement.

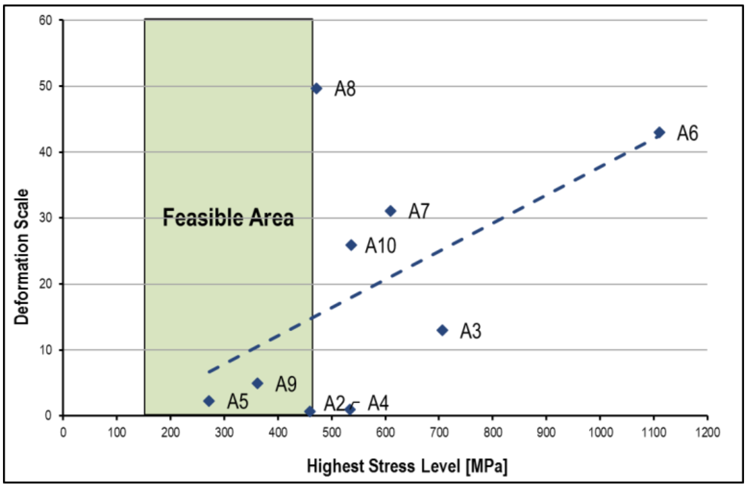
Design-Set	Front Cover Thickness [mm]	Depth [mm]	Highest Stress Level [MPa]	Highest Temp. Level [^{0}C]	Deformation Scale
A2	2	20	460	502	0.72
A3	2	25	706	352.05	12.95
A4	2	20	534	563.05	1
A5	4	25	272	604.05	2.29
A6	2	30	1110	29.65	42.97
A7	2	25	610	-9.95	31.13
A8	2	30	472	128.95	49.71
A9	3	30	362	216.05	4.9
A10	2	25	537	114.25	25.92

Table 6-14: Collected data of the design parameters of each front cover design.

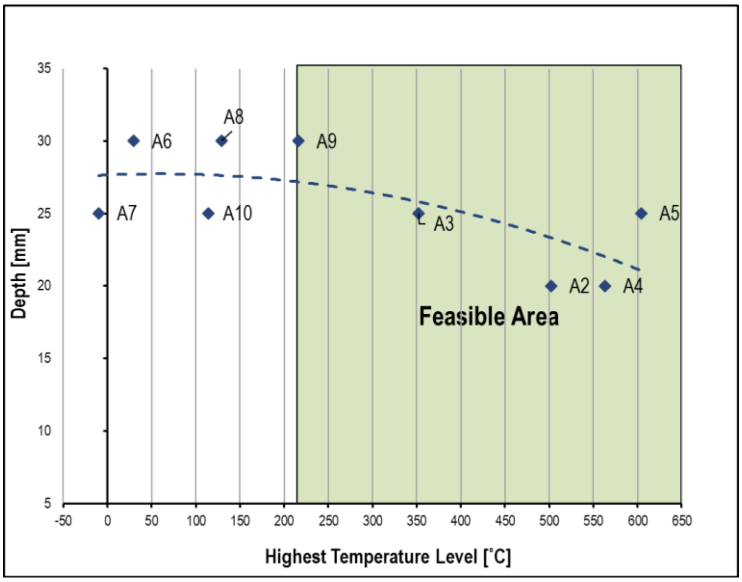
Figure 6-19 below depicts the scaled physics-based ToCs created in this case study, after activities 3.1, 3.2 and 4.1 have been carried out.



(a) ToC 1 – Highest stress level vs. Wall thickness



(b) ToC 2 – Deformation scale vs. Highest stress level



(c) ToC 3 – Depth vs. Highest temperature level

Figure 6-19: Physics-based ToCs related to the impact and fire resistance performance of the product

4.3. Communicate and compare the design solutions:

After generating the physics-based ToCs and identifying the feasible design area of each ToC, as shown in Figure 6-19, the possible design solutions were selected and are presented in Table 6-15.

Related physics-based ToC	Selected design solutions
ToC 1 (Figure 6-19(a))	A5 and A9
ToC 2 (Figure 6-19(b))	A5 and A9
ToC 3 (Figure 6-19(c))	A2, A3, A4 and A5

Table 6-15: Selected design solutions from the feasible area of physics-based ToCs

Table 6-15 shows that there are five different possible designs selected from the generated physics-based trade-off curves.

4.4. Expand the feasible area if possible:

As demonstrated in Figure 6-19(a) and Figure 6-19(b), the feasible design area could be expanded by setting the target for the highest stress level at 500MPa rather than 450MPa. Thus, two more design solutions would be included in the feasible area. These designs are A2 and A8, since their highest stress levels are slightly higher than 450MPa (460MPa and 472MPa, respectively). Similarly, if the highest temperature level is decreased from 230^{o}C to 200^{o}C in the ToC shown in Figure 6-19(c), design solution A9 would be included in the feasible area.

6.6.1.5 Step 5: Select and narrow down the design-set of the new card reader

5.1. Select the design solutions in feasible area or close to the identified optimal point:

The result of comparing alternative design solutions showed that there were six different possible designs in the design-set which could be considered for further narrowing down. Table 6-16 illustrates these six possible designs: A2, A3, A4, A5, A8, and A9.

Related Physics-based ToCs	Selected design solutions in the feasible area	Selected design solutions in the expanded feasible area
ToC 1 (Figure 6-19(a))	A5 and A9	A2 and A8
ToC 2 (Figure 6-19(b))	A5 and A9	A2 and A8
ToC 3 (Figure 6-19(c))	A2, A3, A4 and A5	A9

Table 6-16: Selected design solutions from the expanded feasible area of physics-based ToCs

5.2. Second stage of narrowing down:

Six design solutions were evaluated and compared to each other, results of which have been presented in Table 6-17. Eventually, there were three design solutions selected (A2, A5, and A9) for further development of the final optimal design solution.

6.6.1.6 Step 6: Enhance design of the new card reader

6.1. Explore the opportunities of creating a new improved design based on combining and/or modifying solutions from the selected designs:

Due to limited amount of data available, this activity could not be completed in this PhD research. However, A9 could be considered for enhancement since the design parameter values show a promising performance in order to meet requirements for the impact resistance and fire resistance. For the enhancement of the design solution, actions could be taken as described in activity 4.3 in subsection 5.3.4.

6.2. Capture and store the obtained knowledge:

As mentioned in activity 6.2 of subsection 5.4.6, this activity has been considered as a future work.

Design	Decision	Rationale
A2	Selected (Minor modification)	Although A2 meets only the fire resistance requirement, the design can be improved by employing minor modifications as mentioned in activity 4.3 in subsection 5.3.4. The new design data can then be used to achieve the optimal design solution.
A3	Eliminated	Although A3 meets the requirement for fire resistance, it is not resistant against the impact applied during the structural analysis. The highest stress level of A3 is 706MPa, while the target should be less than 450MPa.
A4	Eliminated	Although A4 meets the requirement for fire resistance, it is not resistant against the impact applied during the structural analysis. The highest stress level of A4 is 534MPa, while the target should be less than 450MPa.
A5	Selected (As it is)	A5 is the only common solution in the feasible area of all physics-based ToCs, thereby meeting all requirements.
A8	Eliminated	The deformation scale of A8 (49.71) is very high compared to other design solutions. Moreover, the highest temperature level is 128.95 which is much lower than the requirement of 230^{o}C.
A9	Selected (Minor modification)	Although A9 meets the requirement for impact resistance, it does not meet the fire resistance requirement as it stays out of the feasible area as shown in Figure 6-19(c). However, since the highest temperature level of design A9 (216.05^{o}C) is slightly lower than the identified highest temperature level (230^{o}C), this design solution was selected to be considered after applying minor changes as described in activity 4.3 in subsection 5.3.4.

Table 6-17: Results of evaluation and the second stage of narrowing down

6.6.2 Debriefing of the case study

Physics-based ToCs were generated by using the data obtained from the understanding of the physics of the card reader. Physics-based ToCs were used throughout the SBCE process model and supported the activities of comparing and narrowing down the design-set. As a result, design A5 was selected, without modifications, while making the decision on an optimal design. Designs A2 and A9 were also selected, under the condition of applying minor modifications.

6.7 Caltec Case Study

This section presents the application and the validation of the process for using generated knowledge-based and physics-based ToCs within the SBCE process model, as shown in Figure 5-8. Implementing this process enabled the key activities of the SBCE process that are listed below:

1. Identifying the feasible area,
2. Developing a design-set,
3. Comparing possible design solutions,
4. Narrowing down the design-set,
5. Achieving optimal design solution.

Caltec Limited is an engineering company that provides engineering solutions for the oil and gas industry. The company consists of a small team of high-tech specialists, backed by the global resources of a major oilfield services company. The researcher was involved in a research project including six researchers and a supervisor from Cranfield University and two engineers from Caltec (co-founder and designer). The members of “the research team” contributing to this case study are introduced in Appendix B. An overview and characteristics of the surface jet pump, which is the product under consideration in this case study, is presented in the following subsection.

6.7.1 Overview and characteristics of the surface jet pump (SJP)

Surface jet pumps are relatively simple devices used to increase the production rate in the oil and gas industry, and to revive dead oil/gas wells or such with low pressure. The function of an SJP is to boost the pressure of low pressure (LP) fluids, a function which is needed at different stages of the production process. Compared to traditional methods, such as increasing the pressure with compressors, SJPs are highly cost-efficient solutions that provide the same performance. SJPs utilise the Venturi effect (Munson *et al.*, 2010), in which kinetic energy from a high pressure (HP) source is used to increase the pressure of the LP fluid (Beg and Sarshar, 2009). This effect is not too dissimilar from the velocity transfer in a turbofan jet engine (section 6.3.1).

The key components of an SJP are listed below and shown in Figure 6-20:

1. The **HP and LP inlet** of the fluid provides the connection between the wells with high pressure and low pressure.
2. The **nozzle** increases the velocity of the HP fluid by creating a Venturi effect to suck in the LP fluid.
3. The **mixing tube** transfers the energy and momentum between the HP and LP fluid streams.
4. The **diffuser** reduces the velocity and recovers the pressure.
5. The **body** integrates and protects the internal components and provides a suitable flow direction to the fluid.
6. The **discharge outlet** connects the SJP to the rest of the infrastructure, releasing the combined HP and LP fluid.

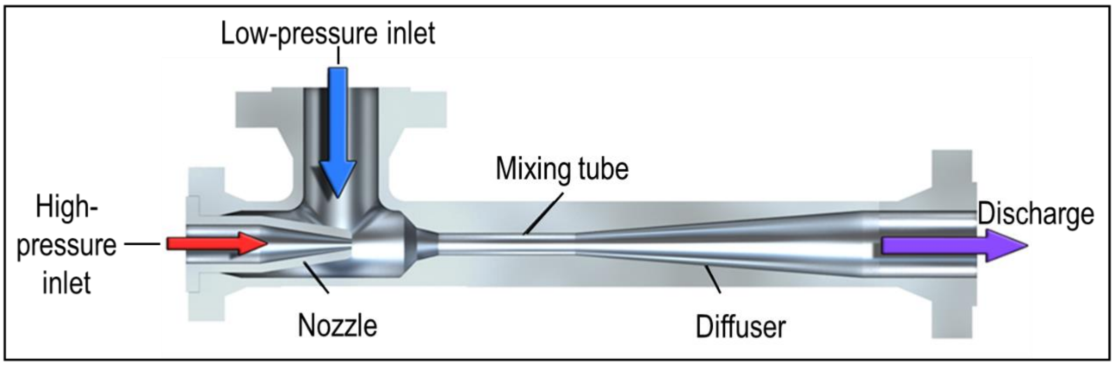


Figure 6-20: Key components of a surface jet pump (SJP) (Beg and Sarshar, 2014)

6.7.2 Developing a new surface jet pump

The main objective of this project was to develop a new surface jet pump with reduced manufacturing cost and improved design performance, when compared to the current product. To achieve this aim, the process described in section 5.5 was employed and the SBCE process model was applied in this case study. The following sub-subsections present the detailed implementation of this process (refer to Figure 5-8).

6.7.2.1 Step 1: Identify key value attributes of the SJP

Key value attributes (KVAs) were identified during brainstorming sessions with the collaborating company. The customer requirements, when compared to the existing product, were established at this stage and are listed below:

1. High mechanical performance,
2. Lower manufacturing cost and time,
3. Material: Carbon steel,
4. Light in weight,
5. Maximum allowable pressure is 571 psi,
6. Removable nozzle,
7. Mixing tube fixed with diffuser,
8. Meeting oil and gas standard ASME B31.3.

Considering these customer requirements, 38 value attributes were identified by the research team as shown in Figure 6-21(Column B), and these values were communicated to the collaborating company. Values that represented similar characteristics were classified into a single value for ease of communication and proceeding through the SBCE process. For instance, values 34 – “Corrosion resistance”, 35 – “Erosion resistance”, 36 – “Stable in subsea environment”, 37 – “Strong type of material”, 38 – “Hard surface inside the SJP” were classified as “Durability”, as presented in Figure 6-21. Similarly, all other values were classified as shown in Figure 6-21(Column C). The resulting classification is listed below:

1. Cost,
2. Manufacturability,
3. Design Performance,
4. Reliability,
5. Installation,
6. Customisation,
7. Durability.

Column A	Column B	Column C	Column D	Column E
Brainstorming	Define Value	Classification	Prioritisation	Key Value Attributes

Column A – Brainstorming

Column B – Define Value

No.	Value description
1	Cheaper possible manufacturing cost
2	No additional energy consumption
3	Maintenance free
4	Zero operational costs
5	Fastest possible manufacturing
6	Machining from very small to large scale
7	Shorter in length
8	Low complexity
9	Alignment of the tube (nozzle to the mixing tube)
10	Smooth surface inside the SJP (minimum friction)
11	Parametric relation between nozzle and diffuser
12	Adjustable nozzle
13	Meeting oil and gas standards from ASME B31.3, B16.5, ASME IX
14	Production rate performance
15	Possibility to connect to several wells
16	Reduced back pressure
17	No moving parts
18	Tolerant to pressures fluctuations
19	Lighter in weight
20	Noise level to be lower than 85dB
21	20 years lifecycle
22	Ability to handle Vibrations
23	Adjustable to different gases and fluids
24	Working conditions – temperature, pressure
25	Clog resistance
26	No leak
27	Not flammable
28	Easy to install
29	Can be installed in tight spaces
30	Minimum modification to existing pipework
31	Flexibility of sources orientation
32	Replaceable parts (nozzle, mixing tube) easy to change and install
33	Easy operation
34	Corrosion resistance
35	Erosion resistance
36	Stable in subsea environment
37	Strong type of material
38	Hard surface inside the SJP

Column C – Classification

No	Value Classification	No.
1	Cost	1, 2, 3, 4
2	Manufacturability	5, 6, 7, 8, 9, 10
3	Design Performance	11, 12, 13, 14, 15, 16, 17, 18, 19, 20
4	Reliability	21, 22, 23, 24, 25, 26, 27
5	Installation	28, 29, 30, 31
	Customisation	32, 33
6	Durability	34, 35, 36, 37, 38

7 Values

Column D – Prioritisation

AHP Matrix Analysis

No	Value	AHP Priority (%)	Priority
1	Cost	13.8%	3
2	Customisation	6.8%	6
3	Design Performance	22.3%	1
4	Manufacturability	21.6%	2
5	Reliability	15.7%	5
6	Durability	16.7%	4
7	Installation	3.1%	7

Column E – Key Value Attributes

Key Value Attributes	Load of importance
Design Performance	38.5%
Manufacturability	37.5%
Cost	24.0%

Values of consideration
Durability
Reliability
Customisation
Installation

Figure 6-21: Identification of key value attributes (Mohd Maulana *et al.*, 2016)

Classified values were prioritised in order to focus on improving the key characteristics of the product. The analytical hierarchy process (AHP) tool was used to prioritise the values and identify the KVAs. Results of the AHP are shown in Figure 6-21(Column D), and the following KVAs were identified:

1. **Design Performance**

   Determines the production rate of the SJP at constant initial conditions.
2. **Manufacturability**

   Relates to the complexity of the design and the required manufacturing process.
3. **Cost**

   Describes the manufacturing cost of the product.

The KVAs that were identified indicated that the focus of improvement should be on the following components: nozzle, mixing tube and body.

6.7.2.2 Step 2: Select previous projects of the similar SJP product

The company has 120 SJP products installed in different locations around the world. Most of them share a similar design. Due to the similarity of the design of the nozzle, the company provided data of one SJP to be the reference design.

6.7.2.3 Step 3: Identify feasible design area of the SJP

Due to limited access to the data from previous projects of Caltec, this step is not applicable in this case study.

6.7.2.4 Step 4: Generate a design-set for the SBCE process of the SJP

The research team developed a set of design solutions, as shown in Figure 6-22, by using the SBCE process model. As it was required by Caltec, the main focus was on three components of the SJP: nozzle, mixing tube and body.

Designs N1, MT1 and B1 in Figure 6-22 are the original designs of the SJP that was provided by Caltec. This original design was used in order to compare it with other designs in the following steps of this case study.

