CRANFIELD UNIVERSITY

SUPRIANA SUWANDA

THE DEVELOPMENT OF KNOWLEDGE-SHELF TO ENABLE AN EFFECTIVE SET-BASED CONCURRENT ENGINEERING APPLICATION

SCHOOL OF AEROSPACE, TRANSPORT AND MANUFACTURING

PhD
Academic Year: 2015 - 2019

Supervisor: Dr Ahmed Al-Ashaab
Associate Supervisor: Dr Fan Ip-Shing
April 2019

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

Abstract

This research thesis presents the development of the Knowledge-Shelf (K-Shelf), a novel knowledge environment concept to support designers throughout Set-Based Concurrent Engineering (SBCE) application. The K-Shelf concept introduces a baseline model to understand the dimensions of knowledge environment in SBCE application as well as its synthetisation with acclaimed SBCE process model as the contribution to knowledge. The K-Shelf concept incorporates three steps of Knowledge Life Cycle (KLC) that comprises of knowledge capture, knowledge representation and knowledge provision. The K-Shelf concept also has three capabilities that supports the set of conceptual design generation, dynamic knowledge capture of design rationale with 5 Whys approach and the comparisons among set of design solutions with Trade-Off Curve (TOC) visualisation. To demonstrate these capabilities, a web-based software is developed based on Rapid Application Development (RAD) approach.

Rigorous research methodology is employed to develop the K-Shelf concept. A systematic literature review is applied to capture the current approaches of knowledge environment in SBCE application. Two industrial case studies of Surface Jet Pump (SJP) and Brake Pedal Box (BPB) are presented to validate the K-Shelf concept. Furthermore, two expert judgements were also obtained. Thus, it was established that the K-Shelf is a knowledge environment to enable an effective SBCE application.

Keywords:

Product Development, Knowledge Environment, Knowledge Provision, Design Rationale, Trade-off Curve, Surface Jet Pump, Brake Pedal Box

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List of Abbreviations

ABI	ABI/Inform
AHP	Analytical Hierarchy Priority
APEX	Application Express
B	Bracket
BPB	Brake Pedal Box
CALTEC	Caltec Production Solutions Limited
CFD	Computational Fluid Dynamic
COM	Company Priority
CSV	Comma Separated Value
DSR	Design Science Research
EBSCO	Elton B. Stephens Co.
EPG	Embedded PL/SQL Gateway
FEA	Finite Element Analysis
FEM	Finite Element Method
GUI	Graphical User Interface
HP	High Pressure
ID	Identifier
JPEG	Join Photographic Expert Group
IT	Information Technology
JLR	Jaguar Land Rover Limited
KLC	Knowledge Life Cycle

K-Shelf	Knowledge-Shelf
KVA	Key Value Attribute
LeanPD	Lean Product Development
LeanPPD	Lean Product and Process Development
LOI	Load of Importance
LP	Low Pressure
PA	Pedal Arm
PD	Product Development
PDF	Portable Document Format
PL	Procedural Language
Q	Question
R&D	Research and Development
RAD	Rapid Application Development
SBCE	Set-Based Concurrent Engineering
SDLC	Software Development Lifecycle
SJP	Surface Jet Pump
SQL	Structured Query Language
TOC	Trade-Off Curve
UK	United Kingdom
UML	Unified Modelling Language

Chapter 1: Introduction

Increased international competition in the current open global market is putting pressure on companies to improve the performance of their product development (PD) process. The key demands are to shorten the lead time and to sustain the design and production of innovative quality product in a cost-effective manner. Therefore, the need exists for an effective PD approach that addresses current PD challenges. This could be addressed by adopting the Set-based Concurrent Engineering (SBCE) process model to provide an environment in which design space is explored thoroughly and leads to enhanced innovation. This is achieved by considering an alternative set of solutions after gaining the knowledge to narrow down those solutions until the optimal solution is reached. Knowledge provision is essential in SBCE application. Hence, there is a need for an appropriate knowledge environment to enable SBCE to provide the proper knowledge to support taking right decisions. At the same time there is a need to capture the rationale of the alternative design decisions taken during narrowing down of the set of the design in the SBCE environment. These design rationales are important knowledge to be re-used in developing new products. In this research, the tool intended to address this research rationale will be called Knowledge-Shelf (K-Shelf). The K-Shelf concept is the major contribution in this research. Furthermore, in order to demonstrate the K-Shelf concept, a web-based software is developed.

1.1 Research Context

The PD phase acts as a channel in the manufacturing process of conceiving an idea, conceptual design and the production phase of a new product roll-out. In short, PD is where a concept becomes reality. As many organisations have demonstrated, the conceptual design phase in PD is conducive to an improvement in competitiveness. It permits a reduction of costs, an increase in quality and often, a shortening of the time necessary to get the product onto the market (Cabello et al., 2012; Joel and Fredrik, 2017). During the conceptual design phase, knowledge-rich key information is taken into account, e.g., stakeholder requirements, preliminary product definition, key value attributes, functional capabilities and level of innovations. Managing vast amounts of knowledge within this phase potentially leads to challenges. Furthermore, it is discovered that 79% of all conceptual design problems could have been prevented by the correct knowledge being provided in the right place at the right time (Maksimovic et al., 2014). A better PD performance may be ensured through a settled knowledge management approach and also through the definition of appropriate product development strategies (Furian et al., 2013; Jonas et al., 2016). A knowledge strategy for PD should accommodate and integrate human processes with technical processes by enabling information and knowledge streams that aid knowledge creation and recombination, via enhanced communication, both formal and informal (Bandinelli et al., 2014; Correia et al., 2014; Essamlali et al., 2017). To improve their PD process, particularly in the conceptual design phase, organisations are implementing various alternative approaches. However, it is almost impossible to reach a verdict in which PD approach is the most appropriate one (Johannesson et al., 2017).

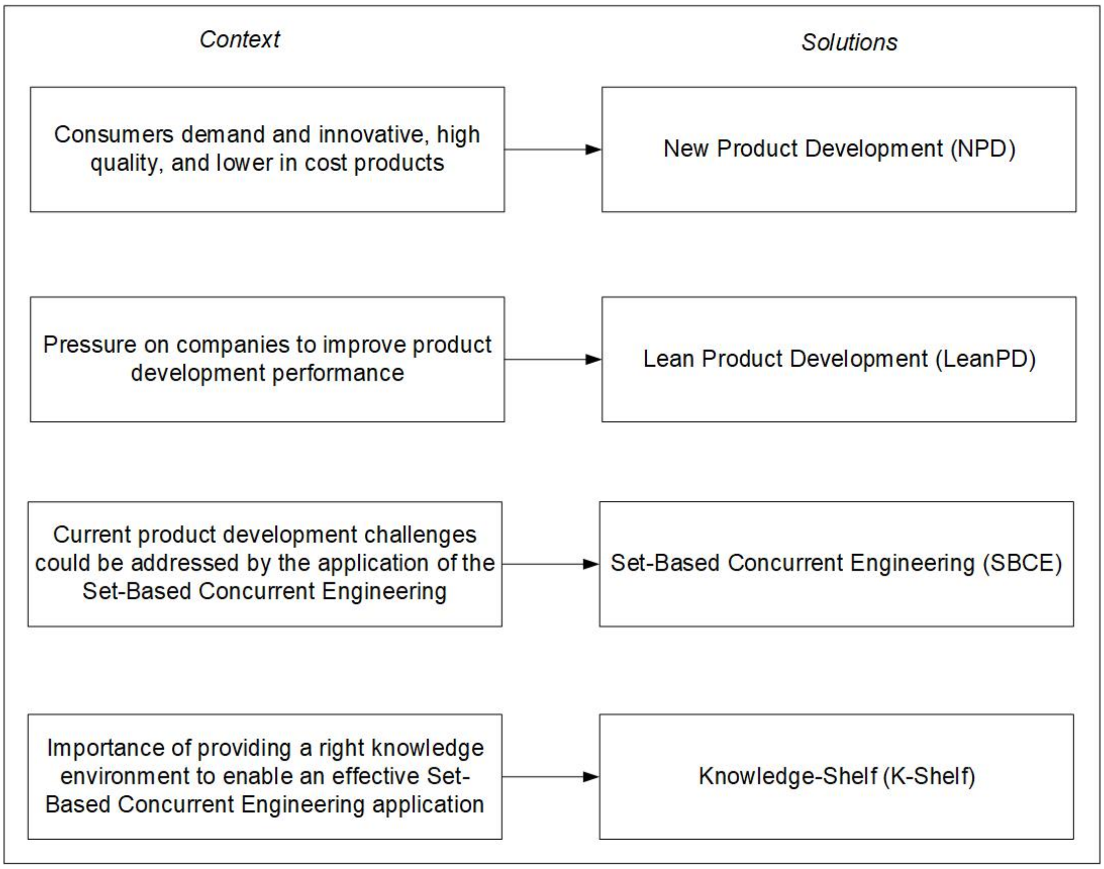


Figure 1-1 Research Context

Over decades, researchers have focused on defining principles and practices to increase effectiveness and efficiency of PD. Among different PD approaches, Lean Product Development (LeanPD) was introduced in the early 1990s based on Toyota's Product Development System (Ward et al., 1995). One highly promising approach advocated as a solution to this challenge is Set-Based Concurrent Engineering (SBCE), a design approach that puts great emphasis on the thorough exploration of more than one design solution (Al-Ashaab and Sobek, 2013).

SBCE enables the focus to be on value and in particular knowledge and learning. It is also considered as the main enabler of LeanPD, along with a knowledge environment which allows learning more about the design alternatives (Khan et al., 2013). However, studies that relate it to the understanding drawn from the practice of providing knowledge seem to be lacking. This research establishes a link between the SBCE process model and knowledge environment through knowledge provision in the conceptual design phase of PD as illustrated in Figure 1-1.

1.2 Research Questions

In this research, four research questions were identified as stated below:

1. What is the right knowledge environment to enable SBCE application?
2. How the design decision rationale in SBCE application can be captured?
3. How the captured knowledge in SBCE application can be structured for future reuse?
4. What is the right IT environment to demonstrate the concept of Knowledge-Shelf?

1.3 Research Aim and Objectives

The aim of the research is to develop the concept and capabilities of the K-Shelf to provide a suitable knowledge environment to enable SBCE applications. This research comprises of five research objectives as follows:

1. Capture the current approaches of knowledge environment in SBCE application.
2. Define the requirements of the K-Shelf concept to enable the SBCE application.
3. Define the mechanism to capture the design decisions rationale in SBCE application.
4. Develop an application software to demonstrate the K-Shelf concept.
5. Validate the K-Shelf software through industrial case studies.

1.4 Thesis Structure

This thesis comprises of seven chapters in sequential order of the research, as shown in Figure 1-2. Chapter 2 describes the methodology adapted to undertake this research.

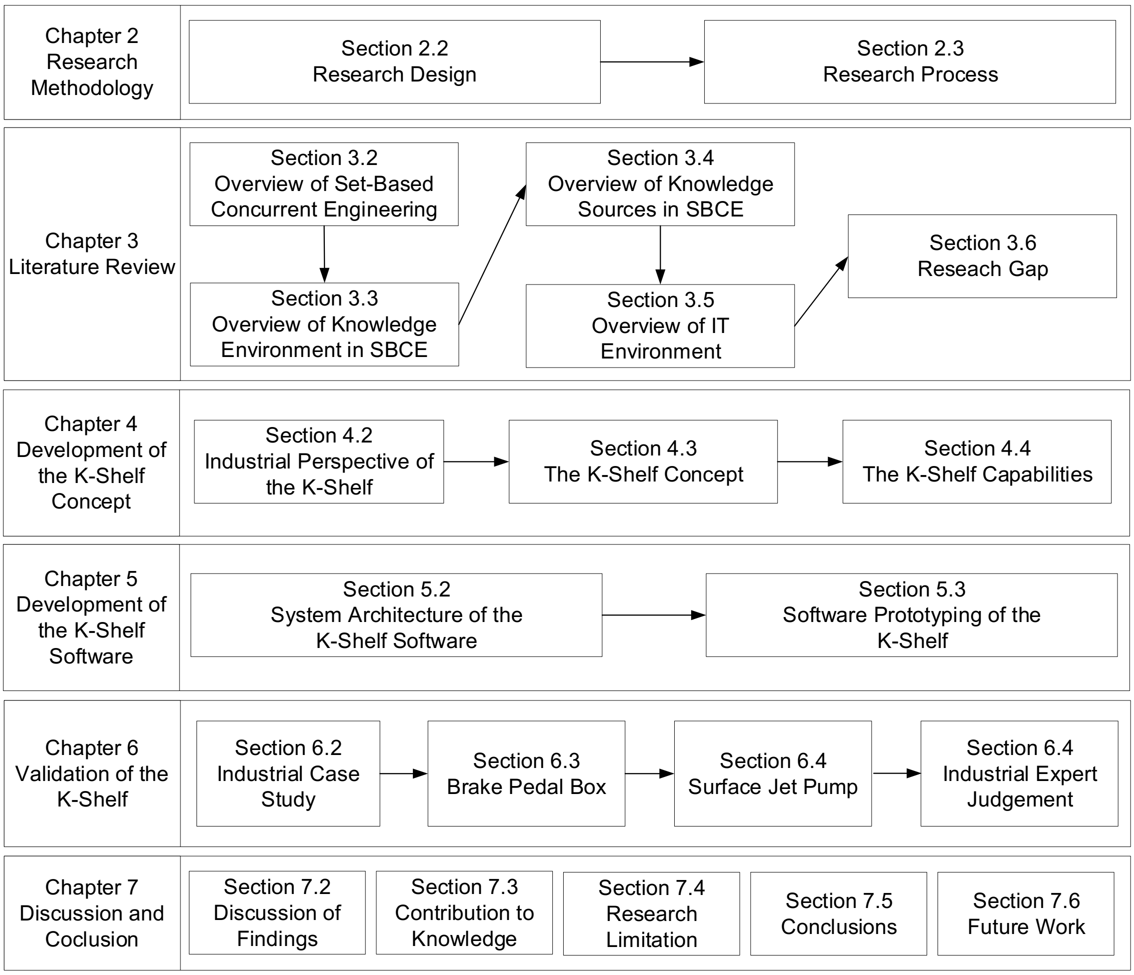


Figure 1-2 Thesis structure

Chapter 3 reviews the literature related to knowledge environment, as well as knowledge infrastructure and introduction of design decision rationale approaches in SBCE application. Chapter 4 presents the K-Shelf concept and capabilities in SBCE application as a major contribution of the work presented research. Chapter 5 presents the software development of the K-Shelf software to demonstrate the K-Shelf concept. This includes, as shown in Figure 1-2, system architecture and software prototyping. Chapter 6 presents the validation of the K-Shelf in two case studies. Chapter 7 discusses the research finding and outlines the contribution to knowledge and research limitations as well as the conclusion and future work.