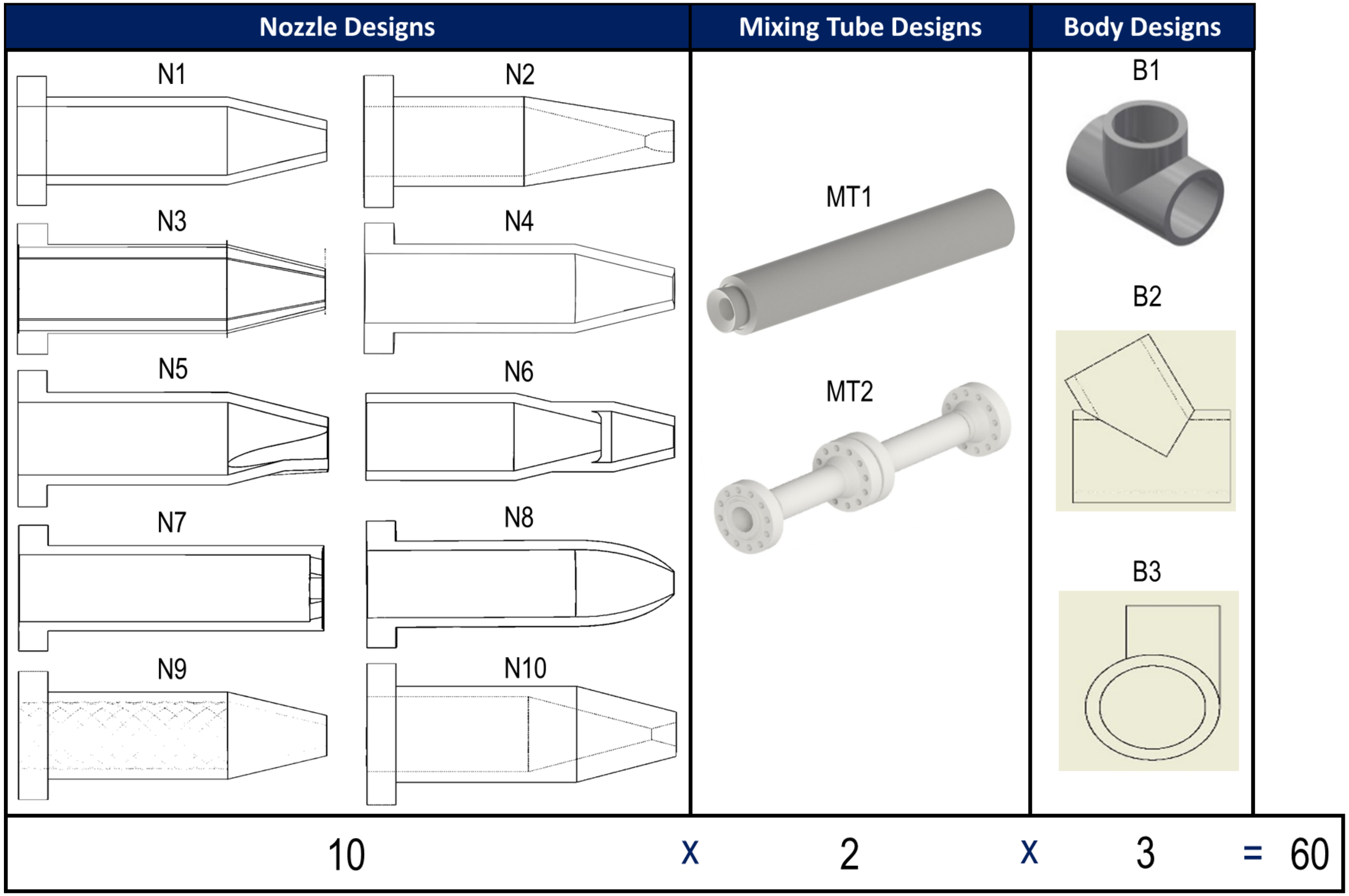


Figure 6-22: Design-set for key components of an SJP: Nozzle, mixing tube and body

As each type of nozzle can be combined with each type of mixing tube and body, there were 60 possible designs in the design-set (10 nozzles x 2 mixing tubes x 3 bodies = 60 possible designs). This design-set was then analysed and developed throughout the SBCE process model. Designs were compared and narrowed down by using physics-based ToCs.

6.7.2.5 Step 5: Compare and narrow down the design-set of SJP components

In order to start generating physics-based ToCs, the research team analysed the fundamental features and physical characteristics of an SJP. Figure 6-23 illustrates the relationships between different design parameters: HP velocity, HP pressure, LP velocity, LP pressure, combined HP and LP fluid velocity, and combined HP and LP fluid pressure.

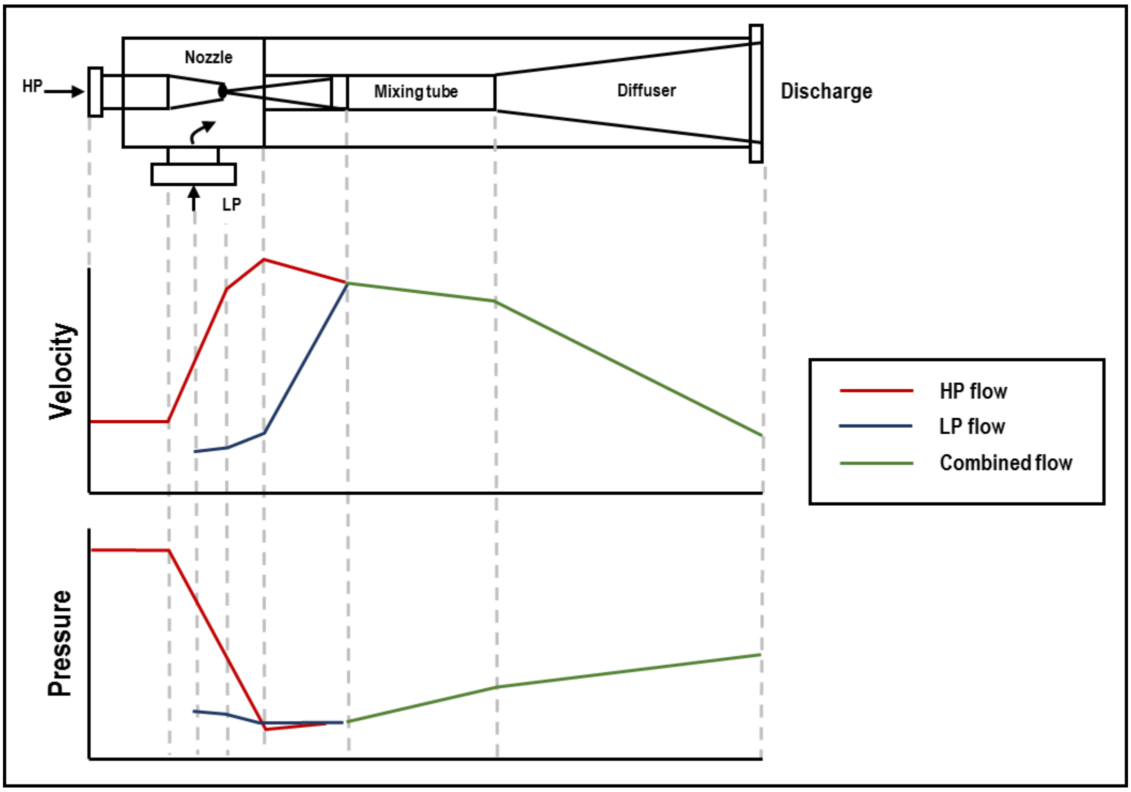


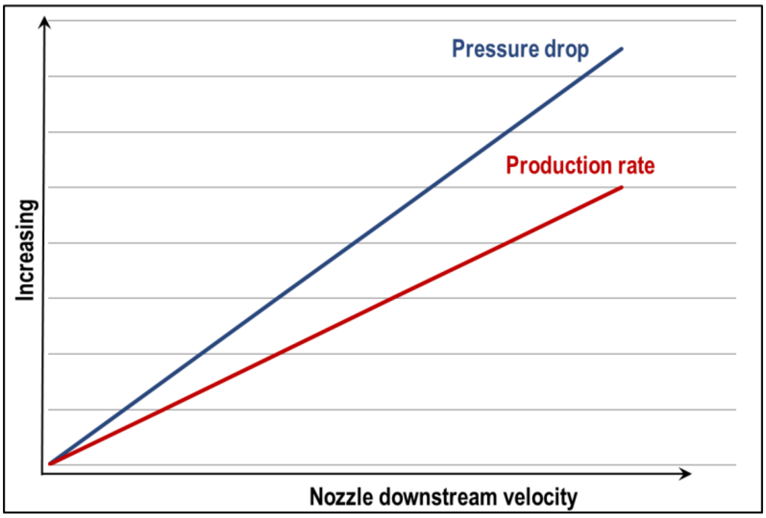
Figure 6-23: Schematic illustration of fundamental physics features of an SJP (Beg and Sarshar, 2014)

As shown in Figure 6-23, when the high-pressure fluid passes through the nozzle, its velocity increases significantly as the result of potential energy (pressure) being converted to kinetic energy (velocity). This reduces the downstream pressure from the nozzle and generates a low-pressure zone which causes the flow of the fluid from the LP well. The HP motive flow carries the LP fluid through the mixing tube, causing a transfer of energy and momentum between both fluid streams. At the outlet of the mixing tube, the mixture is discharged through the diffuser in order to gradually reduce the velocity and pressure recovery (Beg and Sarshar, 2009).

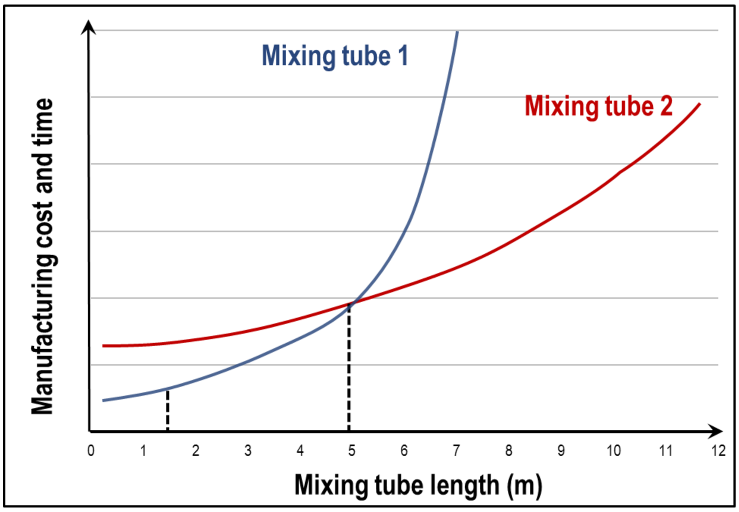
Using the obtained physics-knowledge as explained above, non-scale physics-based ToCs were generated for each component. These trade-off curves are presented in Figure 6-24:

1. **ToC 1** – Nozzle: Nozzle downstream velocity against pressure drop and production rate
2. **ToC 2** – Mixing tube: Mixing tube length vs. manufacturing cost and time
3. **ToC 3** – Body: Cost against manufacturing complexity, weldability, and allowable stress

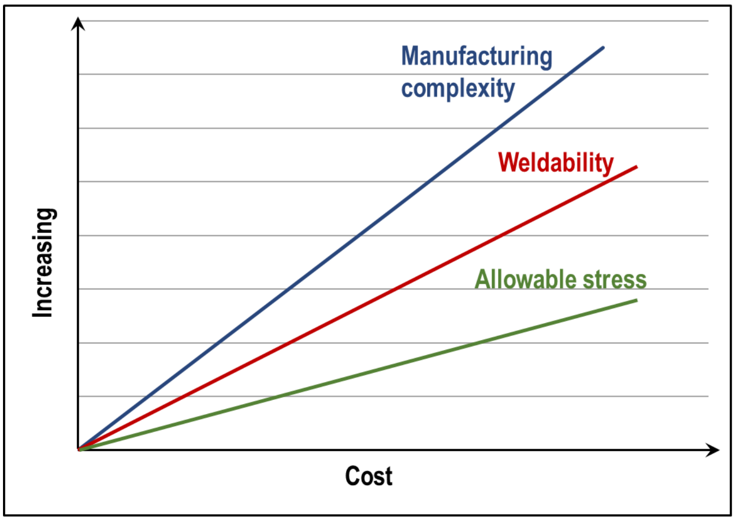
Figure 6-24(a) visualises that a higher nozzle downstream velocity increases the drop of the pressure and the suction of the entrained LP fluid. Thus, the production rate increases. Figure 6-24(b) shows that manufacturing cost and complexity of the mixing tube are determined by the body-length. Increasing the length beyond five meters (5m), however, will cause difficulties in manufacturing with the tools available at the current manufacturer. Therefore, the mixing tube would need to be cut in half and manufactured in two parts. MT2 is a design that is manufactured in two parts. Since the length of the mixing tube is required to be less than 5m by the customer in this case study, where the target value was 1.3m, design MT2 was eliminated. Figure 6-24(c) illustrates the physics-knowledge of the body component. It is apparent that different designs of the LP inlet affect the HP/LP pressure ratio, allowing to obtain the desired discharge pressure with less pressure from LP. Thus, design performance is increased. However, both manufacturing cost and complexity of the body increase significantly.



(a) ToC 1 - Nozzle



(b) ToC 2 - Mixing tube



(c) ToC 3 - Body

Figure 6-24: Non-scale physics-based ToCs for each key component of an SJP

Analysing these three non-scale physics-based ToCs for each component facilitated decision-making about the feasible solution for the mixing tube. After selection, ten nozzles, one mixing tube (MT1) and three bodies remained in the design-set. Multiplying the possible design solutions provided 30 possible configurations (10 nozzles x 1 mixing tube x 3 bodies = 30). For evaluating these possible designs and for further narrowing down, additional trade-off curves for each component were generated to help designers with the decision-making on the best designs among the design-set. Knowledge for these ToCs was obtained from both understanding the physics of the SJP and experience of the manufacturing supplier. Thus, knowledge-based data and physics-based data was presented in a single ToC.

1. Generating ToCs for comparing nozzle designs:

The design parameters for evaluation and comparison of nozzle designs were identified considering the KVAs and are listed below:

- Nozzle downstream velocity – (KVA: Design performance):

  Data for this design parameter was collected based on the physics of the product, considering the KVA of design performance. Autodesk inventor software was used for design modelling and Ansys software was used for CFD simulations. The results are represented as a three-dimensional trade-off curve in Figure 6-25. Input parameters were identified as shown in Table 6-18.

Input Parameters	Input Values
HP Flow rate	10.33 kg/s
Nozzle Outlet Pressure (Atmospheric)	196 psi
Nozzle inlet Temperature	88 °C
Properties of gas	Natural Gas
HP Molar Weight	24.89 kg/kmol
Specific Heat	2340 J/kg*K
Dynamic viscosity	1.03971 e-10 kg/m*s

Table 6-18: CFD analyses inputs

- Manufacturing complexity – (KVA: Manufacturability):

This design parameter was identified considering the KVA of manufacturability. The values of manufacturing complexity were scaled from 1 to 5. Table 6-19 provides the basis of this scale. Data for manufacturing complexity was collected from a manufacturing supplier of the collaborating company (Reddecliffe, G., Works Manager, Woodfield Systems Ltd, personal communication, August 2016). Results are presented in Table 6-20.

	Manufacturing complexity scale
1	**No** changes of manufacturing method and operations
2	**Low** - Slight changes of geometry, arrangement, assembly required additional operation(s)
3	**Medium** - Major changes of geometry, arrangement, assembly required new machining operations
4	**High** - changed subsystem design, required new technology and/operations/prototyping
5	**Very high** - Changed subsystem design, required complex machining operations/new technology and prototyping

Table 6-19: Manufacturing complexity scale

- Manufacturing cost – (KVA: Cost Efficiency):

This design parameter was identified considering the KVA of cost efficiency. The values of manufacturing cost were scaled from 1 to 5. In this scale, 1 represents low cost and 5 represents high cost. Data for manufacturing cost was collected from the manufacturing supplier (Reddecliffe, G., Works Manager, Woodfield Systems Ltd, personal communication, August 2016). Results are presented in Table 6-20.

Design code	Manufacturing cost (1-5)	Manufacturing complexity (1-5)	Velocity (m/s) (CFD)
N1	1	1	485.187
N2	2	3	834.252
N3	3	4	429.3
N4	1	1	546.56
N5	4	4	255.094
N6	3	5	494.994
N7	1	2	194.681
N8	5	5	593.586
N9	2	2	500.2
N10	2	2	772.627

Table 6-20: Data collected for each of the nozzle designs

Figure 6-25 illustrates a three-dimensional trade-off curve, which was generated by using the data collected from understanding the physics as well as from the manufacturing supplier's experience and knowledge.

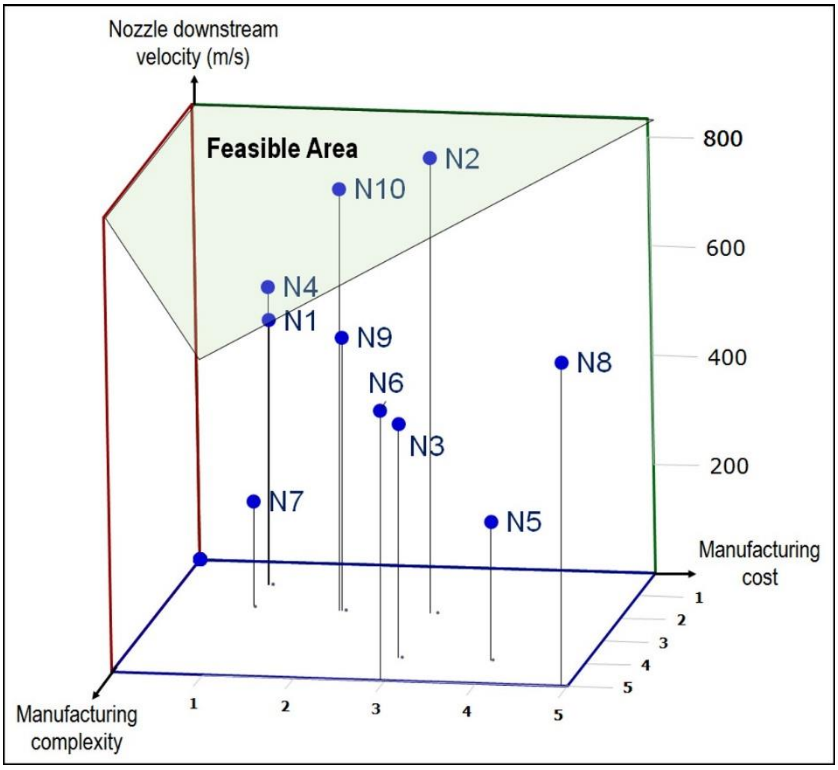


Figure 6-25: Three-dimensional ToC based on physics and knowledge of the nozzle

Following the evaluation and comparison of nozzle designs in Figure 6-25, it is apparent that N3, N5, N6 and N8 have high manufacturing cost and complexity, while the velocity is even lower than the original design N1. Therefore, these four designs were eliminated from the design-set of the nozzle. Although N7 shows sufficient performance in manufacturing cost and complexity, the velocity is low when compared to other design solutions. Thus, N7 was also eliminated. N9 was another design to be eliminated as the design performance was lower than N1. The final output of this evaluation showed that N2, N4 and N10 are designs that have the potential to meet the key value attributes.

2. Generating ToCs for comparing mixing tube designs:

There was only one mixing tube, which is the original design, MT1. Therefore, MT1 was retained in the design-set for further narrowing down.

3. Generating ToCs for comparing body designs:

The design parameters for evaluation and comparison of body designs were identified considering the KVAs as listed below:

- HP/LP pressure ratio – (KVA: design performance):

  Data for this design parameter was collected based on understanding the physics of the product. Ansys software was used for CFD simulations to collect data. The results are presented in Figure 6-26. A higher ratio value means maintaining the same discharge pressure while using less LP pressure, and therefore higher performance of the design.
- Manufacturing cost and complexity – (KVA: Manufacturability and Cost Efficiency):

  This design parameter was identified considering the KVAs of manufacturability, and cost efficiency. The values were scaled from 1 to 5. Data was collected from the manufacturing supplier of Caltec (Reddecliffe, G., Works Manager, Woodfield Systems Ltd, personal communication, August 2016). A scale was provided separately for manufacturing cost and manufacturing complexity of the body designs. The average value of the scales for each body design are illustrated in Figure 6-26.

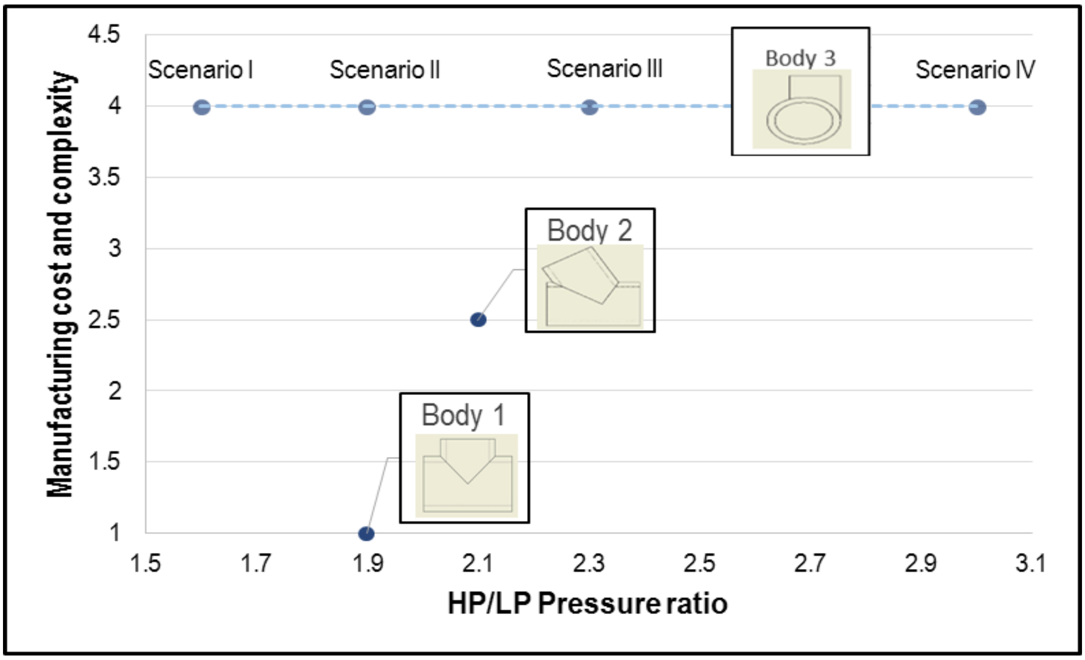


Figure 6-26: Physics-based and knowledge-based ToCs for evaluation and comparison of body designs

Figure 6-26 shows a two-dimensional trade-off curve that represents data of physics on the X axis and data of experience on the Y axis. Due to resource constraints, only body 1 and body 2 were simulated using CFD software. For the design of body 3, four ranges of the HP/LP ratio values were considered:

1. HP/LP < 1.9 – lower than the original (body 1) design,
2. HP/LP = 1.9 – equal to the original design,
3. HP/LP > 1.9 – higher than the original design,
4. HP/LP >> 1.9 – significantly higher than body 1.

As shown in Figure 6-26, Body 2 shows a higher performance than the original design (Body 1), however, it has higher manufacturing cost and complexity. On the other hand, Body 3 has the highest manufacturing cost and complexity. Thus, its HP/LP ratio must present the highest value and a significant improvement compared to other body designs in order to be considered as a feasible design. In this case study, body 3 was excluded from the design-set due to its high cost and manufacturing complexity. However, it is suggested that this design should be considered in the future.

As a result of comparing and narrowing down the design-set at the component/subsystem level, the new design-set consists of eight possible design configurations to be evaluated throughout the SBCE application (4 nozzles x 1 mixing tube x 2 bodies).

6.7.2.6 Step 6: Compare and narrow down the design-set of SJP converged systems

The research team needed to generate more ToCs in order to evaluate eight design configurations on the system level. The following design parameters were identified based on the knowledge obtained during earlier project stages:

- Inlet LP pressure,
- Inlet HP pressure,
- HP/LP pressure ratio.

Data for these design parameters was collected from CFD simulations, and results are presented in Table 6-21. Subsequently, a physics-based trade-off curve was generated, as shown in Figure 6-27, for enabling the comparison and evaluation of design configurations on the system level.

No.	Design Configuration	Inlet HP Pressure [psig]	Inlet LP Pressure [psig]	HP/LP Pressure Ratio
Design A	N1+MT1+B1	550.22	283.34	1.9
Design B	N1+MT1+B2	552.25	263.8	2.1
Design C	N2+MT1+B1	2343.37	169.73	13.8
Design D	N2+MT1+B2	2377.57	164.71	14.4
Design E	N4+MT1+B1	464.71	341.55	1.4
Design F	N4+MT1+B2	464.5	341.74	1.4
Design G	N10+MT1+B1	2466.93	170.63	14.5
Design H	N10+MT1+B2	2665.25	170.75	15.6

Table 6-21: CFD simulation results of each design configuration

Figure 6-27 shows that design configurations with Body 2 (B2) provide similar performance as design configurations with Body 1 (B1). For example, the difference between HP pressure of Design E and F is only 0.21psig, which does not have a significant impact on design performance. Nevertheless, it was previously found in Figure 6-26 that B2 had a higher manufacturing complexity and cost compared to B1. Therefore, the research team decided to eliminate design configurations with B2 from the design-set. Additionally, Design A also was removed from the design-set since it is identical to the existing product. Thus, there were three designs remained to be evaluated in order to achieve the optimal design solution: Design C, Design E, and Design G.

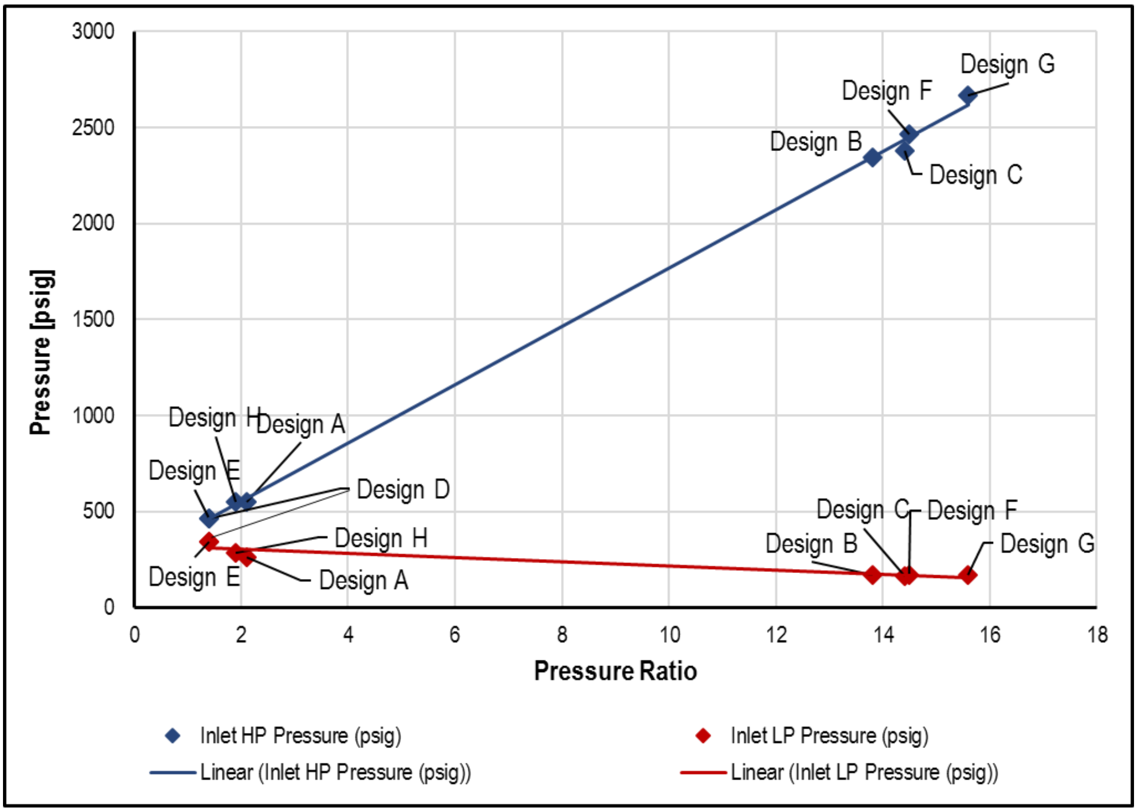


Figure 6-27: Physics-based ToCs on the system level

6.7.2.7 Step 7: Achieve an optimal design solution

In order to achieve an optimal design from the design-set, the research team generated another trade-off curve that presents the performance of design configurations according to the KVAs.

- Discharge pressure – (KVA: Design Performance):

  A higher discharge pressure reflects a higher design performance. Data for discharge pressure was obtained through CFD simulations.

- Manufacturing complexity and cost – (KVAs: Manufacturability and Cost):

  Lower values of this design parameter are required to achieve a simple and cost efficient product, which at the same time features a high design performance. Design configurations consist of the same mixing tube (MT1) and body (B1). Only nozzle designs are different in each design configuration of the narrowed down design-set. Therefore, data was reused from Table 6-20 by calculating the average value of manufacturing complexity and manufacturing cost of the nozzle designs. For example, the manufacturing cost for N2 is “2” while the manufacturing complexity is “3”, which means the average value is “2.5”.

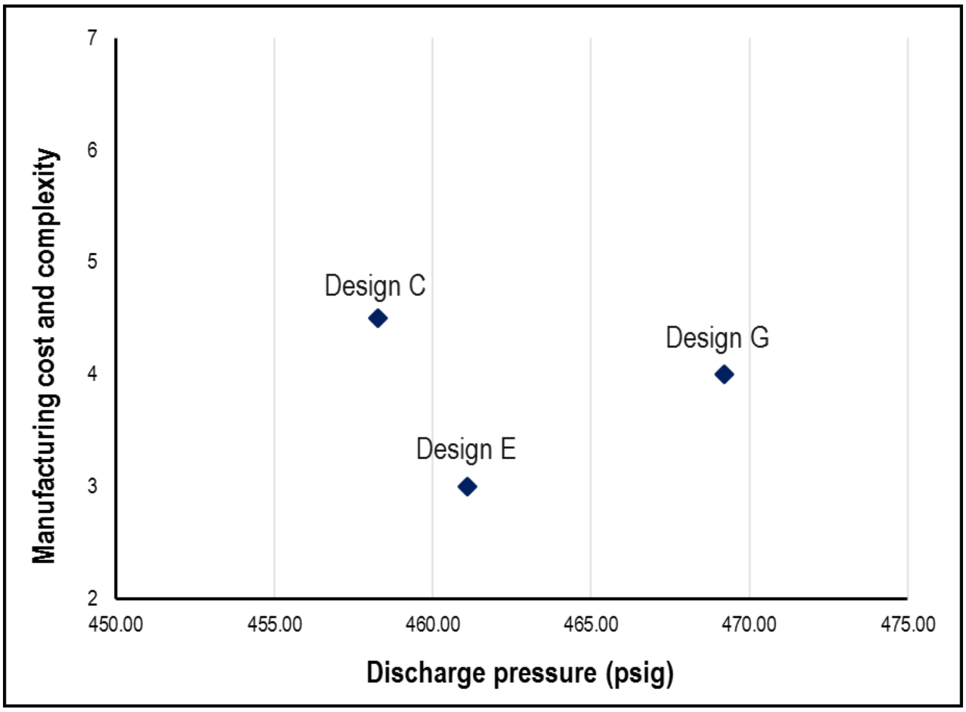


Figure 6-28: Knowledge-based and physics-based ToC to achieve the optimal design

Following the evaluation and comparison of these three designs as shown in Figure 6-28, it was identified that Design G is the best design configuration in the design-set. Table 6-22 describes the evaluation of each design.

Design	Decision	Rationale
Design C	Eliminated	Although there is but a slight difference between the discharge pressure of Design C and Design E, the manufacturing cost and complexity of Design C is higher than Design E.
Design E	Eliminated	Design E shows a reasonable performance in discharge pressure and has the lowest manufacturing cost and complexity. However, HP and LP pressures are significantly lower than Design C and Design G as shown in Figure 6-27.
Design G	Selected	Design G shows the best performance compared to Design C and E and has a reasonable manufacturing cost and complexity value. Figure 6-27 also presents that Design G has better values in HP and LP pressures and HP/LP pressure ratio.

Table 6-22: Decisions made for the selection of optimal design

Eventually, it was determined that Design G fully meets the KVAs of design performance, manufacturability and cost. Figure 6-29 illustrates a technical drawing, measurements of which are removed due to confidentiality. This final optimal solution showed a better performance than the existing product. Although the manufacturing cost and complexity stayed the same, the design performance increased by around 60% (refer to Mohd Maulana *et al.*, 2017 for further details).

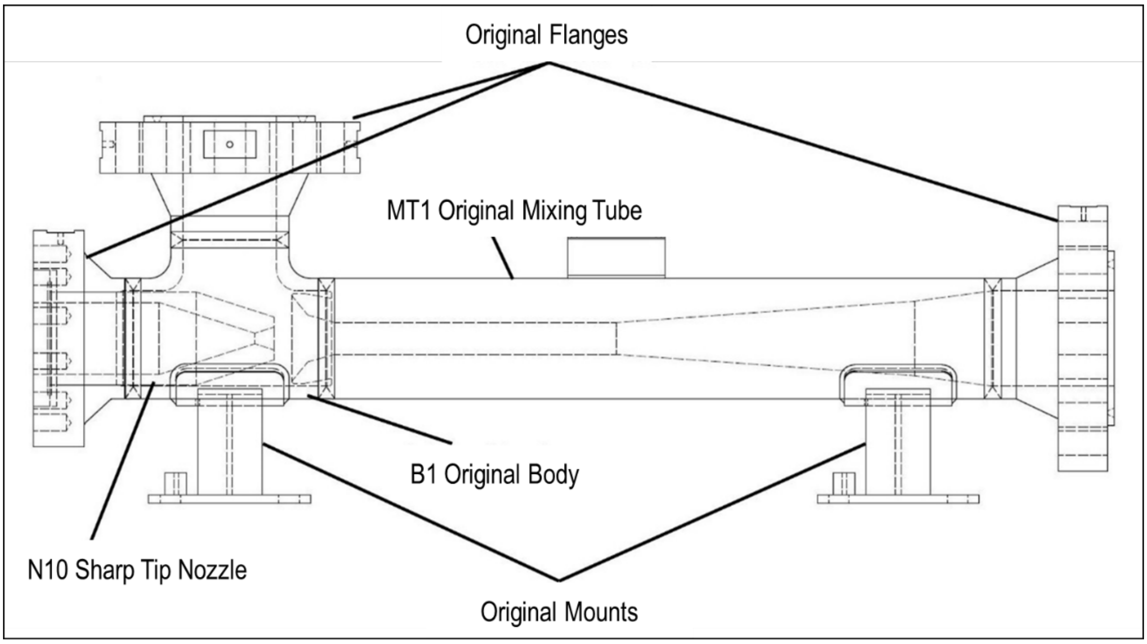


Figure 6-29: Technical drawing of the final optimal design of the SJP

6.7.3 Debriefing of the case study

Knowledge-based and physics-based ToCs were generated to support achieving an optimal design of a new surface jet pump while proceeding through the SBCE process model. The research team developed a design-set consisting of 60 possible designs. As a result of comparing and narrowing down this design-set on the component level, initially 30 and then eight possible configurations were selected for further development in SBCE. Selected eight designs were evaluated on the system level, and five designs were eliminated from the design-set. Finally, the remaining three designs were evaluated in order to achieve an optimal design. As a result, the configuration of N10, MT1 and B1 was selected as the optimal design, and presented in Figure 6-29. The design performance of this optimal design increased by nearly 60%.

6.8 Industrial Expert Judgement

Expert opinions on the processes, which were developed for the generation and application of ToCs, were captured and documented in this section. Two experts, who have specialised in product development and each have several years of experience, were identified to capture their feedback and comments on the following processes:

1. The process for generating knowledge-based ToCs (section 5.3)
2. The process for generating physics-based ToCs (section 5.4)
3. The process for using the generated ToCs in the SBCE process model (section 5.5)

These three processes are subsequently referred to as “the processes” in order to facilitate a clear flow of this section. For the same reason, and to aid confidentiality, the masculine form has been chosen to refer to all experts.

Each expert judgement session commenced with a brief definition and overview of trade-off curves, as described in section 3.2.1. Thereafter, the proposed processes, as listed above, were explained briefly. After the presentation, questions were asked of the experts in order to incentivise a discussion. During the discussion, feedback and comments from the experts were received and captured. In order to facilitate a constructive and results-oriented session, a semi-structured questionnaire was developed as presented in Appendix D.

Expert 1 is a technology director in Caltec, with more than 20 years of experience in the field of petroleum engineering, multiphase flow metering, surface jet pump and separation technology. The expert is holding a number of patents and has authored and co-authored numerous technical papers in his area of expertise. He has also won national and international awards for innovation.

Expert 2 is a retired former director of the research and development department of Rolls-Royce with decades of experience in aviation industry. Presently, he is a professor and continues to work in the area as a special advisor.

The following subsections present the documented expert judgements.

6.8.1 Expert Judgement 1

Expert 1 was asked to comment regarding the structure of the processes. He found the processes easy to understand and follow, and also well-structured. He indicated that his company had always carried out similar activities based on personal experience, but not systematically. Therefore, he appreciated having a systematic process for knowledge creation and visualisation as described in chapter 5. On the other hand, regarding the level of detail in the processes, his opinion was that when one looks at the process, they might think that the processes appear to be overlapping or to be having too many steps and activities. However, according to expert 1, when one starts applying a process, detailed guidance may initially be required. Later on, some of the activities can be removed depending on the need of the designers. Having said that, he expressed that this detailed process would be helpful for capturing the main decision point and would provide a guidance to collecting data.

In terms of the practicability aspect of the processes, the expert expressed his opinion as below:

“I am impressed. You turned such a complex method into a fairly streamlined approach.”

Furthermore, the expert said that he would consider using these processes in his company, as they present a systematic way to speed up the product development and a solution that they are looking for. Since, in his opinion, the patience of staff in R&D is generally very low, he thinks that such a documented process would support them by reducing the time spent on designing. Therefore, the expert thinks that the processes do not seem difficult to implement in a company, as long as they are incorporated with the existing quality management systems of the company, which seems quite possible.

Regarding the knowledge creation and visualisation using ToCs, expert 1 thinks that the processes are very valuable by referring to the saying “a picture paints a thousand words”. Additionally, he believes that having such well-structured processes provides the practitioners with more control throughout the product development process.

The expert added an important point to the effect that trade-off curves can also be considered in the concept of environmental quality management systems. ToCs focus on optimising the design parameters in order to eliminate waste, which indirectly affects the environment.

6.8.2 Expert Judgement 2

The expert thinks that customer needs should be explored, however, innovative companies should also stimulate customer needs. Since the customer sometimes does not know what they really want, there should be an action taken to develop innovative products. Therefore, it was discussed that defining decision criteria before generating trade-off curves provides the designers and engineers with an environment where they can explore the opportunities of innovative designs by using their creativeness. Furthermore, understanding the physics of the product could also help with identifying the customer value. However, the expert suggested that before the final decision is made, the possible designs should be dialogued with the customer. The advantages of ToCs in facilitating communication with different stakeholders can be used in this dialogue.