Chapter 2: Research Methodology

2.1 Introduction

This chapter describes the methodology followed by author in order to conduct the research. The importance of defining and justifying the research method is signified to ensure the investigation will provide an answer to the research questions. As shown in Figure 2-1, the research methodology as a systematic approach consist of a research design, Section 2.2, and research process, Section 2.3. The first one compares different characteristics of three research methods considered in this research as well as depicting adequate research methods.

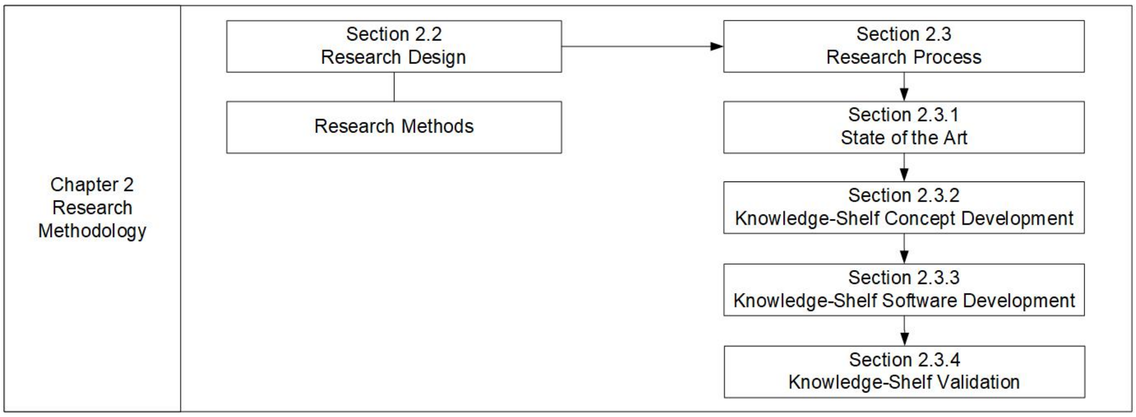


Figure 2-1 Chapter 2 Structure

The research process provides the overall phases needed to complete the research alongside its anticipated output. The research phases include state of the art, the K-Shelf concept development, the K-Shelf software development and the K-Shelf validation.

2.2 Research Design

The design of research is not only oriented towards problem solving but also produces knowledge that can serve as a reference for the improvement of theories. A research work can be defined as a systematic investigation whose central goal is usually the development or refinement of theories and, in some cases, the solution to problems (Gregor and Hevner, 2013). One may further add that the need for research work arises from the realisation that adequate and systematised information to answer some given problem is missing (Peffers et al., 2007). Research should be designed based on an application of rigorous methods in both the construction and the evaluation of artefacts.

Three main points considered in this research comprises of: (i) the method should address the research question, (ii) the method must be recognised by the scientific community and (iii) the method should clearly demonstrate the procedures that were adopted for the research (Dresch et al., 2015). Table 2-1 demonstrates the main differences and similarities among the three research methods being considered in conducting this research – Design Science Research (DSR), case study and action research. Table 2-1 does not attempt to be exhaustive but instead demonstrates the main differences and similarities among these methods.

The main differences among these three research methods are their objectives, the form used by the method to evaluate the results, the role of the researcher in conducting activities, the potential for the generalization of knowledge, the potential collaboration between the researcher and the persons researched (researcher-researched collaboration), and the requirement of an empirical basis for the study. The DSR is based on the systematic form of designing, whereas the action research and case study are linked to the natural and social sciences. However, depending on the purpose of the research, the joint use of these methods and the use of the case study and action research under the design science paradigm are not disregarded.

Table 2-1 Considered research methods

Characteristics	DSR	Case study	Action research
Objectives	Develop artefacts that enable satisfactory solutions to practical problems	Assist in the understanding of complex social phenomena	Solve or explain problems of a given system by generating practical and theoretical knowledge

	Design and recommend	Explore, describe, explain and predict	Explore, describe, explain and predict
	• Define the problem • Suggest • Develop • Evaluate • Conclude	• Define conceptual structure • Plan the case(s) • Conduct pilot • Collect data • Analyse data • Generate report	• Plan actions • Collect data • Analyse data and plan actions • Implement actions • Evaluate results • Monitor (continuous)
Results	Artefacts (constructs, models, method instantiations) and improvement of theories	• Constructs • Hypothesis • Descriptions • Explanations	• Constructs • Hypothesis • Descriptions • Explanations • Actions
Type of knowledge	How things should be	How things are or how they behave	How things are or how they behave
Researcher's role	Builder and/or evaluator of the artefacts	Observer	Multiple, due to the action research type
Empirical basis	Not mandatory	Mandatory	Mandatory
Researcher-researched collaboration	Not mandatory	Not mandatory	Mandatory
Implementation	Not mandatory	Not applicable	Mandatory
Evaluation of results	• Applications • Simulations • Experiments	Comparison against the theory	Comparison against the theory
Approach	Qualitative and/or quantitative	Qualitative	Qualitative

Specificity	Generalisable to a certain class of problem	Specific situation	Specific situation

Among the considered methods of research, DSR was selected as the overall phases needed to complete this research. The DSR is a method that establishes and operationalises research when the desired goal is an artefact. An artefact is a symbolic representation or a physical instantiation of design concept. The DSR, unlike other research methods (e.g. case study, action research) seeks to produce knowledge in the form of prescription or a design. A prescription supports the solving of a particular real problem, while a design builds new artefact.

Two essential factors for the success of the DSR are rigour and relevance (Dresch et al., 2015). Figure 2-2 outlines adopted research design and its relationship between rigour and relevance. DSR should consider the relevance of research to organisations. Rigour should also be considered to make the research valid and reliable and can contribute to an increased knowledge base in a given area. The knowledge base is where established foundations and methods that are recognised by the academic community are located. These methods primarily support the justification and evaluation activities of a constructed artefacts or improved theory.

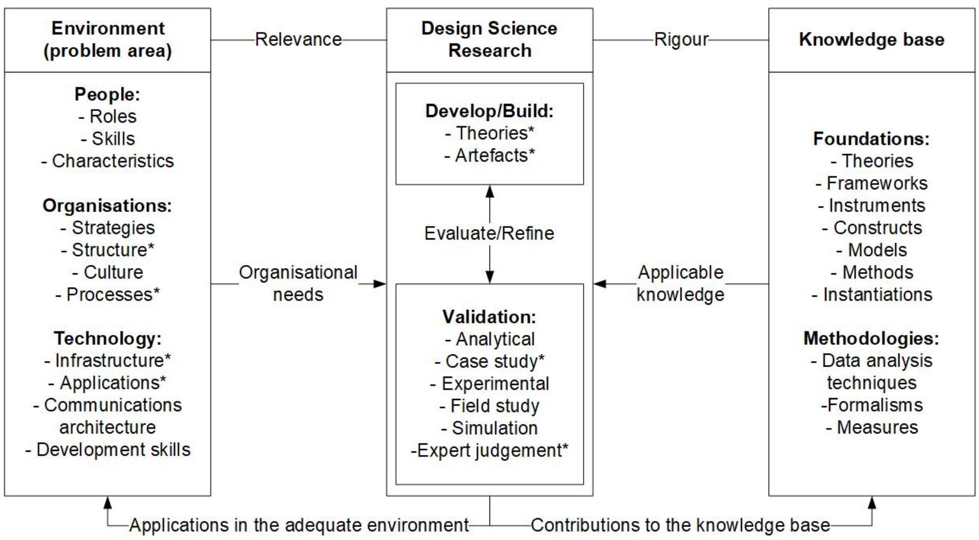


Figure 2-2 Research rigour and relevance (adopted from Dresch et al., 2015)

To address research objective 1, which is capture the current approaches of knowledge environment in SBCE application, as presented in Section 1.3, knowledge base is seen as adequate to understand theories and artefacts were previously used or developed. Such applicable knowledge subsequently supports research objective 2 and 3, which are to define the requirements of the K-Shelf concept to enable the SBCE application and to define the mechanism to capture the alternative design decisions rationale. The organisational needs were observed to address research objective 2 and 3, which includes; organisations (structure and processes), and technology (infrastructure and applications) as tagged with asterisks (*) in Figure 2-2. Based on the observed organisational needs and the aim of research to provide the suitable knowledge environment to support SBCE application, DSR is utilised to develop the theory – the K-Shelf concept.

In addition, to address research objective 4, which is to develop an application software to demonstrate the K-Shelf concept, an artefact of web-based software application is developed. Artefact can also be defined as any element in a software development project. It includes executable modules of a software including its documentation, images and database structure. Artefact of a web-based software application mentioned in the thesis is the K-Shelf software. The K-Shelf software underwent validation as part of research objective 5, which is to determine practical implication of the K-Shelf capabilities via two case studies and two expert judgements.

2.3 Research Process

Upon a selected research method, research process presents the phases, tasks and methods adapted as well as its resulting output. As shown in Figure 2-3, the adapted research process comprises of four phases, namely state of the art, the K-Shelf concept development, the K-Shelf software development and the K-Shelf validation.

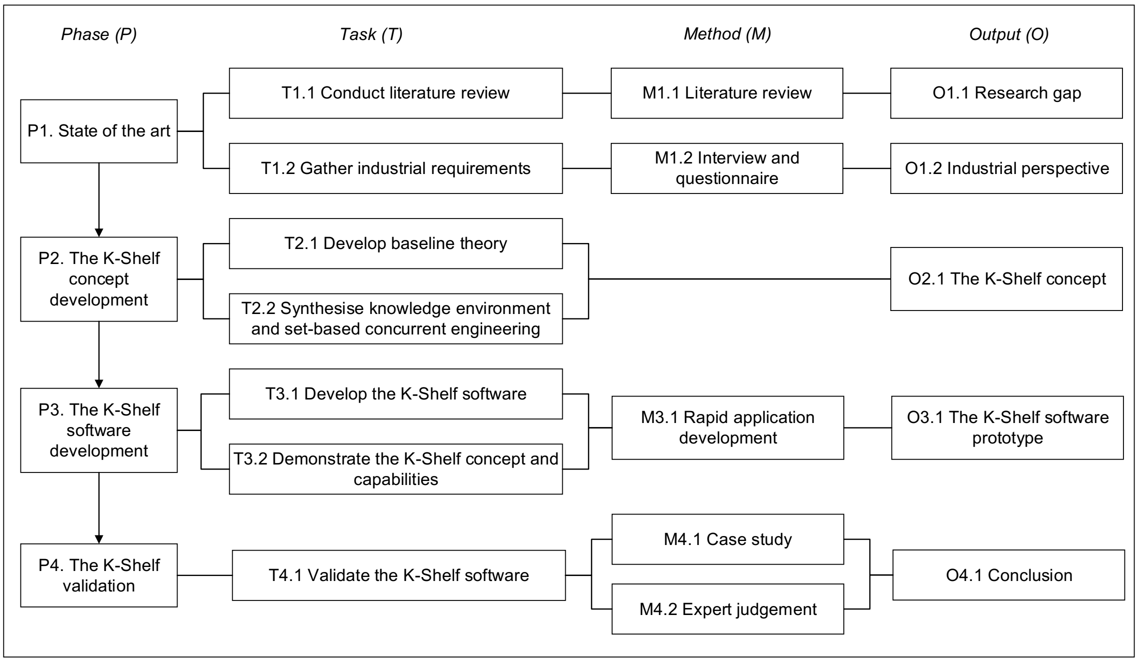


Figure 2-3 Research Methodology

The research phases of the chosen methods are explained as the following paragraphs.

2.3.1 State of the Art

In this phase, the state of the art in the literature as well as in current industrial knowledge environment practices are explored. The phase of state of the art was undertaken using three methods for data collection, namely literature review, interview and questionnaire.

2.3.1.1 Literature Review

The proposed research is positioned in the intersection between two fields of study – SBCE and knowledge environment. Four scholarly journal databases were chosen to provide the richness of literature and to accommodate the interdisciplinary view of the topic under review. Scopus and Web of Science provided literatures that mostly focussed on science and engineering, whereas Elton B. Stephens Co. (EBSCO) and ProQuest also suggested literature in other disciplines which might be relevant to the topic.

For each online database and review question, keywords search was developed to retrieve as many related papers as possible. Some suggestions from an information specialist and research supervisors were incorporated into these search strings along with independent selection and cross-references, as illustrated in Figure 2-4. Keyword search used in this research is presented in Table 2-2.

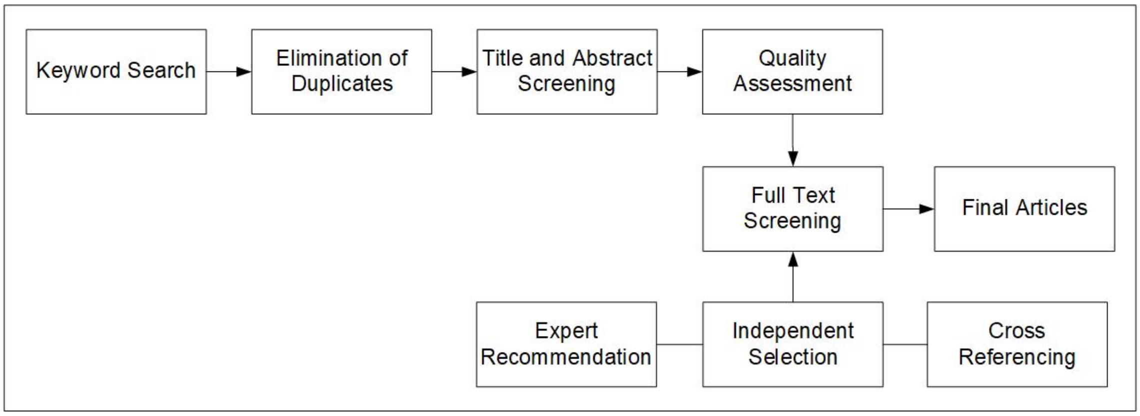


Figure 2-4 Literature Review Strategy

During the search process, some general limitations were applied for all online databases. Only peer-reviewed academic journal articles in English were retrieved. From 257 retrieved peer-reviewed articles in English as seen in Table 2-2, 74 duplicate values found and removed; 183 unique articles remained for title and abstract screening. Subsequently, the author performed title and abstract screening upon the remaining article to find articles that match with the research questions; 98 articles remained for quality assessment.

Table 2-2 Developed search strings for literature review

Research questions	Keyword search	Results (number of articles)				
		Scopus	Web of Science	EBSCO	ProQuest	Total
What is the right knowledge environment to	(TITLE-ABS-KEY (knowledge AND (environment OR "life-cycle" OR "life cycle"	20	0	0	0	20

enable SBCE application?	OR “based environment” OR management)) AND TITLE-ABS-KEY (“set-based concurrent engineering” OR “lean product development” OR “set-based design”))					
How the design decision rationale in SBCE application can be captured?	(TITLE-ABS-KEY (design AND (rational OR rationale OR reason OR justification OR notation OR annotation OR relationship OR explanation OR documentation OR guidance)) OR TITLE-ABS-KEY (capture OR capturing OR structure OR reuse OR model OR approach OR concept OR application OR software OR method OR representation) AND TITLE-ABS-KEY (“set-based concurrent engineering” OR “lean product development” OR “set-based design”))	121	68	22	5	216

How the captured knowledge in SBCE application can be structured for future reuse?	(TITLE-ABS-KEY (knowledge AND (identification OR representation OR creation OR structure OR captur* OR sharing OR reuse)) AND TITLE-ABS-KEY (“set-based concurrent engineering” OR “lean product development” OR “set-based design”))	8	4	6	1	19
What is the right IT environment to demonstrate the concept of Knowledge-Shelf?	(TITLE-ABS-KEY ((“information technology” OR “ICT”) AND (infrastructure OR model OR approach OR concept OR application OR software OR method)) AND TITLE-ABS-KEY (“set-based concurrent engineering” OR “lean product development” OR “set-based design”))	2	0	0	0	2
Total		151	72	28	6	257

The technique followed by the author to assess the quality of articles is shown in Table 2-3. The author measured the quality of articles using following dimensions: quality of the study performance, relevancy to the review questions, and relevancy to the review focus. Synthesis technique adopted in the review was ecological triangulation began with tabulation of selected primary studies to form a map of obtained result.

Table 2-3 Articles quality assessment

Research questions	Title and abstract inclusion criteria	Full text inclusion criteria
What is the right knowledge environment to enable SBCE application?	Research problem, significance, methodology, result and conclusion talk about knowledge environment approach in SBCE application	1. Method is clear 2. Results are supported by facts and data 3. Relevance to research questions 4. Context similarity (e.g. study conducted in a similar product development approach)
How the design decision rationale in SBCE application could be captured?	Research problem, significance, methodology, result and conclusion talk about capturing design decision rationale in SBCE application	
How the captured knowledge in SBCE application could be structured for future reuse?	Research problem, significance, methodology, result and conclusion talk about structuring and reusing knowledge in SBCE application	
What is the right IT environment to develop the Knowledge-Shelf to demonstrate the concept?	Research problem, significance, methodology, result and conclusion talk about IT architecture and infrastructure practice in SBCE application	

After the articles underwent quality assessment, a total of 69 articles were obtained including some articles advised by academic supervisors, the author selections and cross-referencing articles. The resulting literature review is presented in Chapter 3.

2.3.1.2 Interview and Questionnaire

Interview and questionnaire are essentially empirical where the researcher acts as an observer and should not interfere in the study. The interview is one of the most widely used methods for qualitative research (Robson and McCartan, 2015). 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 capturing design decision rationale for alternative conceptual design 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.

2.3.2 The K-Shelf Concept Development

In this phase the author develops the K-Shelf concept supported by a baseline theory to increase understanding for future researcher which will be addressed in Section 4.3.1. In addition, the synthesising of the K-Shelf stages comprises definition of requirements and capabilities which will be explained in Section 4.3.2. Both contribute to the output of the resulting the K-Shelf concept accomplished through DSR and are explained as follows.

2.3.2.1 Design Science Research

A key feature of Design Science Research (DSR) as a method is that it is oriented to solving specific problems to obtain a satisfactory solution for the situation even if the solution is not optimal. DSR is a method that establishes research when the desired goal is an artefact or a recommendation (Dresch et al., 2015). Its application is most notable in the engineering and computer science disciplines, though it is not restricted to these and can be found in many disciplines and fields. The application of DSR can potentially reduce the existing gap between theory and practice. This method is not only oriented towards problem solving but also produces knowledge that can serve as a reference for the improvement of theories. Hence, the author decided to use DSR for the K-Shelf concept development, the adaptation of which is presented in Figure 2-5.

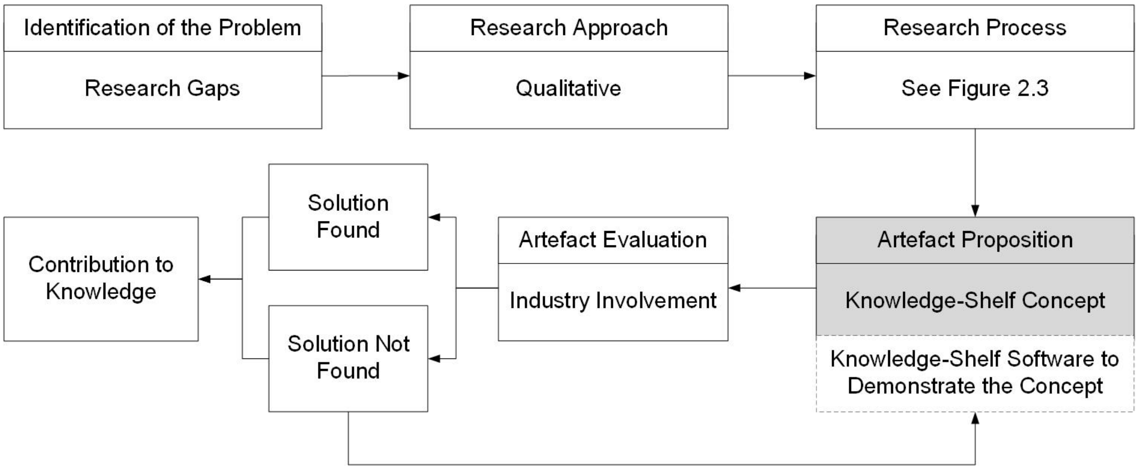


Figure 2-5 Stages of Design Science Research (DSR)

The K-Shelf development comprises of the artefact proposition of K-Shelf concept and software. The K-Shelf concept is the centric stage of this research as shown in Figure 2-5. Its development is directed by stages of identification of problem, research approach and research process. The repetitive loop between artefact evaluation through industry involvement and instance of solution not found provided a major source of data collection to feed back to the previous stages.

2.3.3 The K-Shelf Software Development

The K-Shelf software development is developed using Rapid Application Development (RAD) approach. RAD approach integrates end-user in the development using iterative prototyping emphasizing on delivering a series of fully functional prototype. The RAD is based on agile software development. The agile projects are 28% more successful than traditional projects (Kruchten, 2013). RAD has been applied frequently for the construction of web sites or for web-based interfaces to back-end infrastructure systems.

Martin (1991) divides the RAD process into four distinct phases; requirement planning, used design, construction and cutover as shown in Figure 2-6. The implementation of RAD in the development of K-Shelf software will be presented in Section 5.3. Although RAD is not a new approach in software development, however, this approach is still a sharp alternative to the typical waterfall development model, which often focuses largely on planning and sequential design practices (Naz and Khan, 2015).

At present, there are some commercial RAD tools that are not yet tailored to address product development nor knowledge management workflow. Hence, the author decided to develop the K-Shelf software using an application development tool whilst adopting RAD approach to simplify and speed-up the programming process. With RAD, the basics of analysis and design performed, and work immediately begins on a system prototype. The author decided to use Oracle Application Express (APEX) version 5.0 to develop the K-Shelf software that will be explained in Section 5.2.

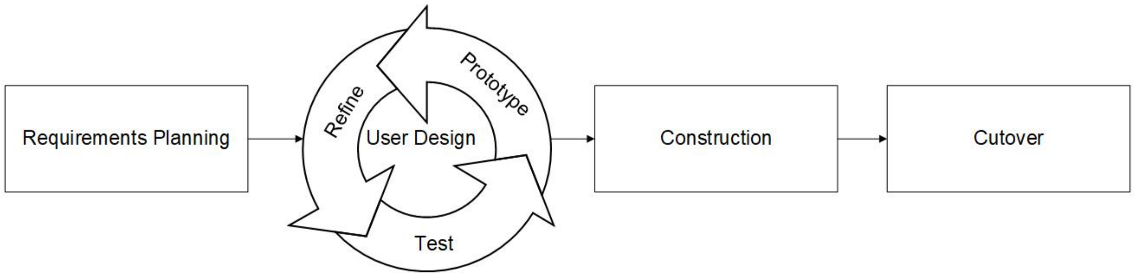


Figure 2-6 Rapid application development model adopted from Martin (1991)

The author adopted RAD approach to develop the K-Shelf software as illustrated in Figure 2-6. It is commenced with requirement planning phase that is the critical step for the accomplishment of the K-Shelf software. During this phase, the author and industrial collaborators communicate to determine the industrial perspectives for the K-Shelf software that will be presented in Section 4.2.

Subsequently, during the user design phase, models and prototypes that represent all system processes, inputs, and outputs are developed. Industrial collaborators continue to participate in the construction phase for software improvement, and finally, cutover is the implementation phase of software. Compared with traditional methods, the entire process of RAD is compressed. It is the reason why the author chooses RAD approach in developing the K-Shelf software to demonstrate the K-Shelf concept.

To do the analysis and design, the author utilised the Unified Modelling Language (UML). The UML provides a common vocabulary of object-oriented terms and diagramming techniques to model the K-Shelf software. It is very suitable for object-oriented analysis and design and therefore can be used to model the interaction with data-objects.

2.3.4 Knowledge-Shelf Validation

2.3.4.1 Case Study

A case study is an investigation that is deemed empirical and that seeks a better understanding of a contemporary and usually complex phenomenon in its real context (Yin, 2014). Case studies are considered valuable because they allow detailed descriptions of phenomena. They are normally based on a diverse set of data sources. 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. 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. Two industrial case studies were conducted throughout this research as presented in Chapter 6.

2.3.4.2 Expert Judgement

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 6.5.

Chapter 3: Literature Review

3.1 Introduction

Chapter 3 presents the review of the related literature. The particular scope of the literature review as defined by the author as shown in Section 2.3.1.1. This chapter is divided into five sections consists of overview of SBCE, overview of knowledge environment in SBCE, overview of knowledge sources in SBCE, overview of Information Technology (IT) and research gaps. The knowledge sources addressed in this research are TOC and design rationale.

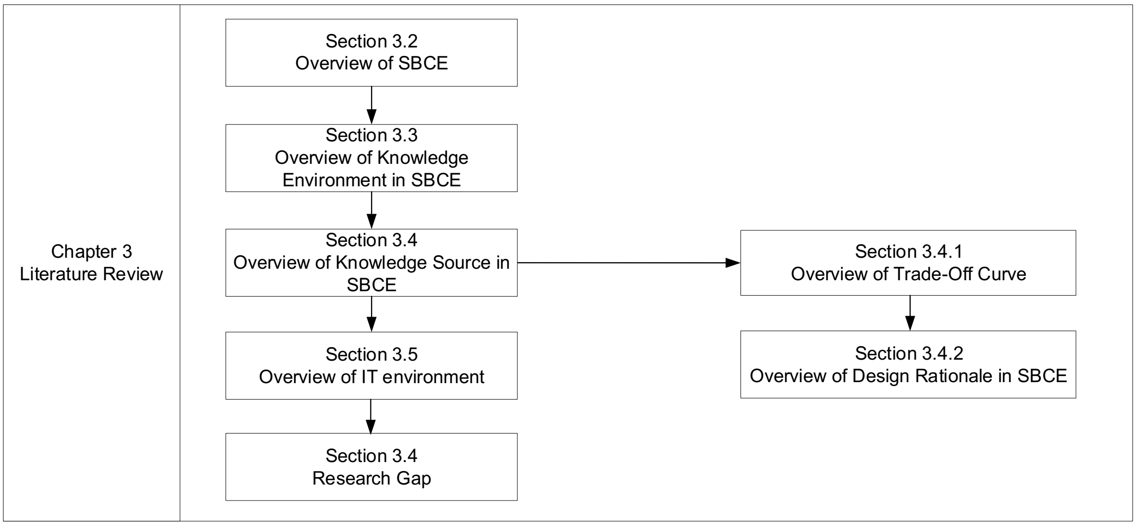


Figure 3-1 Chapter 3 structure

3.2 Overview of SBCE

The Set-Based Concurrent Engineering (SBCE) is a comprehensive framework for dealing with multiple alternative solutions throughout all stages of development, until there is only one candidate left. The framework adheres to the LeanPD philosophy and contains several basic principles which has proven to efficiently provide support for product development in stages such as product planning, concept development, concept screening and detailed design.

PD is essential for business development and companies' sustainability. To overcome the recurrent PD challenges, the application of the Lean Product and Process Development (LeanPPD) and Set-based Concurrent Engineering

(SBCE), its main enabler, provide a solution that permits rework reduction, improved innovation, and a knowledge environment (Khan et al., 2011) as illustrated in Figure 3-2.