The expert asked how the proposed processes handle uncertainty in terms of data accuracy, measurement accuracy and other uncertainty, particularly while turning non-scale ToCs into scaled physics-based ToCs. Additionally, he pointed out the fact that in real life, it is not possible to always get a complete data set. In order to address these issues, the process for generating knowledge-based ToCs provides the step of data collection as described in sub-subsection 5.3.2. In case of missing data in the dataset, the process suggests taking actions such as filtering and refining data and preparing the dataset for generating ToCs. The suggestion of expert 2 was to make assumptions around those missing data in order to get a full dataset. Thus, math-based ToCs, as described in sub-subsection 3.2.3.1, could be a part of the knowledge-based ToCs. Due to the scope of this PhD research, the expert's suggestion is considered to be a viable future work by the author: Different types of ToCs, math-based, knowledge-based and physics-based, could be combined in only one ToC.

Regarding the structure of the processes, the expert thinks that the steps and activities of the processes are in a logical order, and easy to understand and follow. Moreover, he thinks that the processes are very applicable. On the other hand, he stated his opinion that knowledge-based and physics-based ToCs are an *additional* tool to the traditional approaches for decision-making, not necessarily an *alternative* tool. They can be used alongside the other prototyping processes.

In terms of the processes being difficult to implement and the time required, he thinks that it depends on the simplicity of the product. The more complex the product, the more depth the designers may require. For a basic product, not as many iterations might be needed as for a complex product, such as an aircraft engine.

The expert thinks that knowledge creation and visualisation in the form of ToCs is very important. Especially in the beginning of a big project, having ToCs can facilitate the communication between the members of a large product development team. The chief engineer can use them to visualise the trade-offs and targets. In case of the targets or customer requirements changing throughout the product development process, the chief engineer can always refer back to the generated ToCs, identify the new compromise and communicate it with the team members. Therefore, the expert thinks that having knowledge displayed in ToCs will facilitate the understanding of the current project among the team members.

On the other hand, the expert thinks that to a certain extent trade-off curves with slightly different names and dimensions have been used in the past, so it is not totally a new approach. However, the combination of the knowledge-based and physics-based ToCs proposed by the author is seen as a crucial contribution to the product development process.

6.9 Summary of Chapter 6

This chapter presented five industrial case studies in which knowledge-based and physics-based ToCs were used to create a knowledge-environment. It was also demonstrated that ToCs can support key activities of the SBCE process model, as well as decision-making and communication. Results of each industrial case study are discussed in section 7.2. Finally, the opinions of experts, each of whom has more than 20 years-experience in the subject area, were presented.

7 DISCUSSION, CONCLUSIONS AND FUTURE WORK

7.1 Introduction

This chapter, as is illustrated in Figure 7-1, summarises the research conducted for this PhD thesis. Section 7.2 discusses the results obtained from the literature review, industrial field study, industrial case studies and expert judgements. Research limitations are presented in section 7.3, and contributions of this thesis to the knowledge are provided in section 7.4. Implications, conclusions and future work are detailed in sections 7.5, 7.6 and 7.7, respectively.

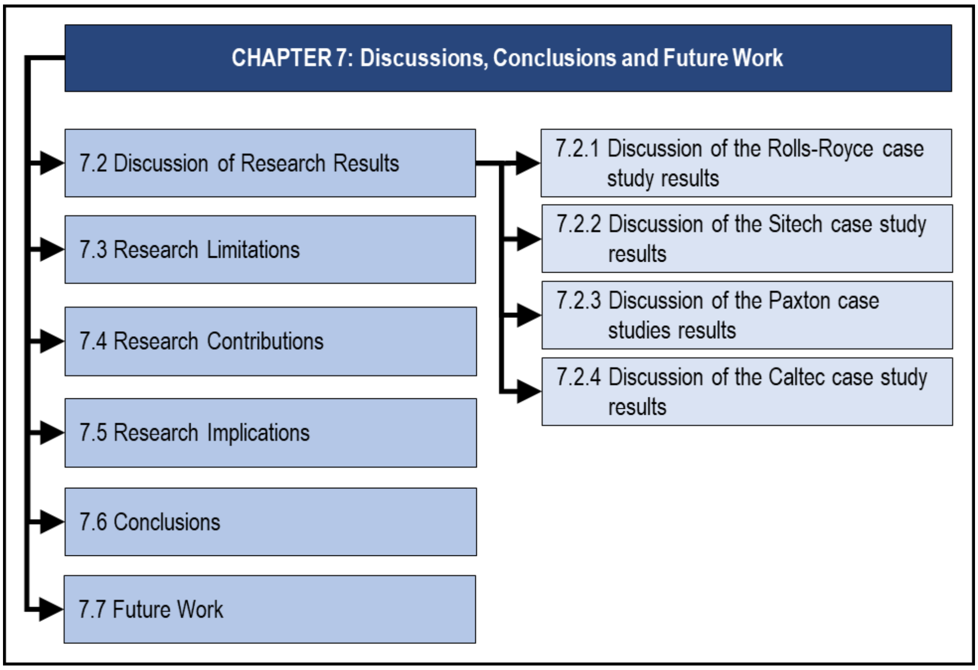


Figure 7-1: Structure of chapter 7

7.2 Discussion of Research Results

Research results indicated that the questions identified in section 1.3 have been addressed. This section provides the discussions of the findings of this research. Reviewing the related literature showed that there is a need for a knowledge-environment to be used throughout the set-based concurrent engineering process. It is a core enabler of the lean product and process development model. Scholars, academics and practitioners indicate that trade-off curves are considered to be useful tools in order to provide this knowledge-environment, and thereby enable SBCE applications. However, it was found that trade-off curves mentioned in the literature were commonly generated by using the data from mathematical equations and formulas. Such trade-off curves are referred to as math-based ToCs in this thesis. Differences and characteristics between different types of ToCs are outlined in section 3.2.3.

SBCE requires a reliable knowledge-environment that is created from already existing knowledge. The knowledge-environment ensures that designers do not *“reinvent the wheel”,* but simply reuse the existing knowledge. This reduces the resources required during the new product development process. Therefore, knowledge-based ToCs are preferred by academics and practitioners. However, the definition of such ToCs was not previously clearly stated. The author critically aggregated the available definitions in the literature and proposed a new, detailed definition which is described in subsection 3.2.1. However, how to generate such trade-off curves was a question that remained to be addressed. Although there were initiatives in generating ToCs that enable SBCE, a systematic approach or process was not described in the literature. Therefore, the author addressed this gap by developing a process for generating knowledge-based ToCs that enable SBCE applications, which is described in detail in section 5.3.

Furthermore, the role of knowledge-based ToCs within the SBCE environment was not clearly explained in the literature. It remained unidentified, for example, which activities of SBCE can be enabled by using knowledge-based ToCs. In order to clarify how to use knowledge-based ToCs to enable SBCE applications, the author compiled the information from several journal papers that are published in the related subject area. The results are presented in section 3.3. They suggest that ToCs can be applied in order to identify the feasible design area and to develop a design-set for trading off and narrowing down, until achieving an optimal design solution within the SBCE process model. In this context, the author developed a systematic process for using generated ToCs within the SBCE environment. This process facilitates ToC applications for practitioners, and is described in section 5.5.

From interactions with industrial collaborators and interviews using a semi-structured questionnaire, the need emerged to generate an understanding of the physics of the product under development. According to the practitioners, this understanding can reduce the resources required during the product development process significantly. Although representing the physics knowledge is important for the practitioners, it was obvious that the literature did not address this need. Therefore, the author developed a process for generating physics-based ToCs that enable SBCE applications. This process is described in section 5.4.

The following sections discuss the results of the case studies, which are presented in chapter 6.

7.2.1 Discussion of the Rolls-Royce case study results

The implementation of the initial version of the process for generating ToCs, which is shown in Figure 5-2, helped the author to improve the process in numerous areas. These are described below:

1. The first step “1. Define decision criteria” required explanation in more detail, in order to guide the designers on how to identify design parameters and how to relate these design parameters to each other. Thus, designers can start collecting data to be plotted against the ToCs.
2. Customer requirements should be obtained at the beginning of the process. This enables designers to understand the requirements upfront, and to define decision criteria accordingly. Thus, it is ensured that any optimal design actually fully addresses the customer’s needs.
3. The process activities are categorised into steps in order to facilitate a smooth flow throughout the process.
4. Activities are described within each step in order to guide designers along a systematic approach to creating ToCs.

The focused product of this case study was a turbofan jet engine. Since it consists of thousands of components, turbofan engine is considered as a high complexity product. During the case study, it was understood that ToCs can be generated even for visualising the conflicting design parameters of a high complexity product. However, the need for physics knowledge emerged in this case study, as it helps designers in dealing with the conflicts between design parameters. Furthermore, for high complexity products, generating ToCs in a multidimensional form appears to be helpful for designers, in order to see several conflicting design parameters in a single diagram and find the balance between them.

7.2.2 Discussion of the SiTech case study results

The case study of a passenger car seat structure presented that ToCs can be used as a decision support tool, while enabling the SBCE process model. Figure 7-2 illustrates the overall approach, step-by-step, which was used in this industrial case study.

After the definition of the decision criteria, a trade-off curve was generated, by using data collected from material providers, in order to select an appropriate material that could meet durability, cost and weight requirements. Two materials, Material 2 and Material 3, were selected as suitable solutions from feasible areas of the generated knowledge-based ToCs. Identifying the feasible area is one of the key activities of SBCE. It was found that ToCs are suitable tools to complete this activity, as well as to develop a set of design solutions. In the case study, ToCs enabled the evaluation of a design-set consisting of 15 previous designs. The data of these designs was visually displayed in order to compare the possible designs (ToC 2, Figure 6-8). It was understood that ToCs are able to support communication within the organisation, since the knowledge is represented in a visual manner. Additionally, ToCs facilitate the presentation of the relations between conflicting design parameters, hence the designers can eliminate the design solutions that are showing lower performance than others. Thus, the design-set is narrowed down.

After narrowing down, there were four conceptual designs that met the identified decision criteria. However, in order to select the best design, ToC 3 (Figure 6-9) was generated, which represented the knowledge for decision-making based on durability and weight. Finally, Design 8 was selected hypothetically as the final optimal design since it satisfied all customer requirements and decision criteria.

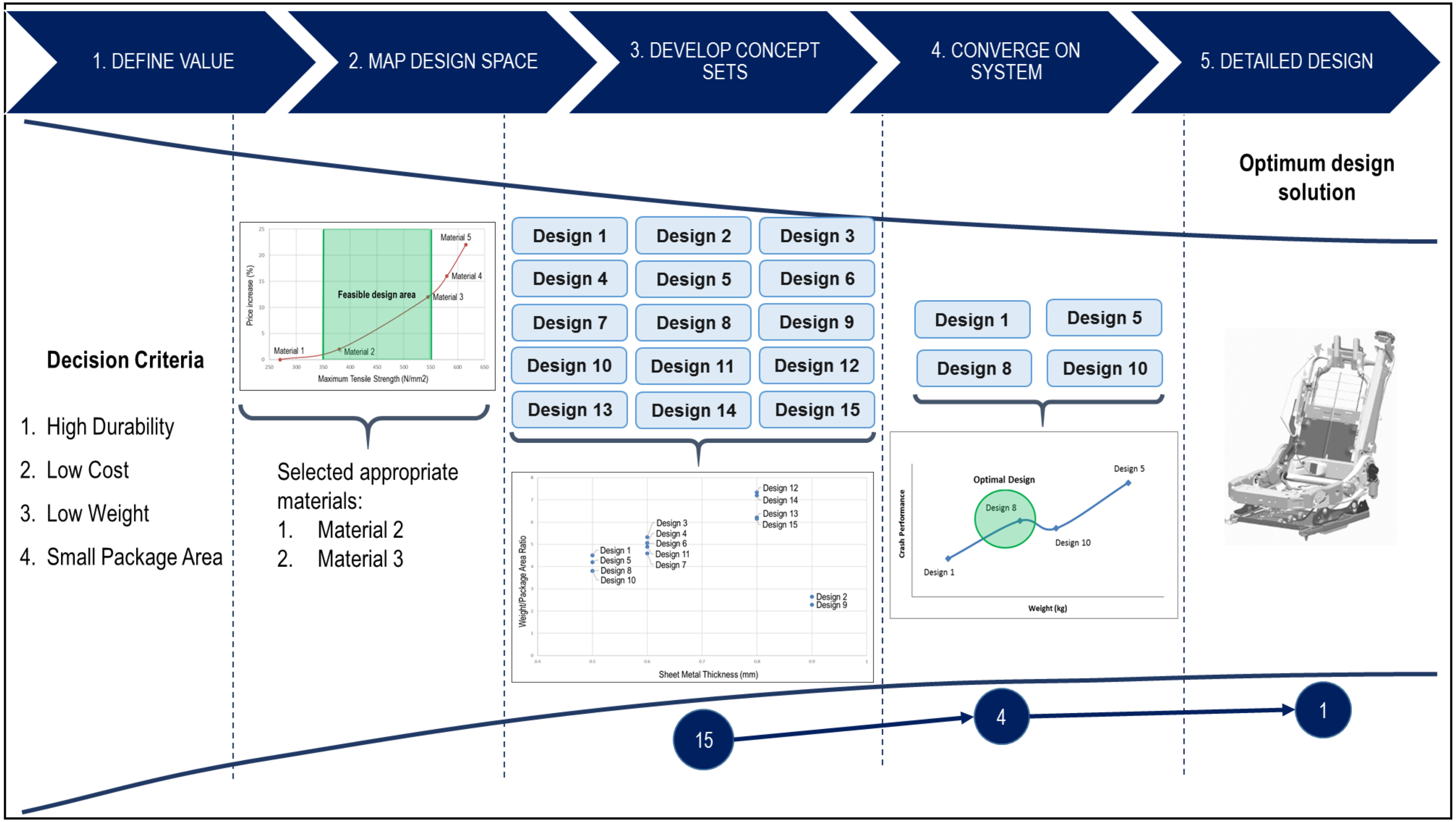


Figure 7-2: Overall approach to generating knowledge-based ToCs for the SBCE of the seat structure

The SiTech case study describes how to generate ToCs, as well as how to use the generated ToCs to enable the SBCE process. However, it was found that the activities of comparing and narrowing down should be explained in more detail, and that physics knowledge should be obtained for an accurate decision-making process that achieves the optimal design. Furthermore, it shows that the knowledge stored in ToCs can be reused in future projects; hence preserving the useful knowledge and saving resources during future design cycles.

This case study provided insights for improving the process for generating knowledge-based ToCs, and created awareness of the need for an understanding of the physical characteristics of the product under development. As a result of this case study, the process for generating knowledge-based ToCs was improved and validated by an industrial case study, which is presented in section 6.5. Additionally, since the need for understanding the physics of the product emerged, the author developed the process for generating physics-based ToCs, which was described in 5.4 and then validated by an industrial case study as shown in section 6.6.

7.2.3 Discussion of the Paxton case studies results

There were two case studies related to the development of a new card reader that is resistant to vandalism. The results of these case studies, as presented in sections 6.5 and 6.6, are discussed in this subsection. Figure 7-3 presents an overall view of the results of these two case studies.

As shown in Figure 7-3, the decision criteria were identified considering customer requirements, and data representing the design parameters was collected from previous projects of the company. It was noticed that the data collection period was tedious and time consuming. The collaborating company established that they were discarding the reusable knowledge from previous projects, which has a considerable value in making decisions for current and future projects. Therefore, initiating the process for generating ToCs in the company created an awareness of the importance of storing relevant data of previous products. Additionally, having a systematic data system might help designers and engineers to retrieve the required data quickly. However, once knowledge-based ToCs are generated, the data can also be stored in the form of trade-off curves.

Knowledge-based ToCs generated in section 6.5 helped the research team to develop a new design-set inspired by the identified feasible design solutions from previous projects. Knowledge-based ToCs, shown in Figure 6-15, provided data for the research team to reuse for developing conceptual design solutions. In order to evaluate, compare and narrow down the developed design-set, further information about the product was required. The process for generating physics-based ToCs, as described in section 5.4, provided guidance to the research team that an understanding of the physics of the product was required. The knowledge obtained of the physics of the card reader helped to generate a non-scale, physics-based ToC as shown in Figure 6-18. Consequently, it was understood that non-scale physics-based ToCs are helpful for understanding the physical characteristics of the product, and communicating the conflicting relations between the design parameters.

After comparing and narrowing down the design-set, six conceptual designs were selected as they had potential to meet the decision criteria of durability, reliability and cost efficiency. In order to evaluate these six conceptual designs and select the most appropriate ones, physics-based trade-off curves were generated as shown in Figure 6-19. The author compared these selected designs to each other in order to extract the solutions that showed higher performance than the others. It was thus understood that conceptual design A5 could be reused without applying modifications to the design while selecting the optimal solution.

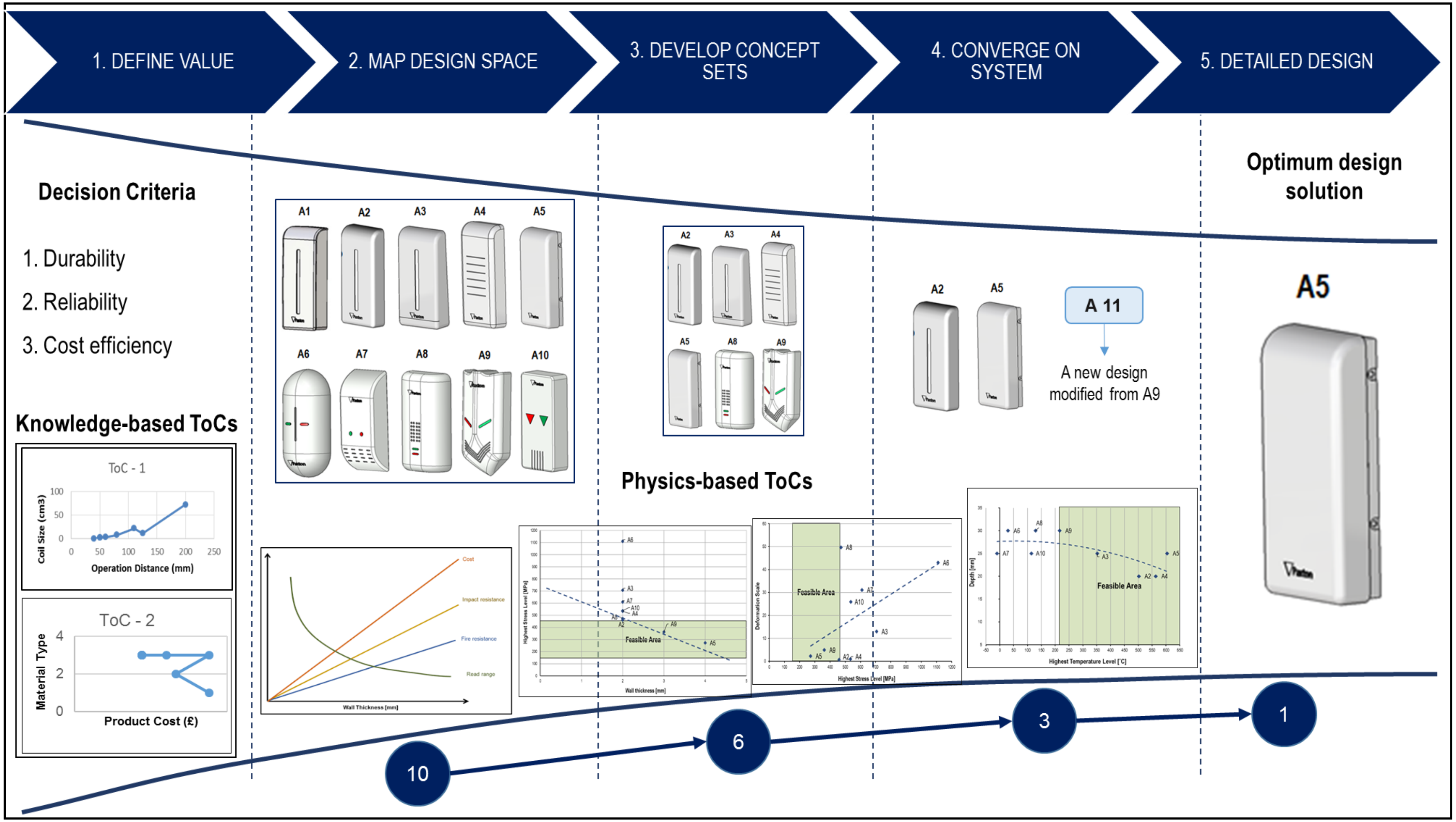


Figure 7-3: Overall view of the SBCE process for a card reader using knowledge-based and physics-based ToCs

Moreover, the data of conceptual designs A2 and A9 showed a good performance in meeting some decision criteria, but minor modifications were needed in order to fully address all decision criteria and customer requirements.