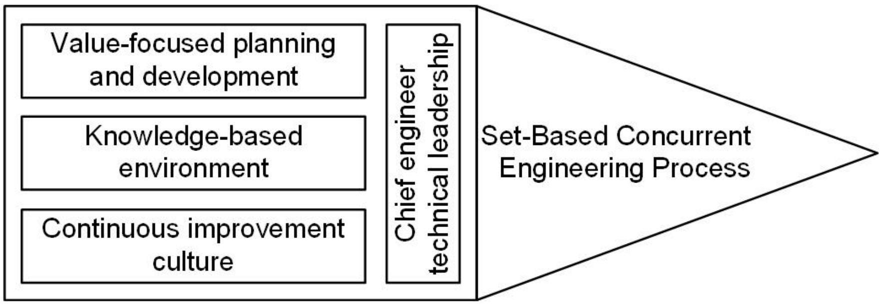


Figure 3-2 The LeanPPD model (Khan et al., 2011)

(Al-ashaab et al., 2013) compiles an extensive state of the art review for both LeanPD and SBCE work. The principles of LeanPD were collected into a conceptual model – Toyota lean PD system (Liker and Morgan, 2006). Ward et al. (1995) discovered that the real success of Japanese manufacturers originated from the Toyota PD System rather than their production system. Ward found this through investigating multiple alternative solutions during the styling activity rather than deciding to pursue one solution.

Design participants practice SBCE by reasoning, developing, and communicating about a set of solutions in parallel. As the design progresses, they gradually narrow down their respective set of solutions based on the knowledge gained. As they narrow, they commit to staying within the sets so that the others can rely on their communication (Sobek, 1996). SBCE approach allows handling of various sources of uncertainties during early stages of product development and make well founded decisions which significantly reduces the need for iteration process (Ward and Sobek, 2014).

The principle of SBCE was described in the conceptual framework which breaks into three broad principles; map the design space; integrate by intersection; and establish feasibility before commitment (Liker et al., 1996). However, they have not provided a detailed SBCE process model. Al-Ashaab et al. (2013) have designed a well-structured SBCE process model which consists of five stages:

define value, map design space, develop concept sets, converge on system, and detailed design as illustrated in Figure 3-3.

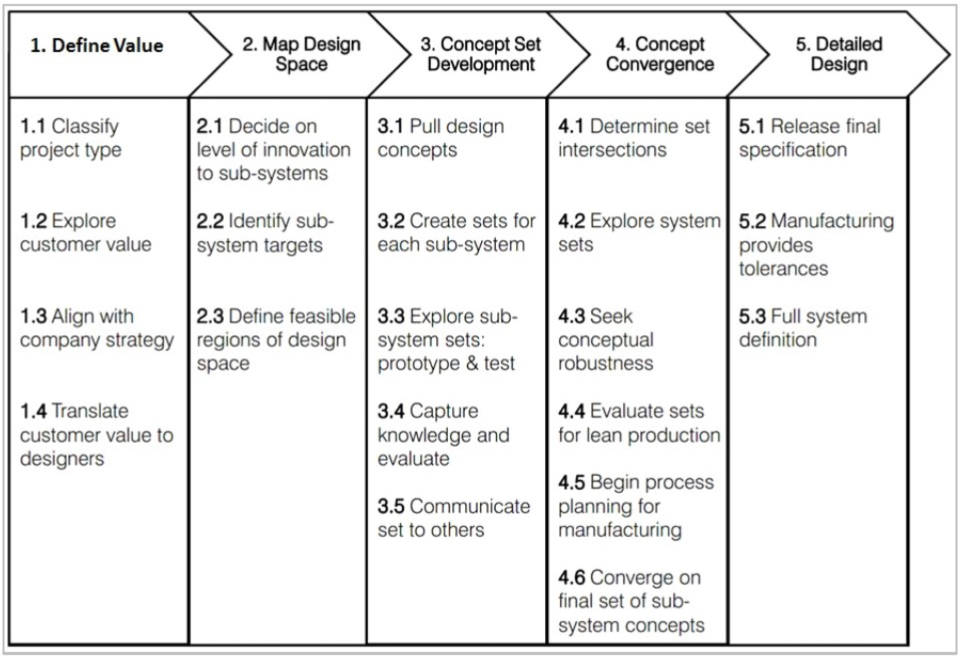


Figure 3-3 The SBCE Process Model (Al-Ashaab et al., 2013)

Several case studies have been performed using their SBCE process model in the area of aerospace, oil and gas, and automotive. Maulana et al. (2017) identified the potential benefit of SBCE application, however it is limited as a paper-based exercise which has not been advanced into a comprehensible format to support designers innovate or improve a product in a knowledge environment.

3.3 Overview of Knowledge Environment in SBCE

Knowledge is considered as an important element of SBCE (Al-ashaab et al., 2013; Ward and Sobek, 2014). Managing knowledge in SBCE is critical since design works are distributed across designers and customers (Liker et al., 1996; Sobek et al., 1999). A knowledge environment in entire product lifecycle is needed to support value creation to the customers and products (Sorli and Stokic, 2012). Kennedy (2012) outline the need of knowledge environment to facilitate the knowledge capturing in SBCE for future use; where the knowledge of feasible and infeasible conceptual designs are captured as illustrated in Figure 3-4.

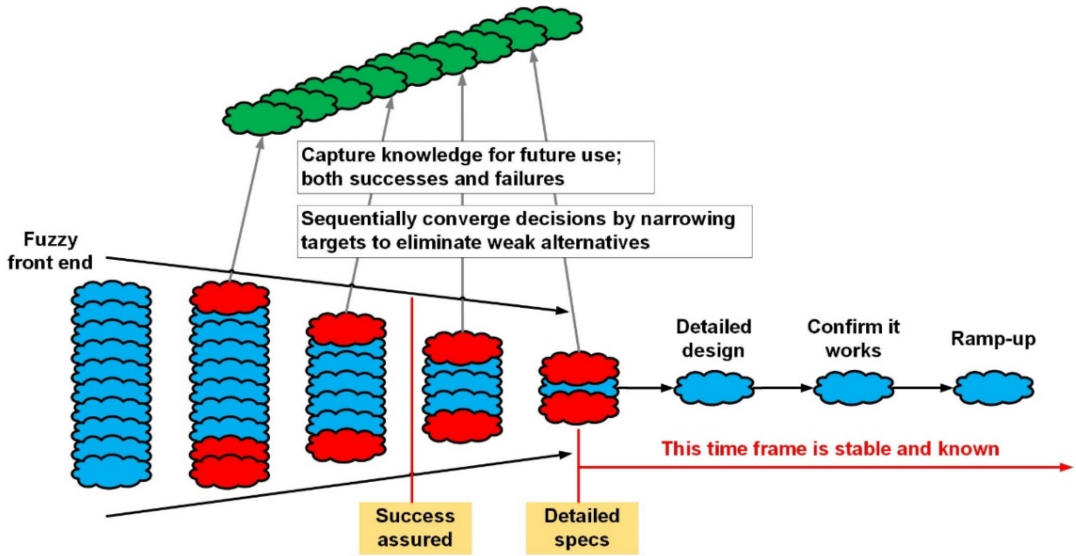


Figure 3-4 The need of knowledge environment in SBCE (Kennedy, 2012)

One of the biggest challenges in knowledge environments in engineering design and manufacturing is the effective capture and decoding of tacit knowledge (Maksimovic et al., 2014; Sung et al., 2012). Although knowledge is considered as an important element of SBCE, very few publications address this issue, of which none provides any detailed knowledge provision, as shown in Table 3-1.

Table 3-1 Research in SBCE Related to Knowledge

Articles	Case study in SBCE	Addressing Knowledge Provision	Implementing Software Application
(Liker et al., 1996)	NO	NO	NO
(Sobek II et al., 1999)	NO	NO	NO
(Ford and Sobek II, 2005)	NO	NO	NO
(Kennedy et al., 2014)	NO	NO	NO

(Al-Ashaab et al., 2013)	YES	NO	NO
(Khan et al., 2013)	NO	NO	NO
(Maksimovic, 2013)	NO	YES	NO
(Wasim et al., 2013)	YES	NO	NO
(Correia, et al., 2014)	YES	NO - Knowledge Sharing	YES
(Levandowski et al., 2014)	YES	NO - Knowledge Representation	YES
(Nahm and Ishi-kawa, 2006)	YES	NO	NO
(Kerga et al., 2014)	YES	NO	NO
(Schäfer and Sorensen, 2010)	YES	NO	NO
(Raudberget, 2010)	YES	NO	NO
(Belay et al., 2014)	YES	NO	NO
(Saranga, 2011)	YES	NO	NO

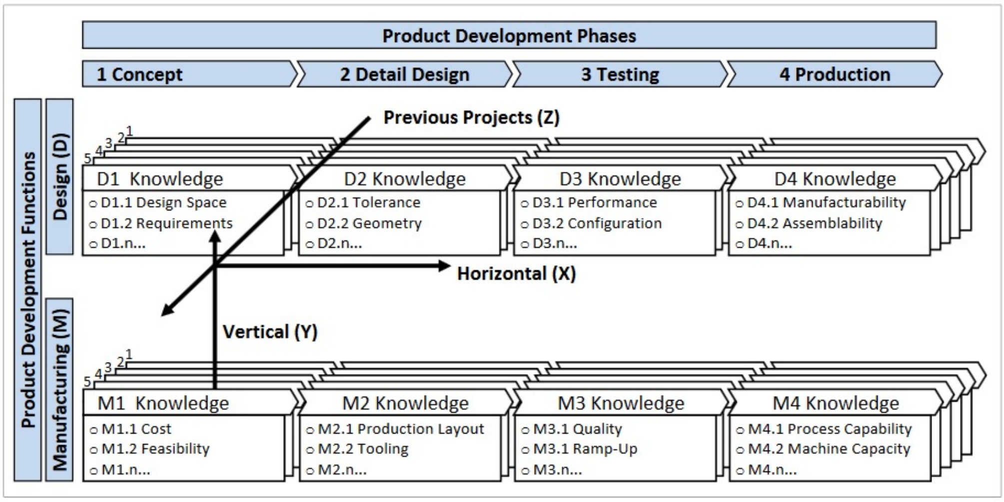


Figure 3-5 Three Dimension of Knowledge Management in Product Development (Maksimovic, 2013)

According to Dalkir (2005), one of key contributing factor in designing a knowledge environment is to introduce a Knowledge Life Cycle (KLC). A KLC transforms information to knowledge, which can be used on decision making. Al-Ashaab et al. (2012) summarised major established approach to achieve KLC. The one that might be suitable to be used in developing a knowledge environment is in LeanKLC framework to support Lean PD (Maksimovic, 2013) which addresses the baseline model of knowledge management practices in PD as shown in Figure 3-5.

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; Kennedy et al., 2014; Lindlöf et al., 2013).

Knowledge environment is an environment that apply a positive influence on human beings engaged to produce new knowledge or innovations (Hemlin at al., 2008). Van den Bosch et al. (1999) distinguished the type of knowledge in knowledge environment of companies into knowledge that related to products, processes and markets. Knowledge environment discussed in SBCE literature aims to highlight the importance of knowledge from different perspectives. (Sobek et al., 1999) for example highlighted the importance of organisational knowledge in forming the exceptional Toyota PD. Lundin et al. (2017) outline the existence of a knowledge value stream that incorporates capture and re-use of knowledge, as an addition to the set-based product value stream.

Reuse of design knowledge from previous design activities could improve engineering design (Baxter et al., 2008). Knowledge provision has been identified as one of the industrial challenges in managing PD, particularly in the issue of timely provision of the accurate knowledge at the right place. (Schuele et al., 2015) pointed out that there are four knowledge provision challenges: form, innovation, time and place. Knowledge provision should facilitate designers to have a greater variety of exposure to alternative design concepts (Zhu et al., 2011) and one method to provide it is the TOC (Araci et al., 2016).

The knowledge environment is advised as the key enabler for the lean product development (Al-Ashaab and Sobek, 2013). Maksimovic (2013) proposed a KLC framework to assist in the creation of knowledge environment to support lean product development. The SBCE, on other hand, is the core process of any lean product development (Ward et al., 2007). Khan et al. (2013) use the terminology of knowledge-based environment in which learning more about the design alternatives as the focus of product development activities. Recent research on software system to support SBCE practices is addressing communicating set of design (Correia et al., 2014; Gray and Singer, 2015), embedding SBCE into PLM software (Essamlali et al., 2017). Documentation of product knowledge in companies stresses the representation of the design, rather than the process of creating it (Ramesh and Sengupta, 1995). In such documentation, a developed design is usually defined in terms of parameters and specifications to describe the way the design works. The documentation, however, does not include the design decision rationale, that is explaining why the conceptual design is designed in the way that it is (Regli et al., 2000). Design decision rationale provides an insight into the reasons and justifications behind the design decisions (Lee, 1997) which can be used to determine what part of the design can be reused or modified.

The reviewed literature outlines that the knowledge environment is one key enabler of the LeanPPD paradigm whilst SBCE as its key enabler (Al-Ashaab, 2012). SBCE is a product development approach, which offers an environment that, not only permits but encourages radical innovation, increased learning and reuse of knowledge, reduces the development risk, and enable shorter and less costly development cycles (Golob, 2017). Hence, a rigorous implementation of SBCE cannot be achieved without having an adequate knowledge environment, which on the other hand requires an underlying framework to identify, capture and re-use the knowledge during product development. The knowledge environment discussed in SBCE literature aims to highlight the important of knowledge from different perspectives.

From the literature, knowledge environment was mostly interested in manifesting theoretical arguments rather than thoroughly investigating or describing closed loop industrial case study applications. More importantly, addressing the issue on knowledge environment related to SBCE has not as yet been thoroughly addressed.

3.4 Overview of Knowledge Sources in SBCE

3.4.1 Overview of Trade-off Curves

Trade-Off Curves (TOC) can be defined as a tool that helps visualise the relationship between conflicting parameters to enable better decision making (Araci, 2016). According to (Kennedy, 2014), a TOC is a relationship between two or more design decisions, and it is the subsystem knowledge from which design alternatives are evaluated and narrowed until the optimal design is chosen and therefore, provides reusable knowledge for future product designs. TOC helps establish the relation between different design parameters (Sobek et al., 1999).