Finally, three conceptual designs remained in the design-set for further development. By using the Pugh matrix method at the last stage of SBCE process model, the research team decided that the conceptual design A5 was the optimal solution for the current project. However, the Pugh matrix provided a subjective manner of evaluating the design-set. The need emerged for an objective tool for creating the knowledge-environment, in order to achieve the optimal solution. Therefore, the author developed the process for using the generated ToCs in the SBCE process model as shown in Figure 5-8. The next subsection discusses the results of applying this process to developing a new surface jet pump.

7.2.4 Discussion of Caltec case study results

The Caltec case study showed the utilisation of generated knowledge-based and physics-based ToCs through the SBCE process model to support achieving the optimal design solution in an objective manner. Figure 7-4 illustrates an overall view of the SBCE for the surface jet pump. Understanding the physics of the product helped the design team to develop a design-set. 60 possible conceptual designs were generated, as shown in Figure 6-22. Non-scale physics-based ToCs were generated for each component (Figure 6-24) with data collected from understanding the physics of the product as well as the experience of the collaborating company's manufacturing suppliers. The ToC in Figure 6-18(b) for the mixing tube component supported the research team in making a decision on eliminating the conceptual design MT2. This decision was made without testing and prototyping, which shows how ToCs are contributing to saving resources such as time and cost. Similarly, conceptual design B3 was eliminated from the design-set using the ToC in Figure 6-26. Its manufacturing cost and complexity were much higher than the other two body designs (B1 and B2). However, it was

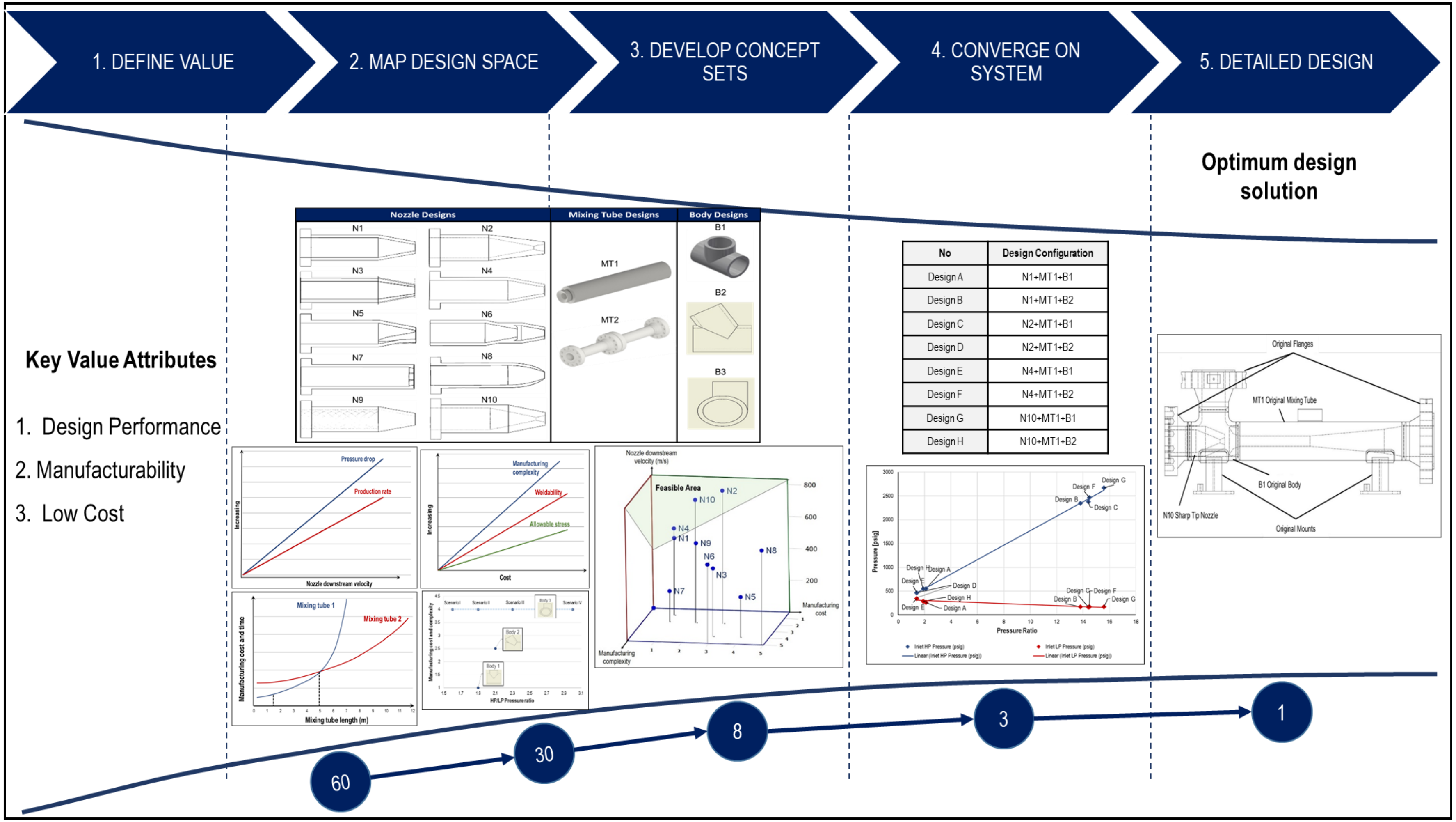


Figure 7-4: Overall view of the SBCE process for a surface jet pump using knowledge-based and physics-based ToCs

found that B3 can be reused in future projects if they require the length of the body to be above 5m. In such cases, data of B3 will be useful for designers. This particular incident shows that ToCs have the capability of knowledge creation.

Evaluating the set of 60 alternative design solutions using a traditional approach would have been very resource intensive. The application of knowledge-based and physics-based ToCs allowed the gradual narrowing down of the design-set in a considerably short period of time. Thus, it enabled a significant enhancement of the product development process, compared to its previous performance, by considering different design solutions in parallel. Additionally, generated trade-off curves saved a significant amount of resources by providing sufficient knowledge for the research team to make their decisions. Furthermore, the need for prototyping was eliminated through the use of both knowledge-based and physics-based ToCs. The design performance of the selected optimal design increased by nearly 60%. This case study also showed how to generate ToCs not only on the component level, but also on the system level.

7.3 Research Limitations

As it is very common in a research environment, six limitations were encountered throughout this thesis. These research limitations are listed below:

1. **The scope of the research**

   There are several product development approaches and processes in the literature, for example:

   - Tollgate systems,
   - Global product development,
   - Concurrent engineering,
   - Design for six sigma.

   SBCE is an efficient product development approach which addresses the PD challenges while eliminating waste. Therefore, SBCE has been applied in this thesis, as the research scope is outlined in section 1.1. However, the use of knowledge-based and physics-based ToCs is not investigated in other PD approaches. The reason for this limitation is, firstly, the necessity of having a specific and certain research topic, and secondly the constraints of conducting research in a specified time period.

2. **Employed research approach**

   As described in sections 2.2 and 2.3, qualitative research methods were employed in this thesis. Qualitative research inherits bias, which is inevitable. However, in order to reduce the negative consequences of bias, the author took necessary actions, such as triangulation. Triangulation in this thesis involves the literature review, interactions with industrial collaborators, interviews, case study validation and expert judgements. The results of these methods are analysed and cross-checked in order to achieve reliable conclusions.

3. **The developed processes**

   Although using ToCs through the SBCE process reduces time significantly, data collection for generating ToCs may be hectic, especially if the company does not have an established data platform. Therefore, initiating the use of ToCs may be resource intensive. However, once knowledge-based and physics-based ToCs are generated, the data will be naturally stored in the form of ToCs and will be available for reuse in future projects.

4. **Data access**

   Collaborating with industry resulted in limitations while carrying out the research. One limitation was the access to the data required for conducting the industrial case studies due to confidentiality issues. Since the aim was to represent real data using ToCs, in the cases of limited data access, the author collected publicly available data, which is still real-life data but has no confidentiality.

5. **Time constraint**

   The PhD research is limited to a specific time-period. Accordingly, the time invested for industrial case studies was relatively short. However, working as a research team mitigated the time constraint in order to obtain tangible and sufficient results in the end of each case study.

6. **Skills constraints**

   During the industrial case studies, it was noted that certain skills, background and knowledge are required for developing each product that are the focus in industrial case studies. This challenge was eliminated through the use of knowledge-based and physics-based ToCs. While generating these ToCs, the author gained sufficient background and knowledge to be able to carry out the research.

7.4 Research Contributions

In the light of the research aim and objectives of this thesis, the author conducted an extensive literature review (Chapter 3) and an industrial field study (Chapter 4). Consequently, research gaps were identified as shown in section 3.5. This PhD research addressed these research gaps and contributed to the scientific knowledge in several aspects. The overall contribution to the body of knowledge is that the proposed three processes, as listed below and explained in chapter 5, are the first comprehensively structured, step-by-step approach to generating and utilising trade-off curves that enable applications of SBCE.

1. A process for generating knowledge-based trade-off curves that enable set-based concurrent engineering applications.
2. A process for generating physics-based ToCs that enable SBCE applications.
3. A process for using generated ToCs in the SBCE process model.

Another contribution of this PhD research to the knowledge is a comprehensive definition of trade-off curves in the context of SBCE. The trade-off curves clearly defined for the first time in this research are generated using data from experience and an understanding of the physics of the product under development.

7.5 Research Implications

The three processes defined in this thesis address several challenges that designers face throughout their product development activities. Generated knowledge-based and physics-based trade-off curves can be utilised by designers, engineers, senior managers (including the ones without engineering backgrounds), product development/design team members and R&D departments.

The managerial implication of this PhD research is that knowledge-based and physics-based ToCs help the PD manager to have a more systematic and methodological approach in visualising key data and converting them into knowledge in the form of curves to support the product design and development from the conceptual stage onwards.

The methodological implication of this PhD research is that there are three different processes generating ToCs and utilising them in a systematic approach in order to provide a step-by-step guide to the company on how to manage manage certain aspects of the PD knowledge cycle.

Knowledge-based trade-off curves provide guidance to understanding customer requirements and identifying decision criteria for visualising conflicting design parameters. Additionally, they guide the collection of historical data for reuse in current projects. This reduces the resource requirements of the PD process.

Physics-based ToCs provide guidance to understanding the physics and functions of the product under development. Thus, they support communication and decision-making without the need for prototyping and testing.

7.6 Conclusions

As the result of the comprehensive research presented in this thesis, the following conclusions were drawn:

1. The finding of the literature review endorsed the statement that set-based concurrent engineering is a more efficient approach to new product development activities within companies when the knowledge-environment is provided. Trade-off curves have the capability of creating such an environment.

2. The findings of the research showed that there are different types of trade-off curves, which are generated by using different data sources: math-based and knowledge-based ToCs.
3. Generated knowledge-based and physics-based ToCs support:
    a. Decision-making throughout the product development,
    b. Communication between different stakeholders,
    c. Creativity of designers.
4. Generated knowledge-based and physics-based ToCs enable the following key activities of SBCE:
    a. Identifying the feasible design area,
    b. Developing a set of conceptual design solutions,
    c. Comparing the possible designs,
    d. Narrowing down the design-set,
    e. Achieving the optimal design solution.
5. Industrial applications of both knowledge-based and physics-based ToCs showed that ToCs are helpful tools for creating awareness in several aspects. These include:
    a. Identifying and understanding the customer value,
    b. Visualising conflicting issues related to the product design,
    c. Supporting designers to find a balance between conflicting issues,
    d. Creating knowledge,
    e. Storing useful data,
    f. Reusing existing knowledge,
    g. Obtaining knowledge from suppliers and customers.
6. Knowledge-based and physics-based ToCs are applicable in the development of a wide range of products, depending on their level of complexity.
7. Having already generated ToCs allows practitioners to save time, which can be invested in identifying the essential design parameters. It also prevents the possible failure of overlooking important conflicting design parameters during the product development process.

8. Trade-off curves have the capability of responding quickly to dynamic changes throughout the product development processes.

7.7 Future Work

Despite the promising results and conclusions of this thesis, the author recommends that further research be undertaken to investigate the following:

1. The knowledge, obtained from evaluation and comparison of the design data in ToCs, should be captured and stored using a well-established software.
2. A business model should be developed in order to incorporate the implementation of knowledge-based and physics-based ToCs into the current product development strategy of the company.
3. Further industrial applications of knowledge-based and physics-based ToCs should be investigated in different manufacturing sectors, such as chemical and biological products.
4. Further applications of knowledge-based ToCs in the service sector, such as healthcare, telecommunications and catering should be explored.
5. The potential role of knowledge-based ToCs in the sustainable manufacturing concept should be investigated. Such a study may provide a resource-saving approach to waste elimination that directly affects the environment.
6. A combination of math-based ToCs, knowledge-based ToCs and physics-based ToCs can be investigated for future work.
7. Further investigation is needed in order to update generated ToCs with the obtained new data.

REFERENCES

Abido, M. A. (2003) ‘A novel multiobjective evolutionary algorithm for environmental/economic power dispatch’, *Electric Power Systems Research*, 65(1), pp. 71–81. doi: 10.1016/S0378-7796(02)00221-3.

Al-Ashaab, A., Golob, M., Attia, U. M., Khan, M., Parsons, J., Andino, A., Perez, A., Guzman, P., Onecha, A. and Kesavamoorthy, S. (2013) ‘The transformation of product development process into lean environment using set-based concurrent engineering: A case study from an aerospace industry’, *Concurrent Engineering Research and Applications*, 21(4), pp. 268–285.

Al-Ashaab, A. and Sobek, D. K. (2013) ‘Lean product and process development: a value creation paradigm that goes beyond lean manufacturing’, *International Journal of Computer Integrated Manufacturing*, 26(12), pp. 1103–1104. doi: 10.1080/0951192X.2013.834483.

Alavi, M. and Denford, J. S. (2011) ed. by Easterby-Smith, M. and Lyles, M. A. *Handbook of Organizational Learning and Knowledge Management*. 2nd edn. Chichester: John Wiley & Sons.

Alavi, M., and Leidner, D.E. (2001) ‘Review: Knowledge Management and Knowledge Management Systems: Conceptual Foundations and Research Issues’, *MIS Quarterly*, 25(1), pp. 107-136.

Andriopoulos, C. and Dawson, P. (2009) *Managing Change, Creativity and Innovation*. London: SAGE.

Araci, Z. C., Al-Ashaab, A., Garcia Almeida, C. and McGavin, J. (2016) ‘Enabling Set-Based Concurrent Engineering via Physics-Based Trade-off Curves’, in *WSEAS Transactions on Business and Economics*. Bern, Switzerland, 17-19 December 2016, pp. 620–626.

Araci, Z. C., Al-Ashaab, A. and Maksimovic, M. (2016) ‘Knowledge Creation and Visualisation by Using Trade‑off Curves to Enable Set‑based Concurrent Engineering’, *Electronic Journal of Knowledge Management*, 14(1), pp. 75–88.

Askar, S. and Tiwari, A. (2011) 'Finding Innovative Design Principles for jhMultiobjective Optimization Problems', *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, 41(4), pp. 554–559. doi: 10.1109/TSMCC.2010.2081666.

Avigad, G. and Moshaiov, A. (2010) 'Set-based concept selection in multi-objective problems involving delayed decisions', *Journal of Engineering Design*, 21(6), pp. 619–646. doi: 10.1080/09544820802459243.

Baxter, D., Roy, R., Doultsinou, A., Gao, J. and Kalta, M. (2009) 'A knowledge management framework to support product-service systems design', *International Journal of Computer Integrated Manufacturing*, 22(12), pp. 1073–1088. doi: 10.1080/09511920903207464.

Beg, N. and Sarshar, S. (2009) 'Applications of jet pump technology to enhance production from gas fields', in *Technical Conference: Offshore Gas Processing*. London, UK, 18-20 February 2009: Gas Processors Association.

Beg, N. and Sarshar, S. (2014) *Surface Jet Pumps (SJPs) for Enhanced Oil and Gas Production*. Cranfield, UK: Caltec Limited.

Berkelaar, M. R. C. M., Buurman, P. H. W. and Jess, J. A. G. (1994) 'Computing the entire active area/power consumption versus delay tradeoff curve for gate sizing with a piecewise linear simulator', *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, 15(11), pp. 1424–1434.

Bitran, G. R. and Morabito, R. (1999) 'An overview of tradeoff curves in manufacturing systems design', *Production and operations management*, 8(1), pp. 56–75.

Blackler, F. (1995) 'Knowledge, Knowledge Work and Organizations: An Overview and Interpretation', *Organisation Studies*, 16(6), pp. 1021-1046.

Bretthauer, K. M., Shetty, B. and Syam, S. (2003) 'A specially structured nonlinear integer resource allocation problem', *Naval Research Logistics*, 50(7), pp. 770–792. doi: 10.1002/nav.10089.

Browning, T. R. and Eppinger, S. D. (2002) ‘Modeling impacts of process architecture on cost and schedule risk in product development’, *IEEE Transactions on Engineering Management*, 49(4), pp. 428–442.

Bryman, A. (2012) *Social research methods*. 4th edn. Oxford: Oxford university press.

Bryman, A. and Bell, E. (2015) *Business Research Methods*. 4th edn. Oxford: Oxford university press.

Burke, W. J., Merrill, H. M., Schweppe, F. C., Lovell, B. E., McCoy, M. F. and Monohon, S. A. (1988) ‘Trade off methods in system planning’, *IEEE Transactions on Power Systems*, 3(3), pp. 1284–1290.

Cao, Y. and Yang, Z. (2004) ‘Multiobjective process controllability analysis’, *Computers & Chemical Engineering*, 28(1–2), pp. 83–90. doi: 10.1016/S0098-1354(03)00184-4.

Catalão, J. P. S., Mariano, S., Mendes, V. M. F. and Ferreira, L. (2008) ‘Short-term scheduling of thermal units: emission constraints and trade-off curves’, *European transactions on electrical power*. Wiley Online Library, 18(1), pp. 1–14.

Correia, A. T., Stokic, D. and Faltus, S. (2014) ‘Mechanisms for communication and knowledge sharing for set-based concurrent engineering’, *International Journal of Product Development*, 19(5), pp. 328–347.

Dunning, P. D., Stanford, B. K., Kim, H. A. and Jutte, C. V. (2014) ‘Aeroelastic tailoring of a plate wing with functionally graded materials’, *Journal of Fluids and Structures*. Academic Press, 51, pp. 292–312. doi: 10.1016/j.jfluidstructs.2014.09.008.

Fine, C. H., Golany, B. and Naseraldin, H. (2005) ‘Modeling tradeoffs in three-dimensional concurrent engineering: a goal programming approach’, *Journal of Operations Management*, 23(3), pp. 389–403.

Forcadell, F. J. and Guadamillas, F. (2002) ‘A case study on the implementation of a knowledge management strategy oriented to innovation’, *Knowledge and*

Process Management, 9(3), pp. 162-171.

Gardner, Jr. and Everette, S. (1990) 'Evaluating forecast performance in an inventory control system', *Management Science*, 36(4), pp. 490–499.

Goffin, K., and Mitchell, R. (2010) *Innovation Management: Strategy and Implementation Using the Pentathlon Framework*. 2nd edn. Basingstoke: Palgrave Macmillan.

Grewal, C. S., Enns, S. T. and Rogers, P. (2014) 'Measuring the performance sensitivity of replenishment systems using tradeoff curves', *European Journal of Industrial Engineering*. Inderscience Enterprises Ltd., 8(5), p. 646. doi: 10.1504/EJIE.2014.065735.

Haselbach, F. and Parker, R. (2012) 'Hot End technology for advanced, low emission large civil aircraft engines', in Grant, I. (ed.) *28th International Congress of the Aeronautical Sciences*, p. 3.

Hernández-Luna, A. A., Moreno-Grandas, D. P. and Wood, K. L. (2010) 'Trade-off of fuzzy set-based design parameters', in *IIE Annual Conference and Expo 2010 Proceedings*. Institute of Industrial Engineers.

Holtzman, J. M. (1984) 'Automatic Speech Recognition Error/No Decision Tradeoff Curves', *IEEE Transactions on Acoustics, Speech, and Signal Processing*, ASSP-32(6), pp. 1232–1235.

Hong, P., Nahm, A. Y. and Doll, W. J. (2004) 'The role of project target clarity in an uncertain project environment', *International Journal of Operations & Production Management*, 24(12), pp. 1269–1291. doi: 10.1108/01443570410569047.

ICAO (2016) *General information on noisedB database*. Available at: http://noisedb.stac.aviation-civile.gouv.fr/ (Accessed: 7 March 2017).

Inglis, A. (2008) 'Approaches to the validation of quality frameworks for e-learning', *Quality Assurance in Education*. Emerald Group Publishing Limited, 16(4), pp. 347–362.

Joo, S. and Lee, J. Y. (2011) ‘Measuring the usability of academic digital libraries: Instrument development and validation’, *Electronic Library*. Emerald Group Publishing Limited, 29(4), pp. 523–537.

Kennedy, B. M., Sobek, D. K. and Kennedy, M. N. (2014) ‘Reducing rework by applying set-based practices early in the systems engineering process’, *Systems Engineering*, 17(3), pp. 278–296.

Kerga, E., Akaberi, A., Taisch, M., Rossi, M. and Terzi, S. (2013) ‘Lean Product Development: Serious Game and evaluation of the learning outcomes’, *IFIP Advances in Information and Communication Technology*, 397(PART 1), pp. 590–597.

Kerga, E., Taisch, M., Terzi, S., Bessega, W. and Rosso, A. (2014) ‘Set-based concurrent engineering innovation roadmap (SBCE IR): a case on Adiabatic Humidification’, *International Journal of Design Creativity and Innovation*, 2(4), pp. 1–32.

Khan, M., Al-Ashaab, A., Doultsinou, A., Shehab, E., Ewers, P. and Sulowski, R. (2011) ‘Set-Based Concurrent Engineering process within the LeanPPD environment’, in *Advanced Concurrent Engineering*. Boston, MA; United States, pp. 433–440.

Khan, M. S. (2012) *The construction of a model for Lean Product Development*. PhD Thesis. Cranfield University.

Khan, M. S., Al-Ashaab, A., Shehab, E., Haque, B., Ewers, P., Sorli, M. and Sopelana, A. (2013) ‘Towards lean product and process development’, *International Journal of Computer Integrated Manufacturing*, 26(12), pp. 1105–1116.

Kuo, C.-L., Su, C.-P. J., Chu, C.-H. and Miao, H.-Y. (2014) ‘A statistical framework for characterizing the nanotube buckypaper manufacturing process’, *International Journal of Precision Engineering and Manufacturing*. SpringerOpen, 15(8), pp. 1601–1608. doi: 10.1007/s12541-014-0509-4.

Levandowski, C., Forslund, A. and Johannesson, H. (2013) ‘Using PLM and trade-off curves to support set-based convergence of product platforms', in *DS 75-4: Proceedings of the 19th International Conference on Engineering Design (ICED13), Design for Harmonies, Vol. 4: Product, Service and Systems Design*. Seoul, Korea, 19-22 August 2013.

Levandowski, C., Michaelis, M. T. and Johannesson, H. (2014) 'Set-based development using an integrated product and manufacturing system platform', *Concurrent Engineering Research and Applications*, 22(3), pp. 234–252.

Li, Y.Z.; Sheng, M.; Yang, C.G.; Wang, X. J. (2013) 'Energy efficiency and spectral efficiency tradeoff in interference-limited wireless networks', *IEEE Communications Letters*, 17(10), pp. 1924–1927.

Lindlöf, L., Söderberg, B. and Persson, M. (2013) 'Practices supporting knowledge transfer – an analysis of lean product development', *International Journal of Computer Integrated Manufacturing*, 26(12), pp. 1128–1135. doi: 10.1080/0951192X.2011.651160.

Maksimovic, M. (2013) *Lean knowledge life cycle framework to support lean product development*. PhD Thesis. Cranfield University.

Maksimovic, M., Al-Ashaab, A., Shehab, E., Flores, M., Ewers, P., Haque, B., Furian, R., von Lacroix, F. and Sulowski, R. (2014) 'Industrial challenges in managing product development knowledge', *Knowledge-Based Systems*. Elsevier, 71, pp. 101–113. doi: 10.1016/j.knosys.2014.07.016.

Maksimovic, M., Al-Ashaab, A., Sulowski, R. and Shehab, E. (2012) 'Knowledge visualization in product development using trade-off curves', in *IEEE International Conference on Industrial Engineering and Engineering Management*, pp. 708–711.

Malak, R. J. and Paredis, C. J. J. (2010) 'Using Parameterized Pareto Sets to Model Design Concepts', *Journal of Mechanical Design*, 132(4), p. 41007. doi: 10.1115/1.4001345.

Michaelis, M. T., Levandowski, C. and Johannesson, H. (2013) 'Set-Based Concurrent Engineering for Preserving Design Bandwidth in Product and

Manufacturing System Platforms', in *Volume 12: Systems and Design*. ASME. doi: 10.1115/IMECE2013-63624.

Van Mieghem, P. and Vandenberghe, L. (2006) 'Trade-Off Curves for QoS Routing.', in *INFOCOM 2006: 25th IEEE International Conference on Computer Communications*. Barcelona, Spain, 23-29 April 2006.

Mohagheghi, M., Kapat, J. and Nagaiah, N. (2014) 'Pareto-Based Multi-Objective Optimization of Recuperated S-CO 2 Brayton Cycles', in *Volume 3B: Oil and Gas Applications; Organic Rankine Cycle Power Systems; Supercritical CO2 Power Cycles; Wind Energy*. ASME. doi: 10.1115/GT2014-27152.

Mohd Maulana, I. I. BIN, Al-Ashaab, A., Flisiak, J., Araci, Z. C., Lasisz, P., Shehab, E., Beg, N. and Rehman, A. (2017) 'The set-based concurrent engineering application: A process of identifying the potential benefits in the surface jet pump case study', in *27th CIRP Design Conference*. Cranfield, UK, 10-12 May 2017 (in press).

Mohd Maulana, I. I. BIN, Flisiak, J. W., Al-Ashaab, A., Araci, Z. C., Lasisz, P. W., Beg, N. and Rehman, A. (2016) 'The Application of Set-Based Concurrent Engineering to Enhance the Design Performance of Surface Jet Pump', in *WSEAS Transactions on Business and Economics*. Bern, Switzerland, 17-19 December 2016, pp. 634–643.

Montiel-Nelson, J. A., Sosa, J., Navarro, H., Sarmiento, R. and Nunez, A. (2005) 'Efficient method to obtain the entire active area against circuit delay time trade-off curve in gate sizing', *IET Proceedings-Circuits, Devices and Systems*. IET, 152(2), pp. 133–145.

Morgan, J. M. and Liker, J. K. (2006) *The Toyota product development system: integrating people, process, and technology*. New York: Productivity Press.

Munson, B., Young, D., Okiishi, T. and Huebsch, W. (2010) *Fundamentals of fluid mechanics*. 6th edn. Hoboken, NJ: John Wiley and Sons Ltd.

Neuman, W. L. (2011) *Social Research Methods: Qualitative and Quantitative Approaches*. 6th edn. Boston, MA: Pearson Education, Inc.

Nonaka, I. (1994) ‘A dynamic theory of organizational knowledge creation’, *Organization Science*, 5(1), pp. 14-37.

Nonaka, I., Kodama, M., Hirose, A. and Kohlbacher, F. (2014) ‘Dynamic fractal organizations for promoting knowledge-based transformation – A new paradigm for organizational theory’, *European Management Journal*, 32(1), pp. 137–146. doi: 10.1016/j.emj.2013.02.003.

Nonaka, I. and Takeuchi, H. (1995) *The knowledge creating company*. New York: Oxford University Press.

Nonaka, I., Toyama, R. and Konno, N. (2000) ‘SECI, Ba and Leadership: a Unified Model of Dynamic Knowledge Creation’, *Long Range Planning*, 33(1), pp. 5–34. doi: 10.1016/S0024-6301(99)00115-6.

Noor, K. B. M. (2008) ‘Case study: a strategic research methodology’, *American Journal of Applied Sciences*, 5(11), p. 1602.

Olympus (no date) *Basic structure of a turbofan engine*. Available at: http://www.olympus-ims.com/en/applications/rvi-passenger-jet-engine/ (Accessed: 7 March 2017).

Oosterwal, D. P. (2010) *The lean machine: how Harley-Davidson drove top-line growth and profitability with revolutionary lean product development*. New York: AMACOM American Management Association.

Otto, K. N. and Antonsson, E. K. (1991) ‘Trade-off strategies in engineering design’, *Research in Engineering Design*. Springer, 3(2), pp. 87–103.

Panduro, M. A., Brizuela, C. A., Covarrubias, D. and Lopez, C. (2006) ‘A trade-off curve computation for linear antenna arrays using an evolutionary multi-objective approach’, *Soft Computing*, 10(2), pp. 125–131.

Paxton (2017) *Previous Products: Net2 Range: Readers*. Available at: https://www.paxton.co.uk/ (Accessed: 7 March 2017).

Pershing, B. (1968) ‘Dragster Aerodynamics, Streamlining versus Weight’, in *Aerodynamics of Sports and Competition Automobiles, Proc of the AIAA Symp;*

Los Angeles, CA, USA, pp. 39–51.

Preetha Roselyn, J., Devaraj, D. and Dash, S. S. (2014) 'Multi-Objective Genetic Algorithm for voltage stability enhancement using rescheduling and FACTS devices', *Ain Shams Engineering Journal*, 5(3), pp. 789–801. doi: 10.1016/j.asej.2014.04.004.

Quirante, T., Sebastian, P. and Ledoux, Y. (2013) 'A trade-off function to tackle robust design problems in engineering', *Journal of Engineering Design*, 24(1), pp. 64–81. doi: 10.1080/09544828.2012.691160.

Raudberget, D. (2010) 'Practical applications of set-based concurrent engineering in industry', *Strojniski Vestnik/Journal of Mechanical Engineering*, 56(11), pp. 685–695.

Rebolledo, C. and Nollet, J. (2011) 'Learning from suppliers in the aerospace industry', *International Journal of Production Economics*, 129(2011), pp. 328-337.

Rhyu, J. H., and Clearance and Kwak, B. M. (1988) 'Optimal stochastic design of four-bar mechanisms for tolerance and clearance', *Journal of mechanisms, transmissions, and automation in design*, 110(3), pp. 255–262.

Richards, Z. D. and Valavanis, K. (2010) 'Particle Swarm trade-off curve analysis for bi-objective optimization', in *IEEE Congress on Evolutionary Computation, CEC 2010*. Barcelona, Spain, pp. 1–6.

Ringen, G. and Holtskog, H. (2013) 'How enablers for lean product development motivate engineers', *International Journal of Computer Integrated Manufacturing*, 26(12), pp. 1117–1127. doi: 10.1080/0951192X.2011.593046.

Robson, C. and McCartan, K. (2016) *Real World Research*. 4th edn. Chichester, UK: John Wiley and Sons Ltd.

Roemer, T. A. and Ahmadi, R. (2004) 'Concurrent crashing and overlapping in product development', *Operations research*, 52(4), pp. 606–622.

Samarasinghe, T., Inaltekin, H. and Evans, J. S. (2013) 'The feedback-capacity tradeoff for opportunistic beamforming under optimal user selection', *Performance Evaluation*, 70(7–8), pp. 472–492. doi: 10.1016/j.peva.2012.04.001.

Sekaran, U. and Bougie, R. (2016) *Research Methods for Business: A Skill-building Approach*. 7th edn. Chichester, UK: John Wiley and Sons Ltd.

Sobek, D. K., Liker, J. K. and Ward, A. C. (1998) 'Another look at how Toyota integrates product development', *Harvard business review*, 76(4), pp. 36–47.

Sobek, D. K., Ward, A. C. and Liker, J. K. (1999) 'Toyota's principles of set-based concurrent engineering', *Sloan management review*, 40(2), pp. 67–84.

Stamm, B. (2008) *Managing Innovation, Design and Creativity.* 2nd edn. Chichester: John Wiley & Sons.

Suwanda, S. (no date) *The Development of Knowledge-Shelf to Enable an Effective Set-Based Concurrent Engineering Application*. PhD Thesis, to be submitted. Cranfield University, UK.

Suwanruji, P. and Enns, S. T. (2007) 'Comparison of supply chain replenishment strategies in a non-capacitated distribution system', *International Journal of Risk Assessment and Management*, 7(1), p. 59. doi: 10.1504/IJRAM.2007.011410.

Tseng, S. (2009) 'A study on customer, supplier, and competitor knowledge using the knowledge chain model', *International Journal of Information Management*, 29(2009), pp. 488-496.

Tyagi, S., Cai, X., Yang, K. and Chambers, T. (2015) 'Lean tools and methods to support efficient knowledge creation', *International Journal of Information Management*. Elsevier Ltd, 35(2), pp. 204–214. doi: 10.1016/j.ijinfomgt.2014.12.007.

Vassilvitskii, S. and Yannakakis, M. (2005) 'Efficiently computing succinct trade-off curves', *Theoretical Computer Science*, 348(2), pp. 334–356.

Wang, J. and Terpenny, J. P. (2003) 'Learning and Adapting Fuzzy Set-Based Trade-off Strategy in Engineering Design Synthesis', *International Journal of Smart Engineering System Design*, 5(3), pp. 177–186. doi:

10.1080/10255810305051.

Wang, Z. and Wang, N. (2012) ‘Knowledge sharing, innovation and firm performance’, *Expert Systems with Applications*, 39(10), pp. 8899–8908. doi: 10.1016/j.eswa.2012.02.017.

Ward, A. C., Liker, J. K., Cristiano, J. J. and Sobek, D. K. (1995) ‘The second Toyota paradox: How delaying decisions can make better cars faster’, *Sloan Management Review*, 36(3), pp. 43–61. doi: http://dx.doi.org/10.1016/0024-6301(95)94310-U.

Ward, A. C. and Sobek, D. K. (2014) *Lean product and process development*. 2nd edn. Cambridge, MA, USA: Lean Enterprise Institute.

Wilkinson, D. and Birmingham, P. (2003) *Using research instruments: A guide for researchers*. London, UK: RoutledgeFalmer.

Womack, J. (2006) ‘A lesson to be learned’, *Manufacturing Engineer*, 85(2), pp. 4–5.

Wu, D., Wu, D. D., Zhang, Y. and Olson, D. L. (2013) ‘Supply chain outsourcing risk using an integrated stochastic-fuzzy optimization approach.’, *Information Sciences*, 235, pp. 242–258.

Yin, R. K. (2014) *Case study research: Design and methods*. 5th edn. Los Angeles: SAGE.

Zadeh, L. A. (1965) ‘Fuzzy sets’, *Information and Control*, 8(3), pp. 338–353.

Zhang, J., Hoenig, S., Benedetto, A. D., Lancioni, R. A., & Phatak, A. (2009) ‘What contributes to the enhanced use of customer, competition and technology knowledge for product innovation performance?: A survey of multinational industrial companies’ subsidiaries operating in China’, *Industrial Marketing Management*, 38(2009), pp. 207-218.

Zhou, A., Qu, B.-Y., Li, H., Zhao, S.-Z., Suganthan, P. N. and Zhang, Q. (2011) ‘Multiobjective evolutionary algorithms: A survey of the state of the art’, *Swarm and Evolutionary Computation*. Elsevier, 1(1), pp. 32–49.

APPENDICES

Appendix A Semi-Structured Questionnaire for Interviews

Cranfield UNIVERSITY

QUESTIONNAIRE

BEST PRACTICES IN PRODUCT DEVELOPMENT

AUTHORS: MATIC GOLOB, CESAR GARCIA ALMEIDA, KONSTANCJA BOCHNIAK, ZEHRA CANAN ARACI AND AHMED AL-ASHAAB

Introduction

*The **objective** of this questionnaire is to investigate some of the most common challenges that organisations are facing in today's rapidly evolving environment. These are related to product development, use and creation of trade-off curves to enable effective product development and collaboration with the commercial department.*

This will help to set a case about the importance of introducing the lean product development and set-based concurrent engineering practices to enhance the performance of the current product development process.