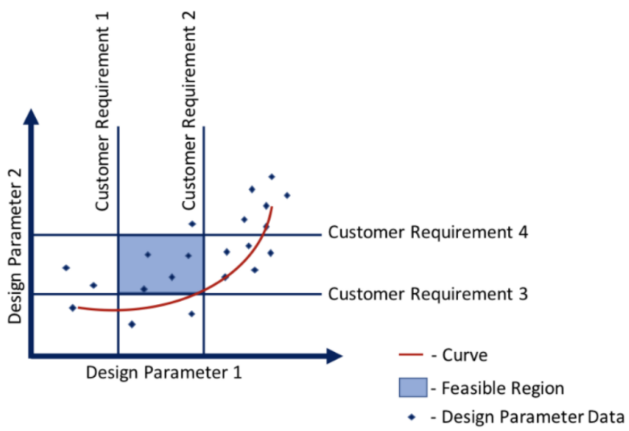


Figure 3-6 Example of Trade-Off Curve (Araci, 2016)

Conflicting design parameters influence the decision-making process significantly during the conceptual design stages of PD. This makes it more important to identify and understand the relationship between the conflicting parameters and to represent it visually(Correia et al., 2014; Maksimovic et al., 2012) TOCs are integral to the application of SBCE; they are important in generating a set of different design solutions as during this stage many different design parameters need to be simultaneously considered (Araci et al., 2017; Kennedy et al., 2014). The reviewed literature is clearly highlighting the importance of TOC in SBCE application. Although the literatures discuss TOC application in PD, however there is a lack of practical software solution that provides TOC in a knowledge environment to enable an effective SBCE application.

3.4.2 Overview of Design Rationale in SBCE

Design decision rationale offers improved collaboration, reuse, maintenance, learning, and documentation. To realize such benefits, the information must be captured in a structured manner. Well-structured design decision rationales can help designers track the issues and alternatives being explored and their evaluations (Gedell and Johannesson, 2013; Wang et al., 2012). In general, it is hard to obtain design decision rationale from design specifications because there is no systematic practice to capture them, even when some design decision rationales are captured, they are not structured in such a way that they can be retrieved and tracked easily (Tang et al., 2007). The realisation of design decision rationale system includes methods and tools to capture, structure, manage and share information across organisations, processes, systems and products.

Considerable effort has been put into developing design rationale systems. However, it appears mostly that the developed design decision rationale systems are not in widespread use in industry, and challenges still exist regarding effectively deploying the systems in industry (Regli et al., 2000). A significant task is to capture the design rationale whilst making the design decisions, known as design decision rationale. Usually, this parallel working is difficult to achieve. The main reason is that the systems often enable capturing design rationale after making the decisions or even when the product is already designed. While capturing design decision rationale is a significant task, simply accessing the design decision rationale is at the same level of importance. Around 20% of the designer’s time is spent searching for information and only 40% of design information requirements is met by documentation sources (Baxter et al., 2007). This implies that design information and knowledge is not often represented in a simply accessible knowledge base. From the literature review, various approaches of capturing design decision rationale have been identified that could be considered during the development and the realisation of the Knowledge-Shelf concept, as shown in Table 3-2.

Table 3-2 Approaches of capturing design decision rationale in PD

Design decision rationale approaches	Key features	Software implementation	Data structure presentation
The Design Process and Trace Modelling (Moones et al., 2014).	1. Multi criteria selection. 2. Decision changes propagation.	NO	NO
The Semantic Information Model (Rockwell et al., 2010).	1. Argument illustration. 2. Compare options.	YES	NO
The Design Rationale Editor (Bracewell et al., 2009).	1. Compares options. 2. Support design iterations.	YES	NO
The Software Engineering Using Rationale (Burge and Brown, 2002).	Support arguments: requirements, assumptions and alternatives.	YES	NO
The Architecture Rationale and Elements Linkage (Tang et al., 2007).	1. Compares options 2. Captures the evolution of design history.	YES	YES
The Kuaba Ontology (de Medeiros et al., 2005).	1. Compares options 2. Support design iterations	NO	NO
The Software Design Argumentation Model (Sigman and Liu, 2003).	1. Identify implicit conflicts 2. Computational evaluation	NO	NO
The Integrated Design Information System (Sagoo, 2012).	Integrate issue-based system and rule-based system	YES	NO

Design decisions in SBCE are made by eliminating the weakest designs, allowing the process to narrow slowly on a solution. The functions of an artefact reveal part of the rationale behind its design and thereby improving the understanding of its behaviour and potential (Raudberget et al., 2014). The research community has defined design decision rationale as a way to know the reasons behind a decision (Bracewell et al., 2009; Wang et al., 2012), but it could also be the justification for it, the design alternatives, and the evaluated trade-offs that led to the decision (Araci et al., 2017). Design decision rationale provides a better understanding of a design definition and often aims at explaining the artefact in the way it is designed, answering the “why” question.

Capturing design decision rationale requires identifying the type of rationale as well as the means and objective for capturing it (Agouridas and Simons, 2008; Balabko et al., 2005). One suggestion for capturing rationale is to first record as much information as possible during the design process and then organize the rationale based on the representation schema (Regli et al., 2000). However, it is not useful when a design decision rationale system captures and represents every possible detail of the design information. This should always be considered to avoid information overload (Ramesh, 1995). The potential value of design decision rationale in SBCE application is significant. however, the methods and systems developed to record, document, and manage design decision rationale are not widely used. Looking at the literature, it shows that the research community has addressed these challenges to some extent. There is a lack of evidence and method in how to capture design decision rationale in a structured manner to be used for future reuse in SBCE application. Although SBCE scholars refer to design decision rationale capturing as knowledge creation, the method and demonstration of design decision rationale in particular capturing and provision has not been addressed yet.

3.5 Overview of Information Technology Environment

Despite advances in data centre technologies and management approaches, many companies struggle to create an optimised Information Technology (IT) environment. The proliferation of data to be managed may cause an organisation to provision more storage, server and database solutions. Yet this may lead to unnecessary over provisioning of resources that may lead to resources being ultimately unused for an extended period of times (Mehta et al., 2018). Wang and

Yu (2012) pointed out that IT environment is one of the convergences of informatisation and industrialisation influencing factors, particularly in the aspect of investment in fixed assets of information, transmission, computer service and software. An effective and efficient IT environment as a corporate strategy should be incorporated in the management process to support the overall strategic business value (Dada et al., 2015; Guillemette and Paré, 2012). Most of the large-scale IT environments are complex, heterogeneous compositions often affected by unpredictable behaviour and poor manageability (Psaier and Dustdar, 2011). However, Gobetto (2014) proposed a homogeneous IT environment to reduce fixed cost of a company. The main advantages of a homogeneous IT environment are: access to the same data from different hardware platform, same CAD models, structural data available in the same environment, and availability of most up-to-date data.

Regarding to creating an IT environment that is conducive to knowledge management in PD, Tavares and Pessôa (2014) pointed out that a company should have architectural knowledge and specific knowledge of components.

3.6 Research Gaps

In total, four research gaps have been identified as a result of the literature review and presented as follows.

1. There is no well-defined knowledge environment to enable SBCE application.
2. There is a lack of evidence and method on how to capture design decision rationale in a structured manner to be used for future reuse in SBCE application.
3. There is no clear concept that will assist the creation of knowledge environment to support SBCE application.
4. There is no clear IT requirement to enable knowledge provision in SBCE application.

Chapter 4: Development of the K-Shelf Concept

4.1 Introduction

Chapter 4 covers the K-Shelf concept development to enable an effective SBCE application. This chapter is divided into three sections consists of industrial perspective, the K-Shelf concept and the K-Shelf capabilities. Figure 4-1 illustrates the development of the K-Shelf concept.

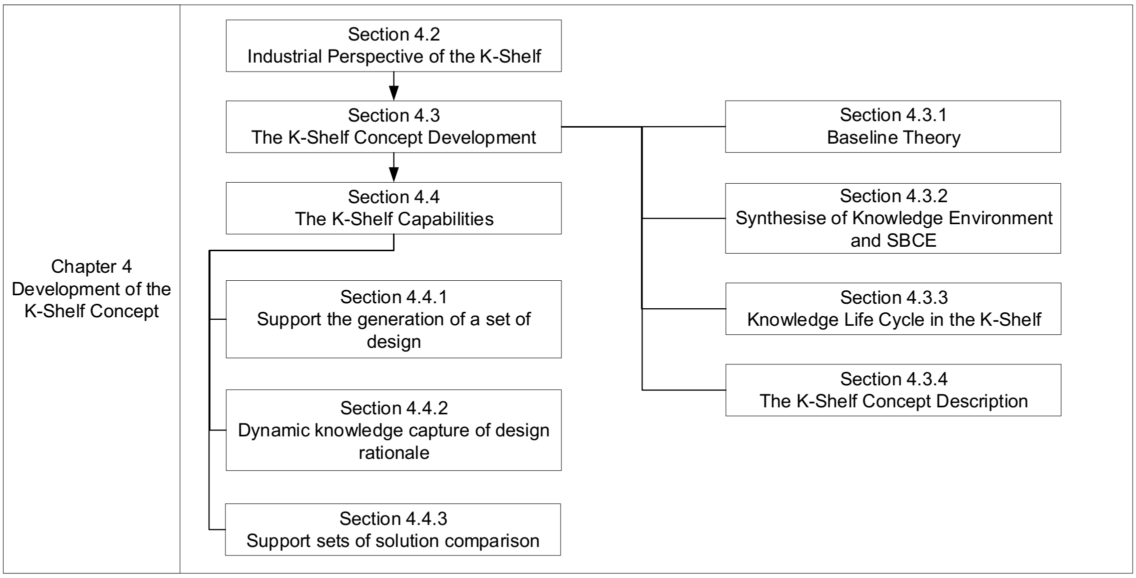


Figure 4-1 Chapter 4 structure

The development of K-Shelf concept starts with explanations of the industrial perspective of having a right knowledge environment in their PD process and it is presented in Section 4.2. These companies either have initiatives to apply SBCE or are interested in using SBCE to support their PD processes. The aim of this section is to provide evidence from the industries about the importance and the need of the K-Shelf.

4.2 Industrial Perspective of the K-Shelf

To get the perspective from industries regarding to their existing knowledge environment, a semi-structured questionnaire was developed to capture the most relevant information from two industrial collaborators in aerospace sector – Airbus and Rolls-Royce. The questionnaire was performed to understand what requirements is needed to establish a right knowledge environment to support their product development. Two companies have given the author the opportunity to undertake the questionnaire in an industry driven research as follows:

1. Airbus
   Airbus is a commercial aircraft manufacturer, with space and defence as well as helicopters divisions. Airbus is the largest aeronautics and space company in Europe and a worldwide leader. The company has aircraft and helicopter final assembly lines across Asia, Europe and the Americas – with roughly 180 locations and 12,000 direct suppliers globally.
2. Rolls Royce
   Rolls-Royce is a British multinational engineering company established in 1904. Today it designs, manufactures and distributes power systems for aviation and other industries. Rolls-Royce is the world's second-largest maker of aircraft engines and has major businesses in the marine propulsion and energy sectors.

The semi-structured questionnaire was completed by four participants from two companies as presented in Table 4-1. Participants were intentionally selected from design department with more than fifteen years of experience. As shown in Table 4-1, interviewees were from aerospace industries in the UK. Interviewing this strong profile of experts has facilitated the collection of reliable and trustworthy information about the practices, regarding knowledge environment, in product development activities of the industry.

Table 4-1 Profiles of the interviewees

No.	Company	Position	Years of Experience	Industry	Country
1.	Rolls-Royce	1. Designer 2. Subsystem integrator	15 - 28	Aerospace	UK
2.	Airbus	1. System design engineer 2. Designer	15 - 23	Aerospace	UK

Appendix A contains K-Shelf industrial requirements questionnaire, as designed by the author to support the development of K-Shelf. The questionnaire address five relevant themes of questions as follows:

1. Knowledge content
2. Knowledge structure
3. Knowledge format and provision
4. Knowledge capture
5. Knowledge sources

Questions 1-5 were designed to capture the existing knowledge approach in the PD practice of the companies. Furthermore, Questions 6-9 were designed to measure the K-Shelf requirements that have value and utility for the companies. The numbering of the following questions corresponds to the numbering as presented in the K-Shelf questionnaire in Appendix A.

Question 1: Do you refer to previous projects when commencing a new project?

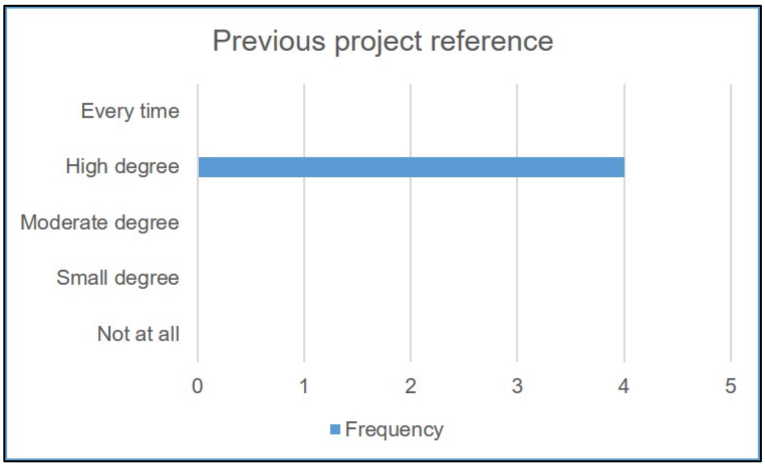


Figure 4-2 Frequency of referencing to previous project

Responses show that collecting information from previous projects to start a new project has a high importance; however, most of them have not established a systematic procedure to retrieve particular information from the previous project they had. There is a need to consider a systematic method to fetch knowledge from previous projects. The K-Shelf will support the set generation of design, one of its resource is knowledge extracted from previous project.

Question 2: What knowledge do you refer to when commencing a new project?

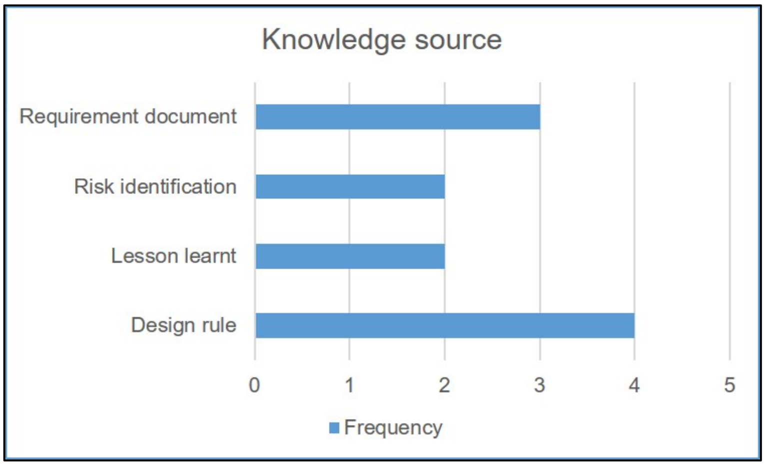


Figure 4-3 Knowledge sources used to commence new project

Knowledge sources were identified from participants responses, design decision rationale and trade-off curves were not commonly elaborated during their product development process. However, they are interested to learn both design decision rationale and TOC in assisting their decision making.

Question 3: How are design concepts represented?

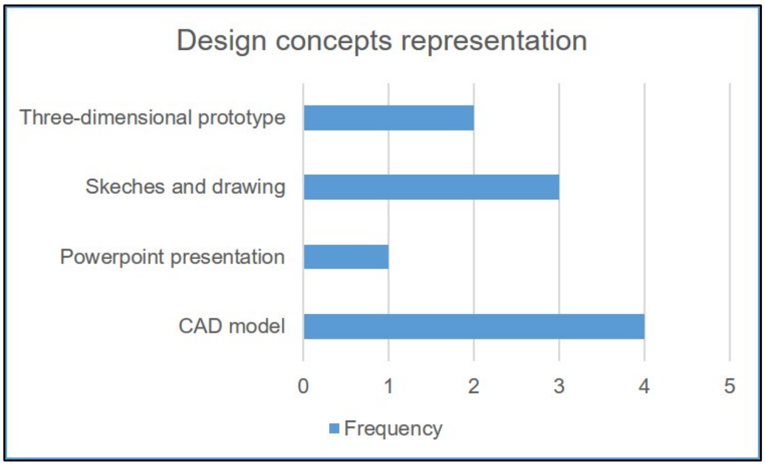


Figure 4-4 Design concepts representation

All participants use CAD model to represent the designs they created. It indicated that there is a need to create a knowledge environment that facilitate the designer to access CAD references in decision making.

Question 4: Do you record design decision rationale of infeasible design solutions?

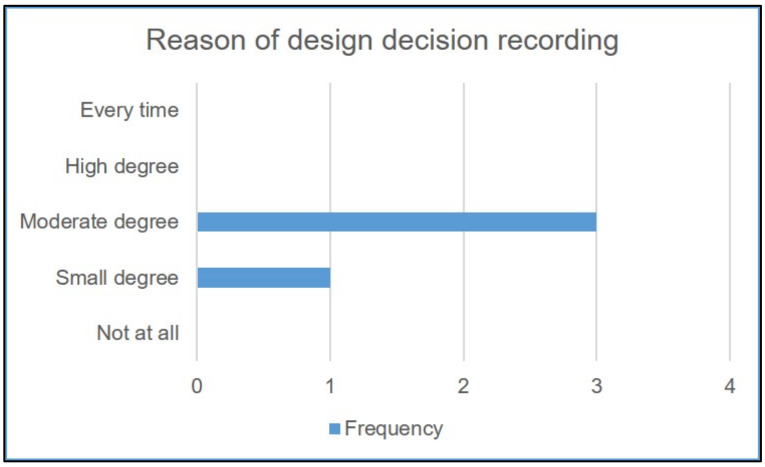


Figure 4-5 Design decision rationale capture

In these questions the existence and inexistence of a formal decision-making process was presented. The participants appreciate the use of design decision rationale, however, they currently do it on a paper note or word processor that is difficult to be retrieved in the future.

Question 5: Do you use any tools to compare multiple design solutions?

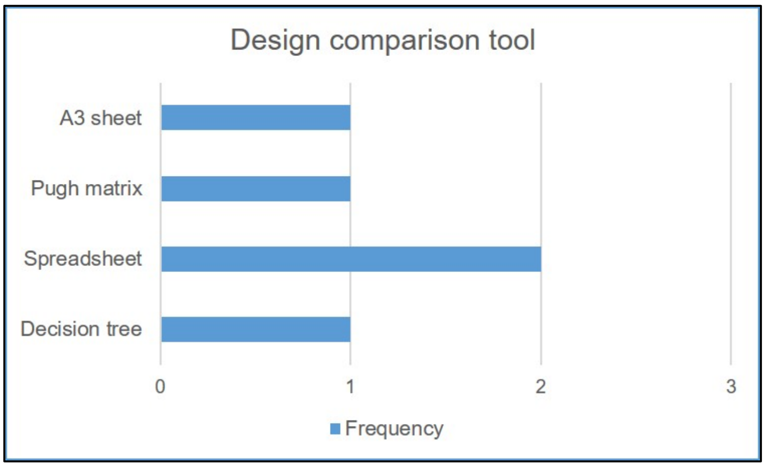


Figure 4-6 Design comparison tool

From Figure 4-6, most of participants use spreadsheet as design comparison tool. In a complex project, to compare designs using spreadsheet or chart will be cumbersome, particularly in a scattered file storage. From the literature review in Section 3.4.1, TOC are deemed as a proven tool to compare conflicting design in PD process. It is an opportunity to introduce the application of TOC in a knowledge environment that can be retrieved in an interactive way.

Question 6: Shall knowledge environment capture the knowledge to support customer value definition?

The aim of this question was to discover whether customer needs and desires should be captured in the K-Shelf to record system targets (e.g. reduce weight by x%) and ensure the necessary provision of customer value.

Question 7: Shall knowledge environment capture the knowledge according to the level of innovation of the new product?

The aim of this question was to discover whether the expected level of innovation at both the system and subsystem level should be captured in the K-Shelf.

Question 8: Shall knowledge environment capture and store existing design concept solutions from previous projects of system/subsystems, research and development, and other internal documents?

The aim of this question was to discover whether extraction of component design documentation from previous projects based on the subsystem concept definition should be facilitated in K-Shelf.

Question 9: Shall knowledge environment store all alternative solutions and capture the reasons why they were identified infeasible?

The aim of this question was to discover whether design decision rationale should be facilitated in the K-Shelf.

From the Questions 6-9 (Q6 to Q9), responses from participants were used to identify a necessary capability, characteristic, or quality factor of the process model in order to have value and utility for the companies. The author compared the importance of the requirements to establish the K-Shelf capabilities against the possibility of introducing and implementing the requirements in the companies. Both of the relevance and feasibility of the K-Shelf requirements were projected into radar chart, as shown in Figure 4-7. To some extent, the factors that will hinder or have a negative impact on the implementation of the K-Shelf were also identified as constraints.

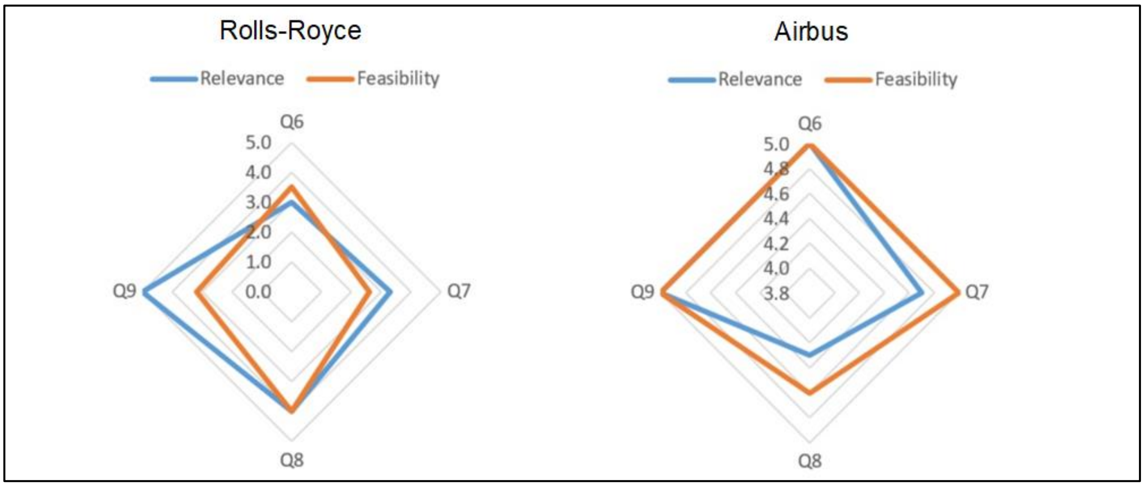


Figure 4-7 The relevance and feasibility of the K-Shelf requirements from industries perspective

The relevance of certain requirement was recorded in a scale of one to five, whereas scale one means ‘not important at all’ to scale five means ‘very important’. In the similar way, the feasibility was recorded in scale one as ‘not at all easy’ to scale five means ‘very easy’ and zero means ‘not applicable’. From Figure 4-7, it shows that capability of knowledge environment in PD to store all alternative solutions and capture the design rationale of infeasible conceptual design as denoted in Q9 is very important.

What emerged from industrial perspective regarding to the knowledge environment might be different compared to a Small Medium Enterprise (SME) or maybe a start-up company have. Bolisani and Scarso (2016) investigated knowledge worker in many SMEs and introduced the use of Wiki as a knowledge management system. Knowledge exchange and concern regarding to the knowledge content and format are prominent issue. SMEs have to manage and expand their knowledge capital. This need is even stronger in knowledge-based industries and e-businesses. Lisanti et al. (2014) discussed a knowledge management system model design for SME, in order to improve SME's performance and competitive advantages. They managed to design a KMS for SME.

4.3 The K-Shelf Concept Development

The baseline model is developed to understand the dimensions of knowledge environment in SBCE application and it is presented in Section 4.3.1. Followed by synthesising of knowledge environment with existing SBCE process model is presented in Section 4.3.2. Then, Section 0 describes the KLC for K-Shelf; these being knowledge capture, knowledge representation and knowledge provision. Lastly, Section 4.3.2.1 explains the K-Shelf concept in detail.

4.3.1 Baseline Theory

There was no common baseline of discussion found by different researchers to describe a knowledge environment in SBCE. Developing a baseline model in the form of knowledge environment in SBCE was regarded as vital due to two main reasons. Firstly, it aims to provide a SBCE centric research foundation for the development of the K-Shelf. Secondly, it is necessary to display where knowledge is located and how it relates within the scope of a SBCE process.

From the industrial perspective, presented in Section 4.2, interviewees stated that to start a new project requires knowledge from previous projects. Hence, knowledge was created during SBCE project undertaken in the past. On the other hand, a set of conceptual designs are narrowed down as a result of the application of SBCE. Therefore, the author contextualise knowledge environment in SBCE within three dimensions comprises SBCE activities, set of conceptual designs and previous project knowledge, as illustrated in Figure 4-8.

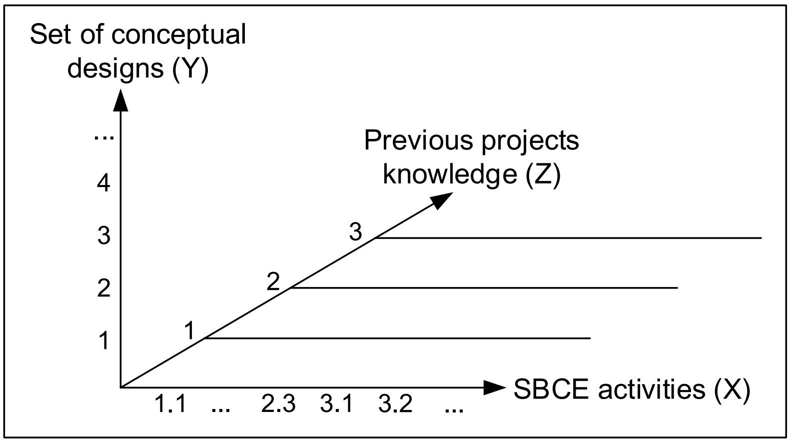


Figure 4-8 Baseline model of knowledge environment in SBCE

Horizontal dimension (axis X) symbolises the SBCE activities (refer to Figure 4-11). Vertical dimension (axis Y) represents the set of conceptual designs. Previous projects dimension (axis Z) symbolises knowledge a company has acquired in the past. For example, during the exploration of set of conceptual design 1 (axis X) in SBCE activities 2.3 (axis X), the designer retrieves design rationale knowledge from previous projects 1 (axis Z).

4.3.2 Synthesise of Knowledge Environment and SBCE

The literature review clearly defines that SBCE is a knowledge intensive process. However, the literature review outlined a gap, see Section 3.6, that currently there is no well-defined knowledge environment to enable SBCE application. This section presents the argument regarding the required knowledge environment to enable SBCE application.

Although synthesising two different subjects, specifically SBCE and knowledge environment, encounters increased complexity, it was evident during the literature review and that there are several points of interest. For instance, formal representation of knowledge in PD has not yet been discussed in the SBCE community; hence its influence on this research is guided from the knowledge management discipline as well as on the findings from industrial collaboration.

Efficient usage of product life cycle knowledge can only be accomplished, if the knowledge is captured and structured in a way that it can be formally represented and provisioned within an organisation to support engineering decisions in product design and development. These procedures are defined as a Knowledge Life Cycle (KLC). Three KLC steps are considered in this research. A KLC step is selected from the literature review, namely knowledge representation (refer to Table 3-1). Two more KLC steps are depicted as a result of the industrial perspective – knowledge capture and knowledge provision (refer to the raised questions in Appendix A).

Table 4-2 Potential link of source of knowledge with KLC steps in the K-Shelf

Source of knowledge from literature in Chapter Chapter 3: and industrial perspective in Section 4.2	KLC steps in Knowledge-Shelf			
	Knowledge capture	Knowledge representation	Knowledge provision	Knowledge reuse
5 Whys	X	X	X	X
A3 sheet	X	X		
CAD model				
Decision tree		X		
Design rationale	X	X	X	X
PowerPoint presentation		X		
Pugh matrix		X		
Sketches and drawing		X		
Spreadsheet			X	
Three-dimensional prototype		X		
Trade-off curve	X	X	X	X

Table 4-2 shows the potential link among source of knowledge from literature in Chapter 3 and industrial perspective in Section 4.2 as currently discussed in the SBCE literature in supporting the steps of the KLC in the K-Shelf and marked with letter X. On the other hand, linking the details of the entire listed tools and techniques, as shown in Table 4-2, would result in a scope that goes beyond one individual research project, therefore, this research will have a primary focus on synthesising design rationale and TOC. This is accomplished by demonstrating the application of the K-Shelf in two distinguished case studies related to the capturing design rationale and provision of TOC to support SBCE at the conceptual stage.