The questionnaire comprises of three parts covering:

1. *Product Development Process*
2. *Trade-off Curves*
3. *Collaboration Between Commercial and Engineering Teams*

Participant's details:

1. *Name:*
2. *Company:*
3. *Position:*
4. *Years of experiences:*
5. *Country:*
6. *Industry sector:*
7. *E-mail:*

NOTE: The results of this questionnaire are expected to be available on 31st October 2014

Trade-off Curves to Enable Effective Product Development

This questionnaire is designed to investigate companies' best practises regarding the knowledge creation and provision in form of trade-off curves during the early stages of product development process.

TERMINOLOGY:

IMPORTANCE: It refers to the importance of the activity to achieve an objective

1. **Very low:** Not important at all
2. **Low:** Not very important
3. **Medium:** Somewhat important
4. **High:** Important
5. **Very high:** Very important

EFFECTIVENESS: How effective is the current method in delivering the service

1. **Very poor:** Not effective at all
2. **Poor:** Not very effective
3. **Good:** Somewhat effective
4. **Very good:** Effective
5. **Excellent:** Very effective

NOTE:

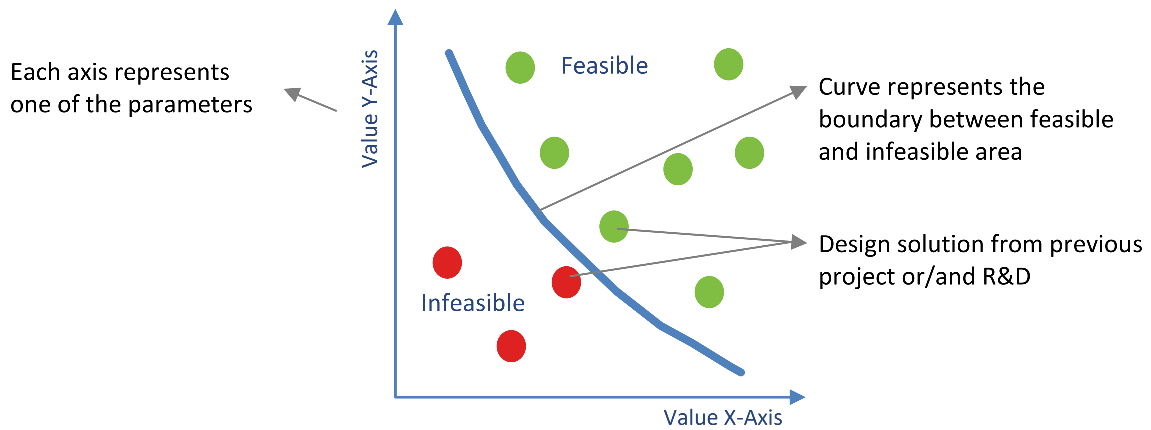
Trade-off curves are a knowledge-based (knowledge from prototyping, testing, etc. rather than simulation based) approach to support decision making throughout the product development process.

If the trade-off curves are currently not being used, please indicate your opinion at each question.

Decision criteria refers to decision making in a new product development project based on the characteristics of product which is under development in order to propose a complying design solution.

Feasible area/design solutions refer to possible conceptual design solutions that meet the decision criteria and the customer requirements for the related project.

Infeasible area/design solutions refer to conceptual design solutions that do not meet the decision criteria and the customer requirements for the related project.



1. HOW WOULD YOU DESCRIBE THE USE OF TRADE-OFF CURVES (ToCs) IN THE CURRENT PRODUCT DEVELOPMENT (PD) PROCESS WITHIN YOUR COMPANY?

   (Please select one statement)

   1. ToCs do not exist and we are not aware of their importance.
   2. We are aware of the importance of the use of ToCs but they are currently not used.
   3. We have initiated a project of creating and introducing the ToCs.
   4. ToCs are loosely used in some projects.
   5. ToCs are formally in use throughout the PD process and in the most of the projects.

2. WHICH OF THE FOLLOWING DESCRIPTIONS IS THE CLOSEST TO YOUR COMPANY'S INTERPRETATION OF TRADE-OFF CURVES IN THE CONTEXT OF EARLY STAGES OF THE PRODUCT DEVELOPMENT P? *(Please select one statement)*

   1. ToCs are a tool to understand the relationships between various design characteristics.
   2. ToCs characterise the relationship between two or more key parameters that relate design decision(s) to factor(s) that customers care about over a range of values.
   3. ToCs are a tool to enable identification, capture, compare, and reuse of knowledge for the new projects.
   4. ToCs describe the limits of performance that are possible with a given design approach in a simple visual form.
   5. Other (please specify):

1. HOW IMPORTANT DO YOU FIND THE FOLLOWING ACTIVITIES IN GENERATING TRADE-OFF CURVES AND HOW EFFICIENT DO YOU IMPLEMENT THESE ACTIVITIES THROUGHOUT THE EARLY STAGES OF THE NEW PRODUCT DEVELOPMENT PROCESS? *(Select as appropriate)*

OPTIONS	IMPORTANCE					EFFECTIVENESS OF YOUR PRACTICE				
	Very Low	*Low*	*Medium*	*High*	*Very High*	*Very poor*	*Poor*	*Good*	*Very good*	*Excellent*
1. Defining decision criteria that have impacts on making key decisions throughout the PD process.										
2. Defining the key parameters that are related to decision criteria to be plotted on the ToC axis.										
3. Collecting data from previous projects, R&D, suppliers, simulations and eng. calculations.										
4. Plotting customer requirements against ToCs.										
5. Defining feasible and infeasible design solutions which are illustrated below as an example.										
6. Other (please specify):										

4. HOW DO YOU DEFINE DECISION CRITERIA FOR GENERATION OF ToCs?

(Select as appropriate)

OPTIONS	IMPORTANCE					EFFECTIVENESS OF YOUR PRACTICE				
	Very Low	*Low*	*Medium*	*High*	*Very High*	*Very poor*	*Poor*	*Good*	*Very good*	*Excellent*
1. Key designers and engineers subjectively define decision criteria.										
2. We define decision criteria using experiences from previous projects, such as conflicting issues and encountered problems.										
3. We define decision criteria by implementing multi-objective optimisation.										
4. We define decision criteria by extracting from customer requirements.										
5. We define decision criteria by interviews with customers.										
6. Other (please specify):										

5. HOW DO YOU OBTAIN THE REQUIRED DATA TO GENERATE TRADE-OFF CURVES?

(Select as appropriate)

OPTIONS	IMPORTANCE					EFFECTIVENESS OF YOUR PRACTICE				
	Very Low	*Low*	*Medium*	*High*	*Very High*	*Very poor*	*Poor*	*Good*	*Very good*	*Excellent*
1. We collect data manually from previous projects and R&D, simulation and engineering calculations.										
2. We dedicate people to collect data.										
3. We collect data by automatically extracting from our current database.										
4. We create data by simulations / prototyping as we need it in related project.										
5. We collect data from material providers and suppliers.										
6. We obtain data by following a process (Process is illustrated below)										
7. Other (please specify):										

Collect available data
(from material provider, equipment and tool provider, engineering and legislation associations, etc.)

↓

Generate Trade-off Curves

↓

Analyse the collected data

↓

Identify the point of interest and missing data

↓

Fill the gap from Previous Projects/R&D

6. IN WHICH STEPS/TASKS/ACTIVITIES OF YOUR CURRENT PRODUCT DEVELOPMENT PROCESS WOULD YOU USE TRADE-OFF CURVES?
(Select as appropriate)

OPTIONS	IMPORTANCE					EFFECTIVENESS OF YOUR PRACTICE				
	Very Low	*Low*	*Medium*	*High*	*Very High*	*Very poor*	*Poor*	*Good*	*Very good*	*Excellent*
1. We use ToCs to generate a set of conceptual designs in the early stages of the PD process.										
2. We use ToCs to narrow down the conceptual designs to achieve an optimal design solution.										
3. We use ToCs to enable key decision-making throughout the process of product development.										
4. We use ToCs to identify the feasible area where the possible design solutions are located. (Feasible and infeasible area are illustrated in the graph below.)										
5. We use ToCs to compare the possible conceptual design solutions regarding the related decision criteria and customer requirements.										
6. Other (please specify):										

Appendix B Members of the Research Teams

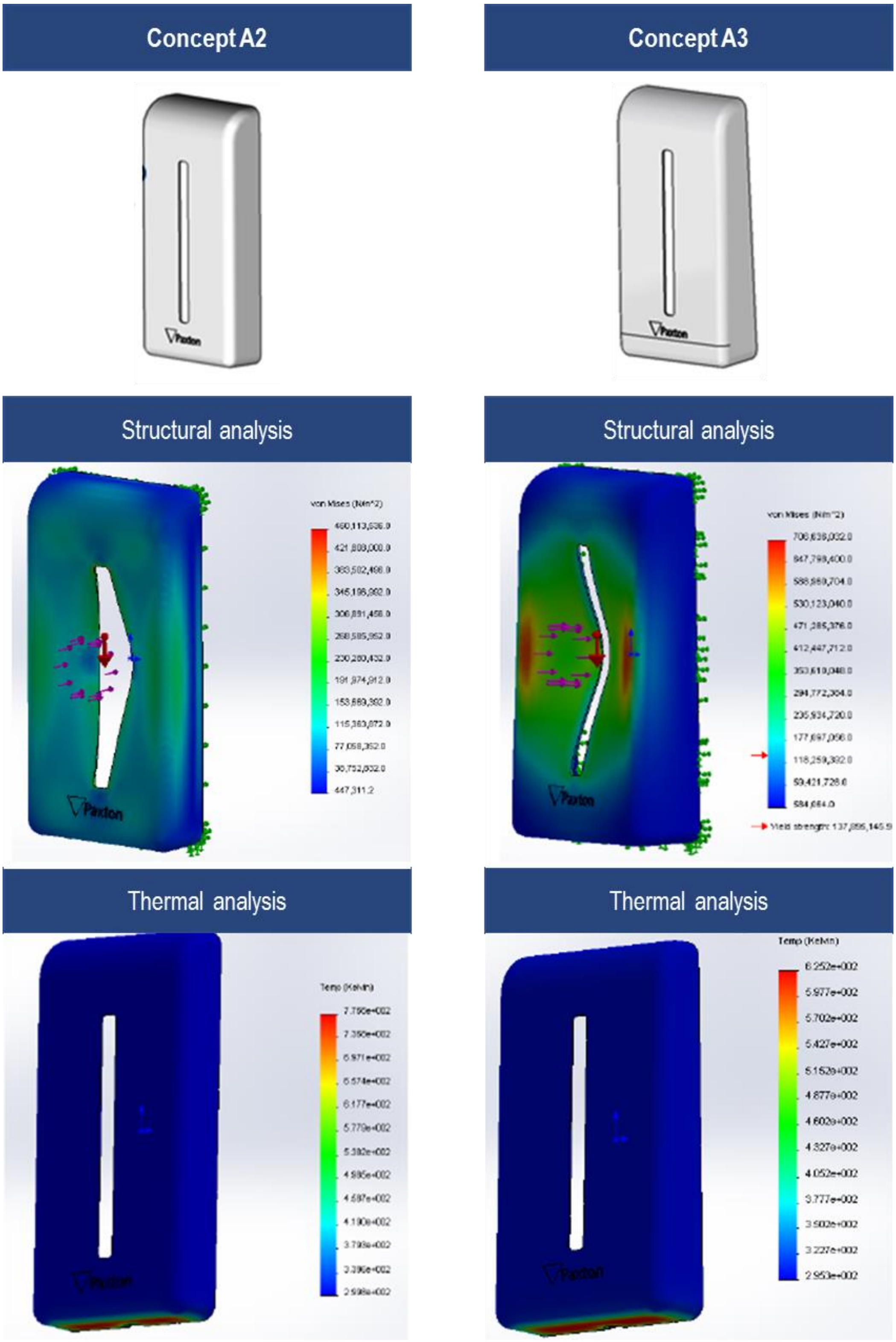
Academic supervisor for all research teams is Dr Ahmed Al-Ashaab.

Case study	Member of the research team	The role in the research
Rolls-Royce	Zehra Canan Araci PhD Researcher	Investigating the development of a knowledge-environment to support the application of set-based design.
	Esraa Al-Ali MSc Student (Erasmus)	
	Dr. Muhammed Khan Research Fellow	Developing new multi-disciplinary SBCE capabilities that can deploy new aircraft and engine designs and configurations more quickly and with greater confidence.
	Matic Golob Research Fellow	
	Dhuha Qays MSc Student (Erasmus)	
	Dr. John Oyekan Research Fellow	Developing a knowledge-shelf structure to support the set-based design implementation
	Emmanuelle Ithier MSc Student	
SiTech	Zehra Canan Araci PhD Researcher	Generating knowledge-based trade-off curves to support decision-making and communication
	Dr. Maksim Maksimovic PhD graduate	
Paxton	Zehra Canan Araci PhD Researcher	Developing the processes for generating knowledge-based and physics-based ToCs that enable SBCE applications
	César García Almeida MSc Student	Set-based concurrent engineering application of a proximity card reader
	Jakub Wojciech Sitek MSc Student	Supporting the design modelling, and structural and thermal analysis
	Younes Laoui MSc Student (Erasmus)	

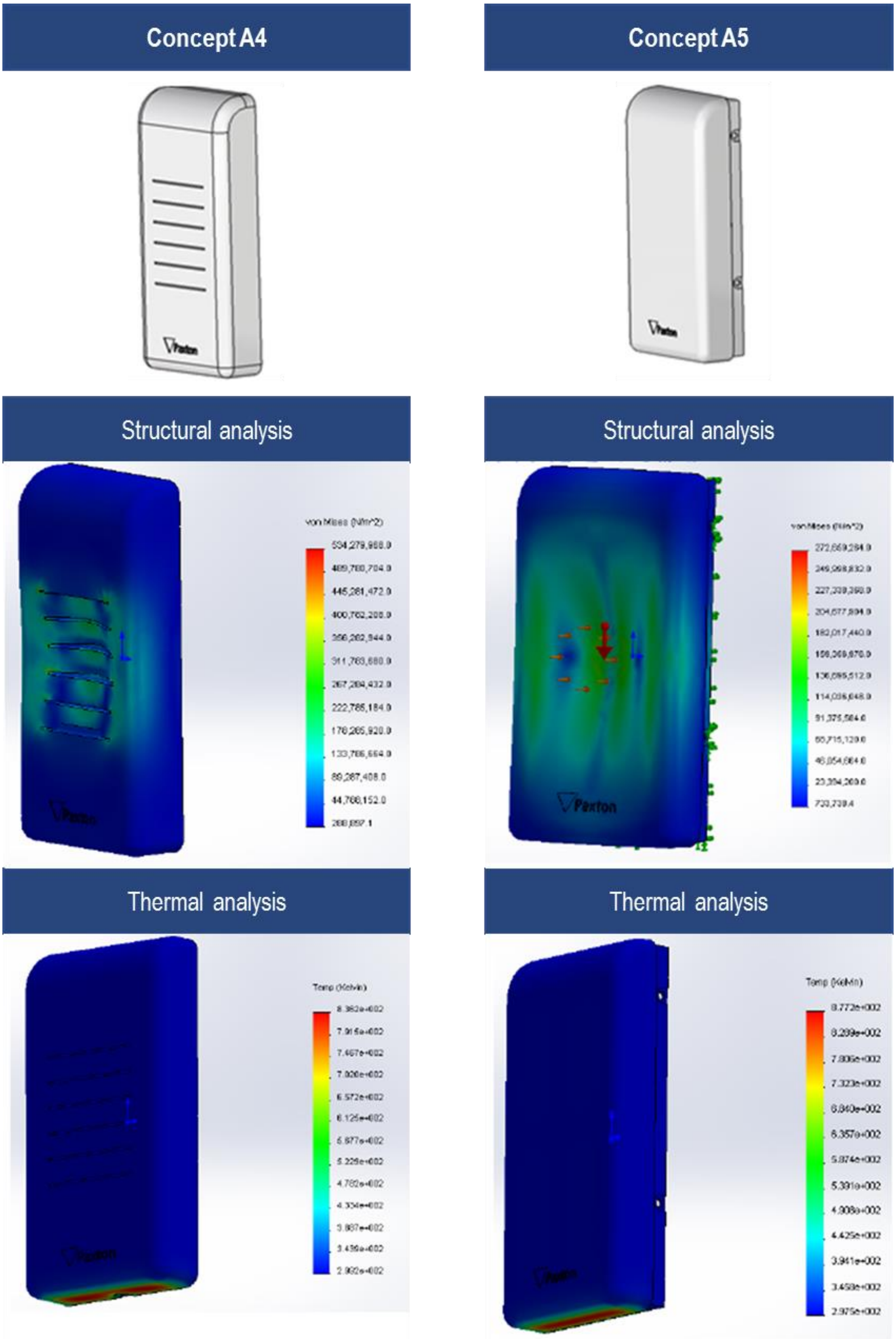
Appendix B Members of the Research Teams

Case study	Member of the research team	The role in the research
Caltec	Zehra Canan Araci PhD Researcher	Creating and visualising a knowledge-environment, by using knowledge-based and physics-based trade-off curves, to enable the SBCE applications.
	Piotr Wojciech Lasisz MSc Student	
	Muhd Ikmal Isyraf Mohd Maulana PhD Researcher	Justification of introducing the SBCE as a new product development approach and investigating the benefits of applying the SBCE process model.
	Jakub Wiktor Flisiak MSc Student	
	Supriana Suwanda PhD Researcher	Developing a software to capture the design rationale throughout the SBCE applications.
	Noodhir Sharma Sobun MSc Student	