The K-Shelf has two different stages of knowledge capturing namely previous knowledge capturing and dynamic knowledge capturing. Previous knowledge capturing comprises the capturing of knowledge from previous project. Dynamic knowledge capturing on the other hand comprises of capturing knowledge which is created during the actual development of a conceptual design.

Table 4-3 Design rationale template

Project	System	Component	Why 1	Why 2	Why 3	Why 4	Why 5
1	S1	C1	…	…	…	…	…
2	S2	C4	…	…	…	…	…
	S						

Previous projects as a source of knowledge are held in a table format of a database. The type of knowledge captured in the K-Shelf is design rationale knowledge which is captured using a design rationale template, as shown in Table 4-3. Design rationale template consist of project name, system name, component and 5 Whys arguments. Although formal representation of knowledge was not addressed by the SBCE community, it is regarded as important to enrich the comprehension of captured knowledge as well as facilitating its computational use. Since the explicit domain knowledge predominates the captured knowledge, the use of object-oriented knowledge presentation is suggested. Hence a corresponding logic among the captured knowledge exists. The author focuses to the explicit knowledge representation. This research disregards tacit knowledge representation due to the technically intensive nature of PD process.

4.3.2.1 The K-Shelf Concept Description

The author used IDEF0 diagram to describe the K-Shelf concept. IDEF0 is a method designed to model the decisions, actions, and activities of an organization or system. IDEF0 is a diagram that presents an integrated picture of the inputs, control, outputs, and mechanisms for a function's decomposition, as shown in Figure 4-9. The two primary modelling components are: functions (represented on a diagram by boxes), data and objects that interrelate those functions (represented by arrows). The mechanisms are the resources and tools that are required to complete the process. This includes people with particular skills, machines and other tools.

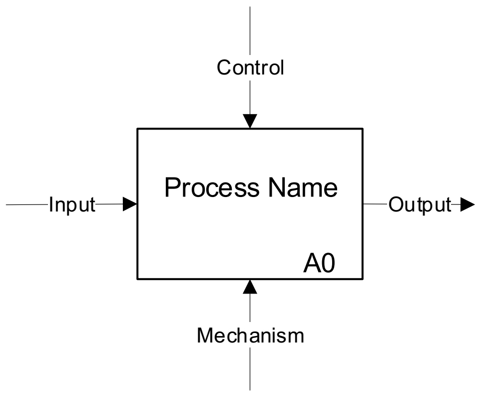


Figure 4-9 IDEF0 diagram

The K-Shelf is a concept being developed in this research to provide a knowledge environment to designers in SBCE application. The K-Shelf function is to capture, represent and provision knowledge from sets of conceptual designs throughout SBCE process represented in Figure 3-3. For the process of generating the set of conceptual design which is situated inside box A0; there are three inputs, three controls, two mechanism and one output. These inputs are as follows: designs that was pulled from previous projects, designs that was pulled from R&D projects and new conceptual designs generated during the project under consideration. The R&D project is the conception phase in the product life cycle, while previous project is the entire process of designing and creating products which is commenced prior to the current project.

To generate the first set of conceptual design from aforementioned inputs, some controls have to be considered. These controls displayed as arrows entering the top side of the activity box A0, as shown in Figure 4-10. The controls during the generation of the first conceptual designs are system boundaries, subsystem boundaries and components boundaries.

In SBCE, as the design progressed, the set is gradually narrowed based on the knowledge gained due to simulation, prototyping, testing and other engineering evaluations, as shown in Figure 4-10 inside A1 box. Worth to note that simulation is done outside of the K-Shelf software, for example, ANSYS is an external software to perform CFD simulation. On other hand, the process of narrowing down the set of designs is realised with the integration of TOC in the K-Shelf to visualise the distribution of set of designs that fall into feasible area.

Narrowed set of designs are forwarded to the next process inside A2 box where the designer explores set of conceptual designs. At this point, infeasible design solutions will be removed from the set whilst the feasible design solutions are carried on. However, these infeasible conceptual designs are saved back to the K-Shelf along with their design decision rationale as shown in Figure 4-10. The reason behind it is that although solutions are not good for the project under considerations; they might be useful for other or future projects.

The second narrowed down set of conceptual design as a result of the application of SBCE. As the design progresses, the set is gradually narrowed based on the knowledge gained and again the designs and their rationale of infeasible solutions are also captured as shown until the final optimised design solution is obtained, as shown in Figure 4-10.

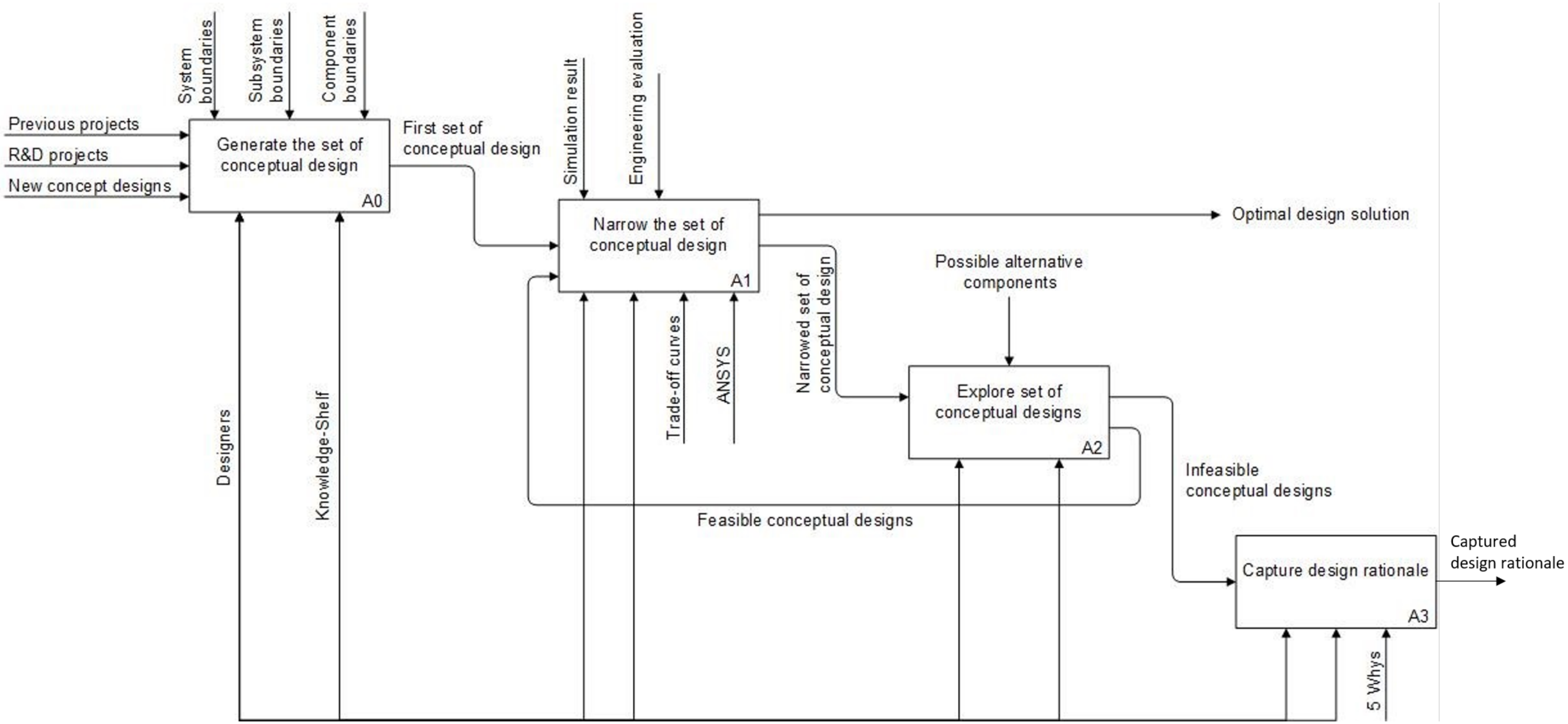


Figure 4-10 The K-Shelf concept

4.4 The K-Shelf Capabilities

The K-Shelf capabilities have been defined as a result of the analysis of both literature review and industrial perspective. The capabilities are:

1. Support the generation of a set of designs
2. Dynamic knowledge capture of design rationale
3. Capture design rationale knowledge in a structured manner
4. Support the comparison of sets of solution to narrow them down

These capabilities have been 4d within the application of several activities as shown in the highlighted activities in and is presented in Chapter 6. In the event of developing the K-Shelf, not all of the SBCE activities were used. The selected activities which were used in this research are the activities that lead to the development of the K-Shelf software as it could demonstrate the K-Shelf concept and capabilities. This selected SBCE activities are highlighted, as shown in Figure 4-11.

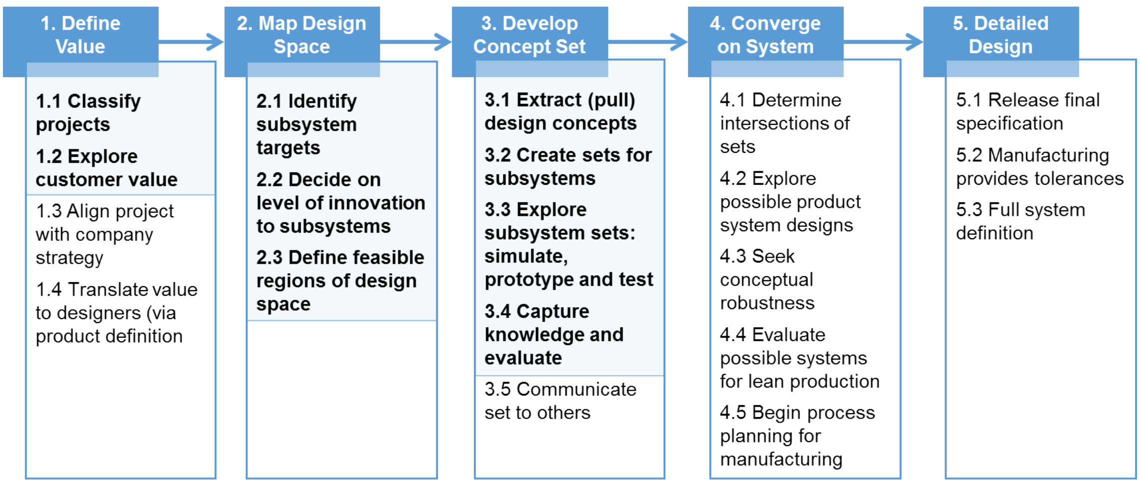


Figure 4-11 Selected SBCE activities

4.4.1 Support the Set Generation of Design

To generate set of designs is the core of SBCE. This is done manually as the K-Shelf should support the generation of a set of designs from the captured knowledge of the previous projects and R&D projects. Generation of a set of design in the K-Shelf is done by specifying boundaries into the database and inform the users if there is any previous project or R&D projects that fits the boundaries. The capability of the K-Shelf to support the generation of a set of design is demonstrated in Section 6.4.1.4.

4.4.2 Dynamic Knowledge Capture of Design Rationale

Dynamic knowledge capture of design rationale is an important task in managing PD knowledge. However, most of the KLC approaches do not consider this feature in literature review. In Section 3.3, Maksimovic (2013) addressed the dynamic knowledge capture in his work of LeanKLC. Hence, the author put the feature of dynamic knowledge capture of design rationale as key capability of the K-Shelf as it is a source of useful knowledge during narrowing down of the design set. The knowledge is the one that helps to decide of keeping the design solution or remove it from the set. The knowledge is to be reused in the future projects. This is the hypothesis of the K-Shelf concept explained in Section 4.3, “although the design solution is not good for the current project, it might be useful for future project”.

The idea is to ensure that knowledge is ready to be reused if it is kept and managed in formal manner. Therefore, realising dynamic knowledge capturing of design rationale for the Knowledge-Shelf are defined as follows:

1. Integrate knowledge capturing of design rationale in PD process.
2. Facilitate a process that captures knowledge of design rationale whilst created.
3. Minimise documentation effort.

Given the above definitions, dynamic knowledge capture of design rationale is done during narrowing down of design set based on the knowledge gained as the result of simulation, prototyping and testing.

4.4.3 Capture Design Rationale in a Structured Manner

Design rationale is a document that provides explicit, logical reasons given intended to justify decisions on design or feature of a product (Chachere and Haymaker, 2011). Section 3.4.2 and Section 4.2 highlighted the need to store captured design rationale knowledge. Therefore, the author put forward the capability of the K-Shelf in capturing design rationale knowledge in a structured manner. To achieve such capability, the author proposes a novel approach to facilitate designers to capture design rationale using 5 Whys approach as shown in Figure 4-12.

Given the SBCE process model as shown in Figure 4-12A, design rationale is captured and its location is identified. In Figure 4-12A, the location where design rationale was initially captured is denoted as a projection of SBCE activity 3.3 and infeasible conceptual design number 4 is identified as the point $P_{cr}(x,y)$, these being $P_{cr}(3.3,4)$ as shown in Figure 4-12B. Design rationale is captured using design rationale template that holds some attributes; project ID, SBCE activity ID, component ID and 5 Whys arguments. The latter is the placeholder to store design rationale knowledge or the reason why conceptual design is thought infeasible.