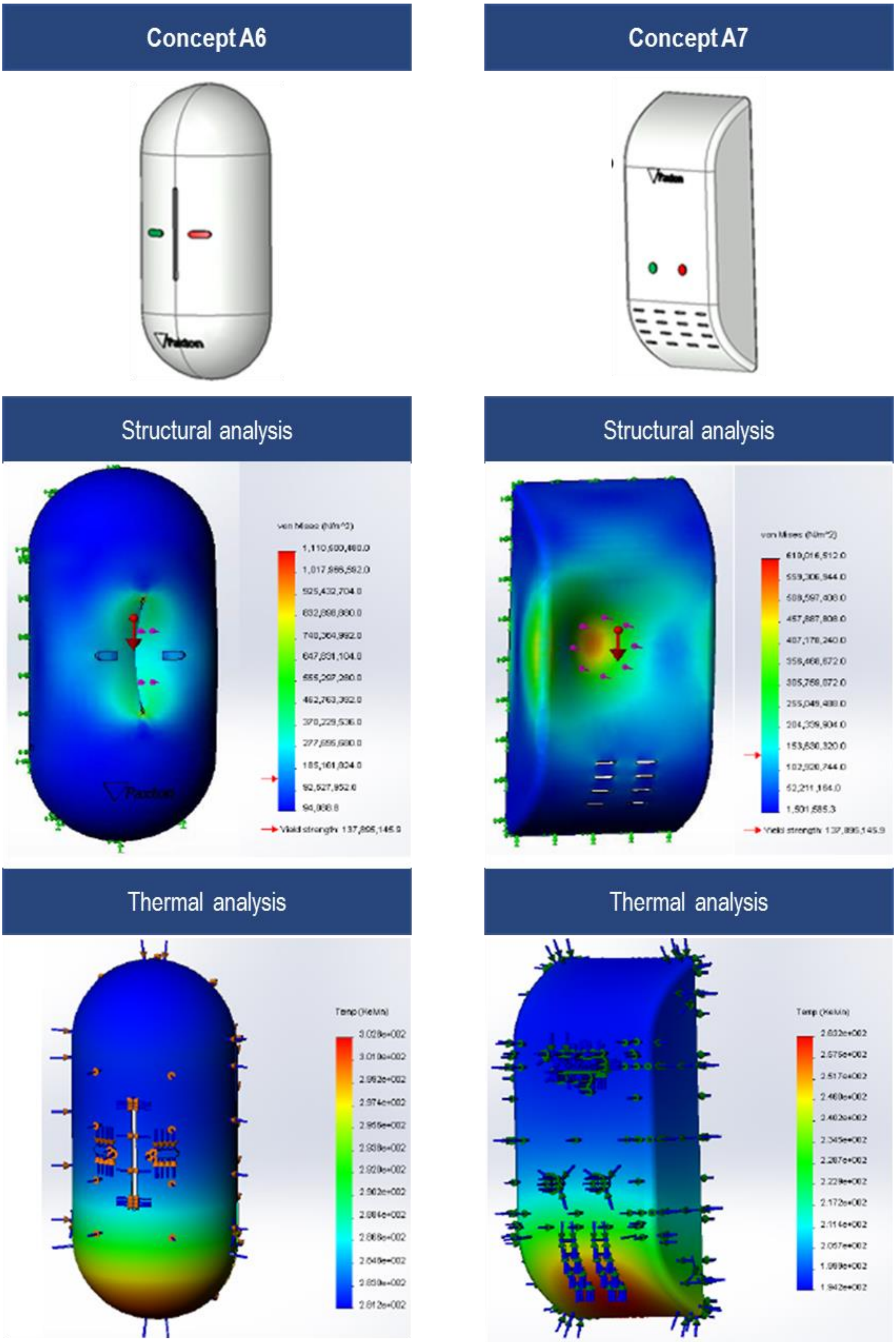
Appendix C Structural and Thermal Analysis for Paxton Case Study

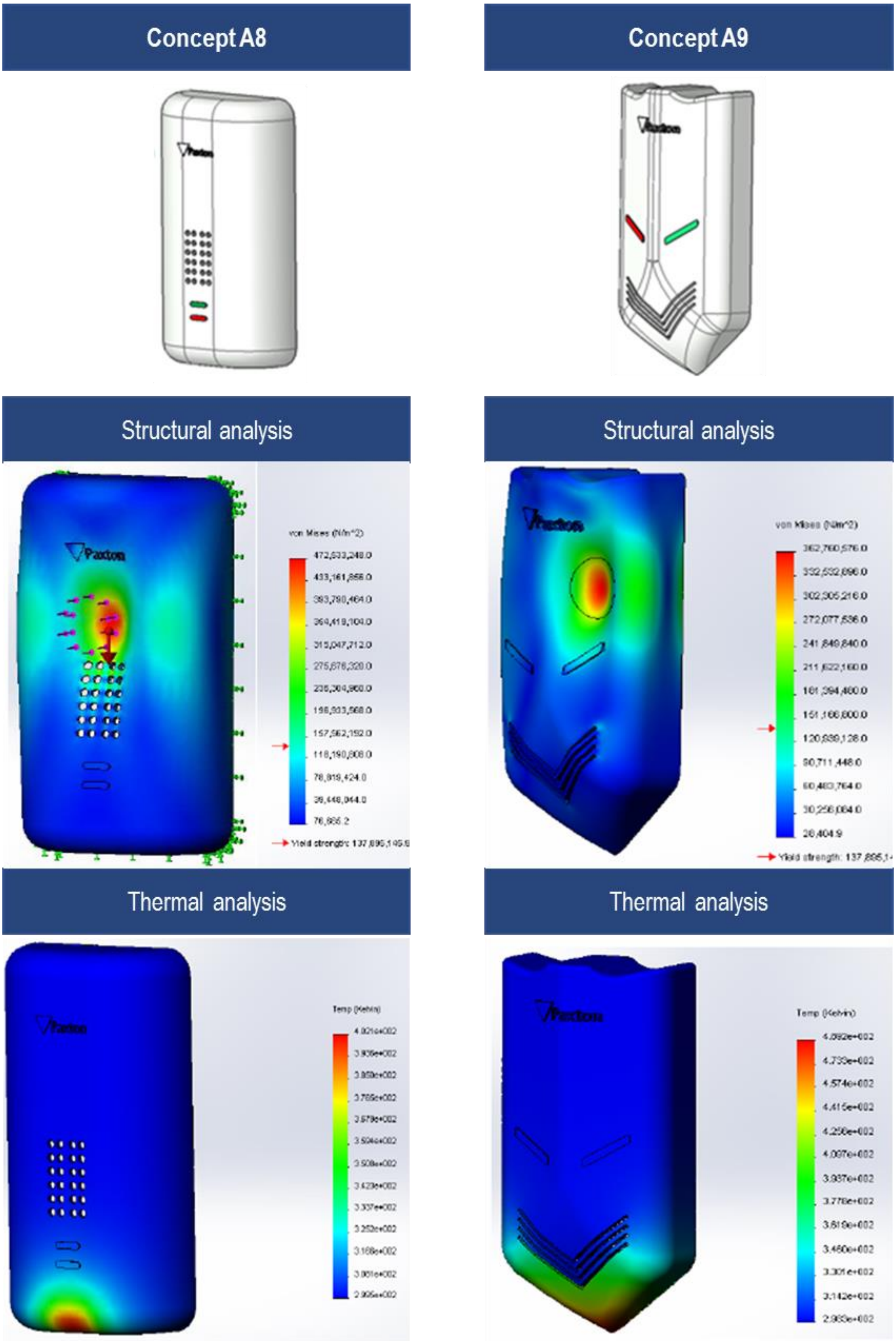


Appendix C Structural and Thermal Analysis for Paxton Case Study

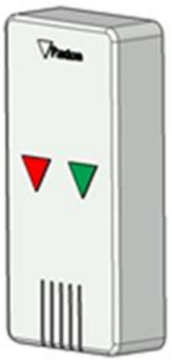


Appendix C Structural and Thermal Analysis for Paxton Case Study

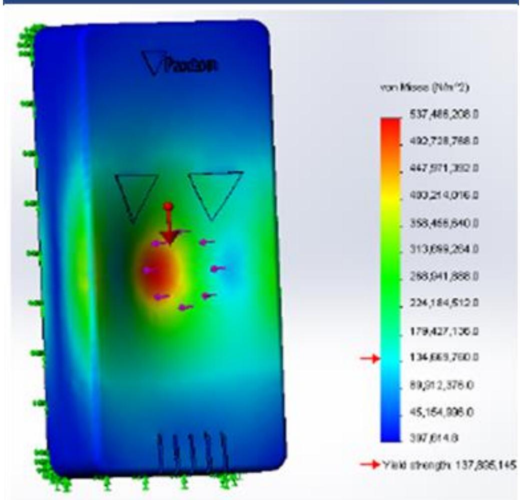



Concept A8
Concept A9
Structural analysis
Structural analysis
Thermal analysis
Thermal analysis
Paxton
Paxton
von Mises (N/m^2)
Temp (Kelvin)

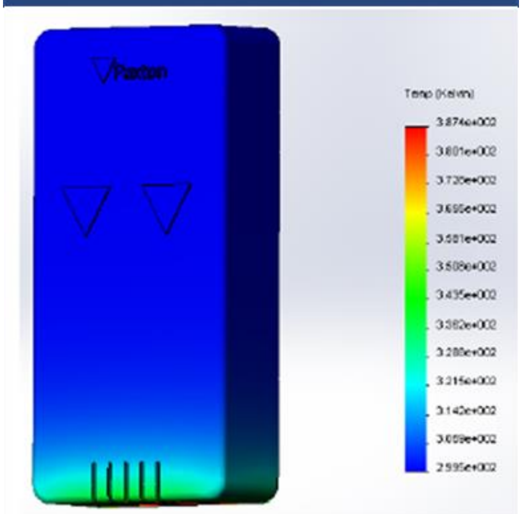
Concept A10



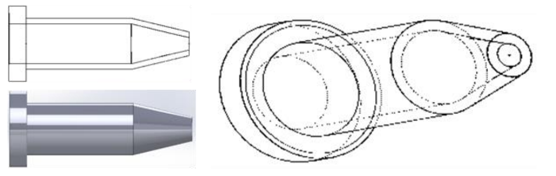
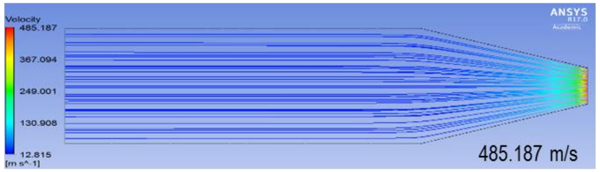
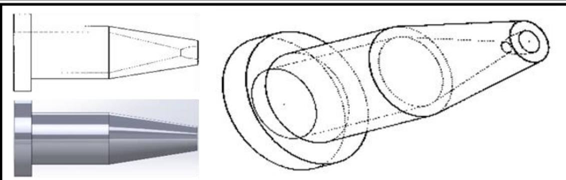
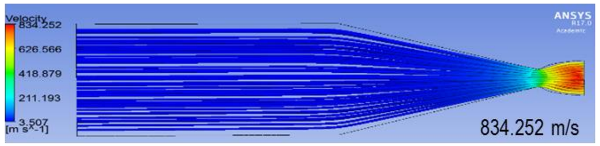
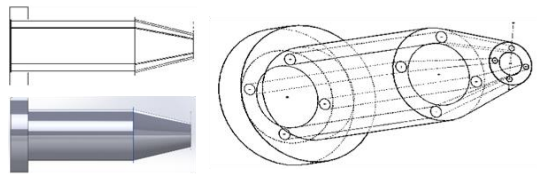
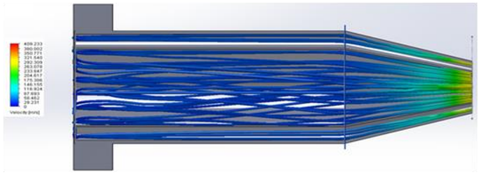
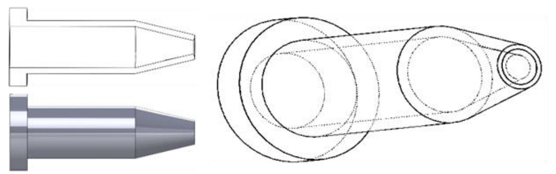
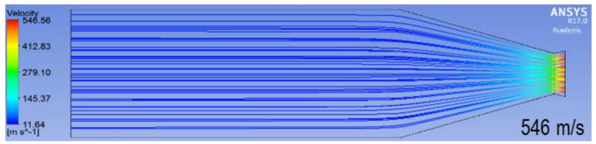
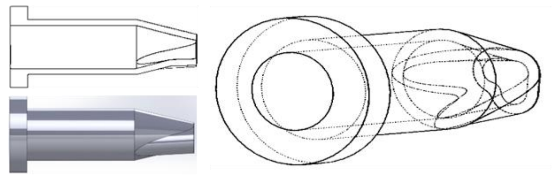
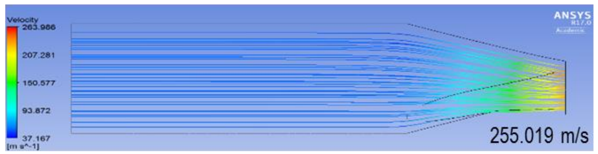
Structural analysis



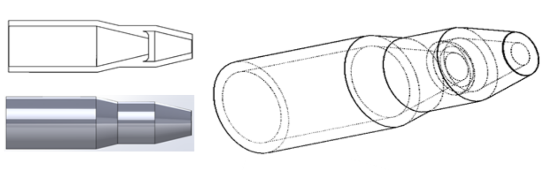
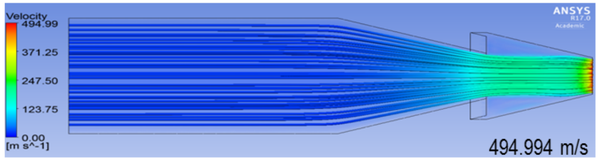
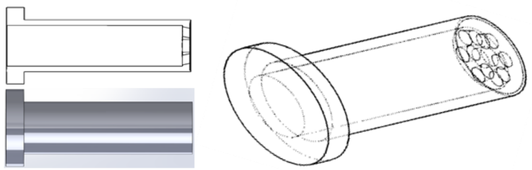
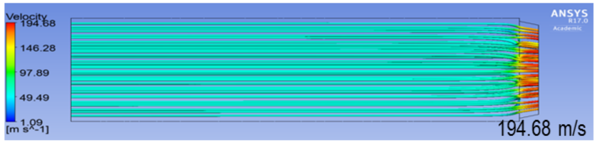
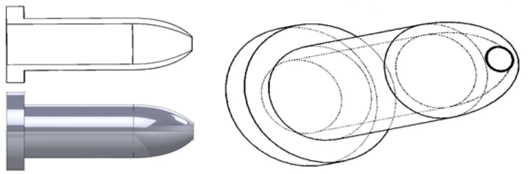
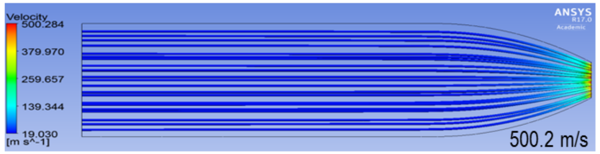
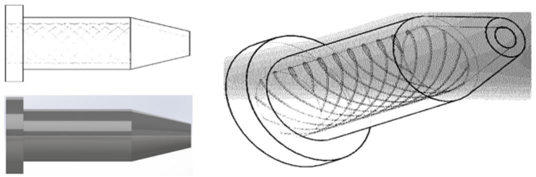
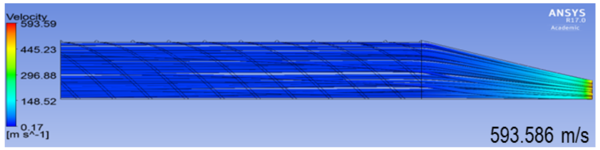
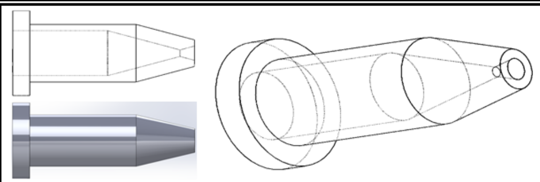
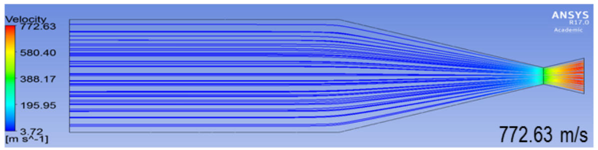
Thermal analysis



Appendix D Caltec Case Study – Nozzle Designs and CFD Simulation Results

No	Nozzle Designs	CFD Simulation Results (Velocity [m/s])	Details About the Nozzle Design
N1			• Existing solution (original nozzle design)
N2			• No moving parts • Replaceable nozzle • N2 could increase velocity by generating a supersonic flow at the tip of nozzle • Concept inspired from the space rocket launcher nozzle
N3		 429 m/s	• No moving parts • Easy to manufacture • Replaceable nozzle • Clog resistant • 4 holes reduce the energy-flow-loss at the tip of the nozzle
N4			• No moving parts • Replaceable nozzle • Small modification to the current design • Lighter in weight • The angle could reduce the energy flow loss and maintain the flow geometry.
N5			• No moving parts • Replaceable nozzle • Reduced backpressure due to its clog resistant ability • N5 could increase penetration rate hence improve flow energy • Clog resistant due to higher penetration flow

Appendix D Caltec Case Study – Nozzle Designs and CFD Simulation Results

No	Nozzle Designs	CFD Simulation Results (Velocity [m/s])	Details About the Nozzle Design
N6			• No moving part • Replaceable nozzle • Increase velocity of the fluid by 2 times • Stabilize the flow of the fluid • Reduce backpressure due to its clog resistant ability
N7			• No moving parts • Replaceable nozzle • Easy to manufacture • The multi jet could increase velocity of the gas or liquid due to its multi holes design.
N8			• No moving parts • Replaceable nozzle • N8 could maintain the flow of gas or liquid based on develop flow geometry • N8 could stabilize the flow of the fluid
N9			• No moving parts • Replaceable nozzle • N9 could generate a vortex flow energy to increase the velocity. • N9 could stabilize the vortex flow of the gas or fluid
N10			• No moving parts • Replaceable nozzle • N10 could increase velocity by generating a supersonic flow • The supersonic flow achieve early at the outlet nozzle tip.

Appendix E Semi-Structured Questionnaire for Expert Judgement

Question 1: *How would you assess the use of these processes from the perspective of a practitioner (Both regarding their structure and their practicability)?*

Structure:

i. Easy to understand
ii. Easy to follow
iii. Well structured
iv. Too many steps and activities
v. Looks crowded

Practicability:

vi. Applicable
vii. An alternative tool to traditional approaches for decision-making
viii. Powerful tool for the work
ix. Useful tool for the work
x. Difficult to implement
xi. Time consuming. if yes, why?
1. Data collection is tedious
2. There are easier tools for knowledge creation and visualisation (if so what are they?)

Question 2: *To what extent do you think it is important to create knowledge using ToCs while developing a new product?*

Answers on a scale from 1 (Very low) to 5 (Very high)

Question 3: *To what extent do you think it is important to visualise knowledge in the form of ToCs while developing a new product?*

Answers on a scale from 1 (Very low) to 5 (Very high)

Question 4: *To what extent would these processes add value to your product development process?*

Answers on a scale from 1 (Very low) to 5 (Very high)

Question 5: *To what extent would you consider using these processes in developing a new product?*

Answers on a scale from 1 (Very low) to 5 (Very high)

Question 6: *To what extent do you think ToCs are useful tools to enable the following:*

Each of the below is to be answered on a scale from 1 (Very low) to 5 (Very high)

a. Creating awareness in identifying and understanding the customer value
b. Visualising the conflicting issues related to the product design
c. Supporting designers to find a balance between the conflicting issues
d. Creating awareness in storing useful data
e. Creating awareness in reusing existing knowledge
f. Creating awareness in understanding the physics of the product
g. Supporting decision-making
h. Supporting communication between different stakeholders
i. Supporting communication between the supplier and the company
j. Supporting communication between the customer and the company