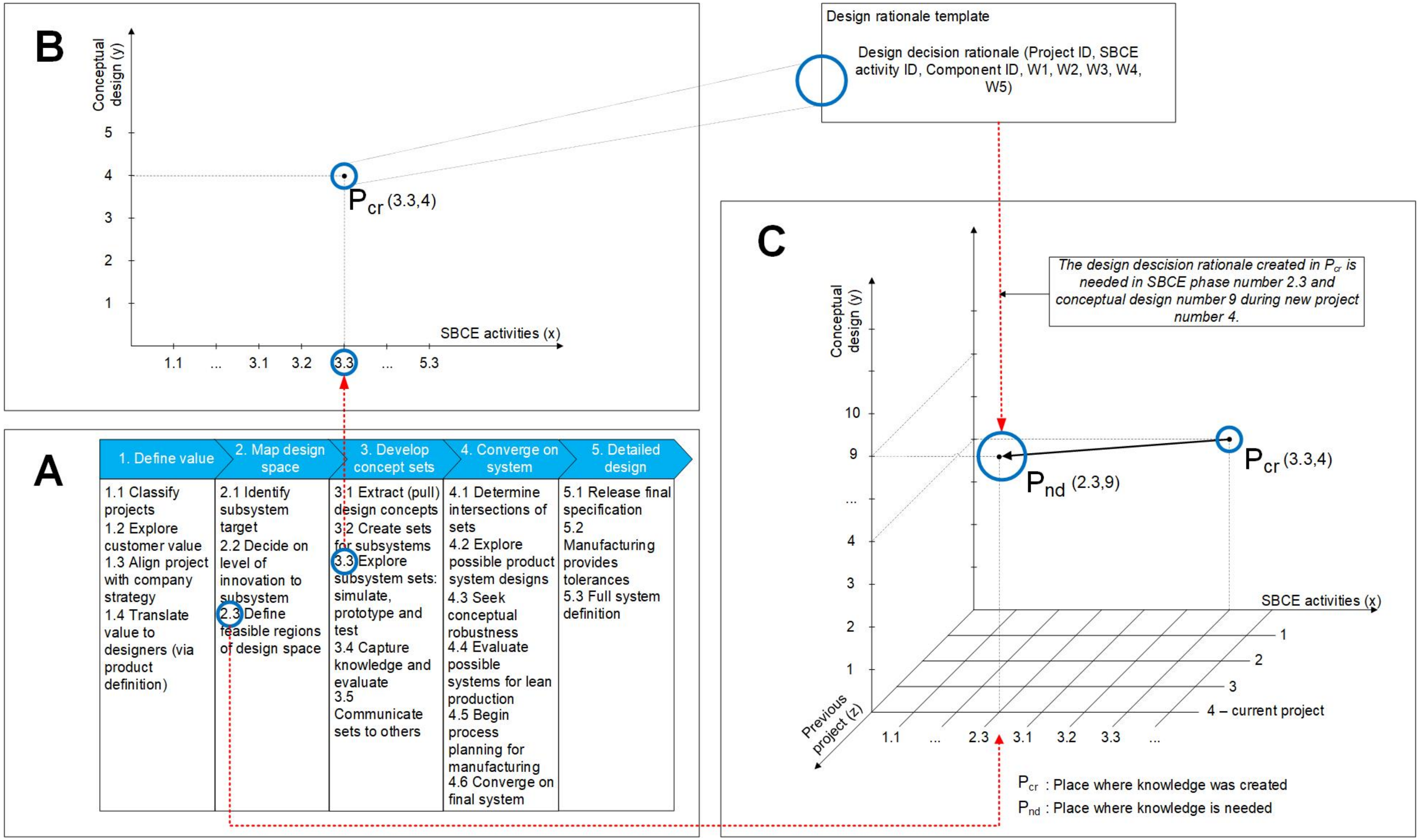


Figure 4-12 Design decision rationale capture and provision in the K-Shelf

The cartesian coordinates being used in this explanation shows how design rationale is captured in a structured manner. This method enables the attribute $P_{nd}(x,y)$ in Figure 4-12C to receive its unique coordinates, which denoted as $P_{nd}(2.3,9)$. Figure 4-12B shows an example of design rationale knowledge captured in SBCE activity number 3.3 and conceptual design number 4 during project number 0 or first ever project. Figure 4-12C shows an example of design rationale knowledge provision in SBCE activity number 2.3 and conceptual design number 9 during project number 4.

4.4.4 Support the Comparison of Sets of Solutions

This activity will lead to the generation of a Trade-Off Curve (TOC) which turns the data into a visual form as one of the K-Shelf capabilities. This is the capability of K-Shelf to convert data into visual form as demonstrated in Section 6.4.3 and Section 6.3.2 This activity will enable the multi-functional teams to create a feasible region in later steps. TOCs are generated by plotting the design parameter data on the related axes of TOCs. The number of TOCs generated is usually the same as the number of defined relationships between design parameters. However, this might vary if some of the design parameter data was filtered in the earlier steps.

The K-Shelf capability to support the comparison among set of solutions solve the problem of not having data represented visually. Additionally, TOCs generated inside the K-Shelf communicates the feasible and infeasible region, thereby communicating the customer requirements; as the feasible region is defined with the help of customer requirements. Moreover, it shows whether the design solution lies within the feasible region or not. The main aspect of creating TOC is finding essential knowledge which is usually stored in different places in order to speed up the decision-making process. For plotting previous projects knowledge in the form of TOC, the company has to refer to proven knowledge obtained in previous design solutions.

Chapter 5: Development of the K-Shelf Software

5.1 Introduction

The analysis of the literature review in Chapter 3, and the captured industrial perspective in Chapter 4, confirmed that an adaptive software development approach is needed to develop a knowledge environment to enable SBCE application.

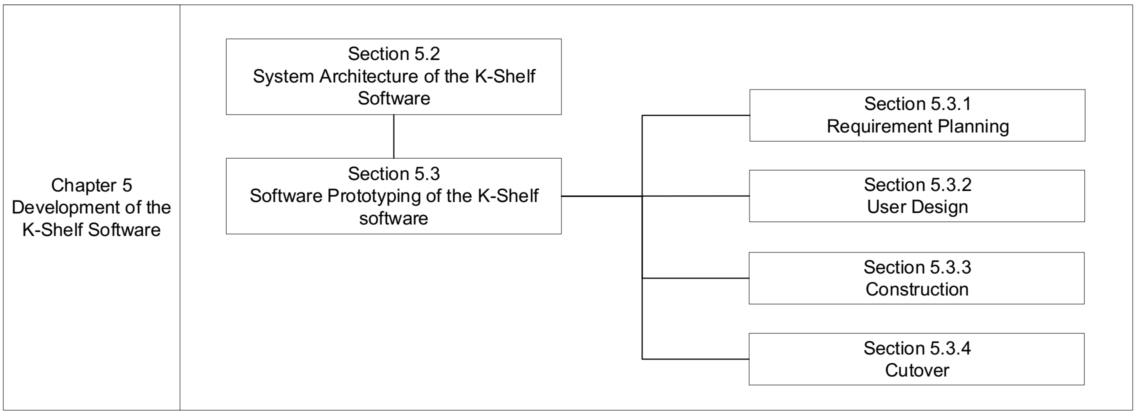


Figure 5-1 Chapter 5 structure

This chapter, as is shown in Figure 5-1, presents required phases that were followed to develop the K-Shelf software. Section 5.2 explains the developed system architecture to Section 5.3 describes how the author adopted Rapid Application Development (RAD) approach to develop the K-Shelf software.

5.2 System Architecture of the K-Shelf Software

System architecture play an important role as a blueprint or reference model for development of K-Shelf software to enable SBCE application. The K-Shelf software system architecture represents the structure of software application at abstract level. Components are delimited parts of software systems, e.g. function, procedures, abstract data objects, abstract data type or object classes.

The K-Shelf software is developed using Oracle Application Express (APEX) and object-oriented Procedural Language/Structured Query Language (PL/SQL) programming. In object-oriented PL/SQL, class is called object type which is similar to the class mechanism found in C++ and Java (Abraham et al., 2013).

Class are composed of attributes and methods. Class and their methods used in the K-Shelf software are stored with the data in the database to ensure a consistent standard and enable object reusability.

The architecture of the K-Shelf software is structured into two tiers; client application and database as shown in Figure 5-2. The K-Shelf software is able to host numbers of SBCE projects. The end user of the K-Shelf software could be assigned as a designer of one SBCE project or several SBCE projects at a time. For example, in Figure 5-2, D1 is a designer in SBCE1 project. D2 is a designer involved in SBCE2 and SBCE3 projects. Both of D2 and D3 are designers involved in the same SBCE3 project. Designers could access the K-Shelf software from web browser installed on laptop, desktop PC or tablet through a web server which is located inside the Embedded PL/SQL Gateway (EPG). Each of SBCE project webpage in the K-Shelf software is triggered by URL request sent from designer's web browser and rendered using metadata stored within the Oracle database. The K-Shelf software utilises database schema as its logical container for data structures, called schema objects. This schema object represents the data structures of conceptual designs during SBCE project under consideration. For example, Schema1 is associated to project SBCE1 and respectively to Schema 2 and Schema 3 are associated to project SBCE 2 and SBCE3 as illustrated in Figure 5-2.

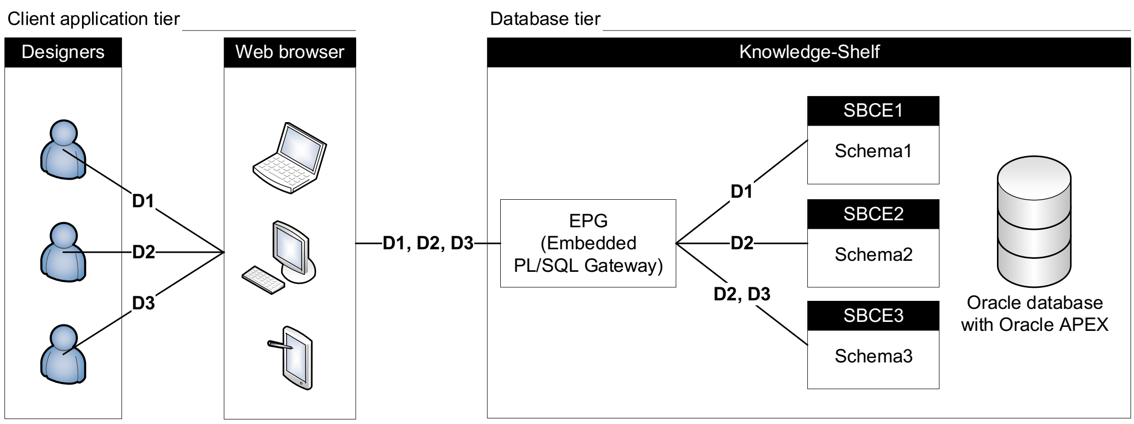


Figure 5-2 System architecture of K-Shelf software

The K-Shelf software is hosted in a server with the following specification:

1. Processor: Intel Core i7-7600U (Intel Core i7)
2. Memory: 32768 MB, DDR4-2400, single-channel, two memory banks
3. Mainboard: Intel Kaby Lake-U iHDCP 2.2 Premium PCH
4. Storage: Samsung SSD PM961 1TB M.2 PCIe 3.0 x4 1024 GB
5. Operating system: Windows 10 Enterprise 64 bit

Oracle APEX supports the current and prior major release of internet browser Configuration of Oracle APEX installation is explained in Appendix B. The K-Shelf is installed and configured inside a development server in Cranfield University that can be accessed by the industrial collaborators via internet.

5.3 Software Prototyping of the K-Shelf

Rapid application development (RAD) is an object-oriented approach to systems development that includes a method of development as well as software tools. RAD focuses on prototyping and iterative development rather than a formalised methodology. The idea behind RAD is to deliver solutions which are more efficient and meet the user requirements in a more dynamic and accurate way. Working with delivery of prototypes and iterative releases also allows the author to address improvement request from industrial collaborators rapidly.

5.3.1 Requirement Planning

During this stage, the author and designers from industrial collaborators as K-Shelf software beneficiaries communicate to determine the goals and expectations for the project as well as current and potential issues that would need to be addressed during the build. The requirement planning can be breakdown into researching the current problem and defining the requirements for the K-Shelf software.

The PD process in CALTEC comprises three phases, namely concept, detail design and testing. During the concept phase, SJP CAD is created. The detail design phase contains the necessary activities to design and develop a physical product. Testing comprises the verification or validation of the physical product in order to conform to the SJP customer requirements. The expected outcome of CALTEC in adopting SBCE and gets the benefit from the K-Shelf implementation. The outcome expectation from the implementation ok the K-Shelf software is summarised in Table 5-1.

Table 5-1 Outcome expectation from implementation the K-Shelf software

Outcome	Detail
Objective	Apply the K-Shelf software in order to realise dynamic knowledge capturing and provision resulting from surface jet pump design.
Scope	Nozzle design optimisation
Definition of knowledge	Any design variations to obtain the highest velocity in the nozzle
Research duration	5 months
Human resources	Software developer, business process analyst

The development of K-Shelf software is adhered to the SBCE process model. For example, in accordance with the SBCE activity 1.2 to explore the customer value, the K-Shelf software allows designer to choose one of two available scenarios. The first scenario offers designer to upload a spreadsheet file in comma separated value (CSV) format as shown in Scenario 1 and will be demonstrated in Section 6.4.1.1. On other hand, the second scenario lets designer to add customer value manually as shown in Scenario 2**.**

Title: Upload customer value in CSV format

Actor: Designer

Scenario: Designer uploads spreadsheet file that contains recorded customer value. Knowledge-Shelf maps and validates uploaded customer value file. Knowledge-Shelf populates customer value and merges similar value classification. Designer can modify the value of AHP priority, company prioritisation, KVA and load of importance of classified customer value. Designer confirm the value modifications. System updates database. Designer adds system targets that is associated with particular KVA. Knowledge-Shelf updates database and displays system target along with its associated KVA.

Extension: AHP priority and load of importance values exceed 100%

(a) Designer removes any contributing value
(b) Designer resets entire values

Scenario 1 Upload customer value in CSV format

Title: Explore customer value manually *Actor: Designer* *Scenario: Designer add new KVA and its relevance in percentage. Designer applies changes. System updates database.* *Extension: Relevance values exceed 100%* *(a) Designer cancel input* *(b) Designer delete a row*

Scenario 2 Input explore customer value manually

5.3.2 User Design

Once the project is scoped out, it is time to jump right into development, building out the user design through various prototype iterations. During this phase, designers from industrial collaborators work hand in hand with the author to ensure their needs are being met at every step in the design process. This method gives the author the opportunity to tweak the model as they go until they reach a satisfactory design.

In opposite to waterfall Software Development Life Cycle (SDLC) where the Graphical User Interface (GUI) is developed after use case are defined, during the development of the K-Shelf software, use case is pre-defined following the SBCE model as shown in Figure 4-11. The K-Shelf graphical user interface (GUI) is designed in accordance with SBCE process model as presented in Figure 4-11. A Unified Modelling Language (UML) visualise the interaction between designers as the user of the K-Shelf software adhered to SBCE processes as shown in Figure 5-3.

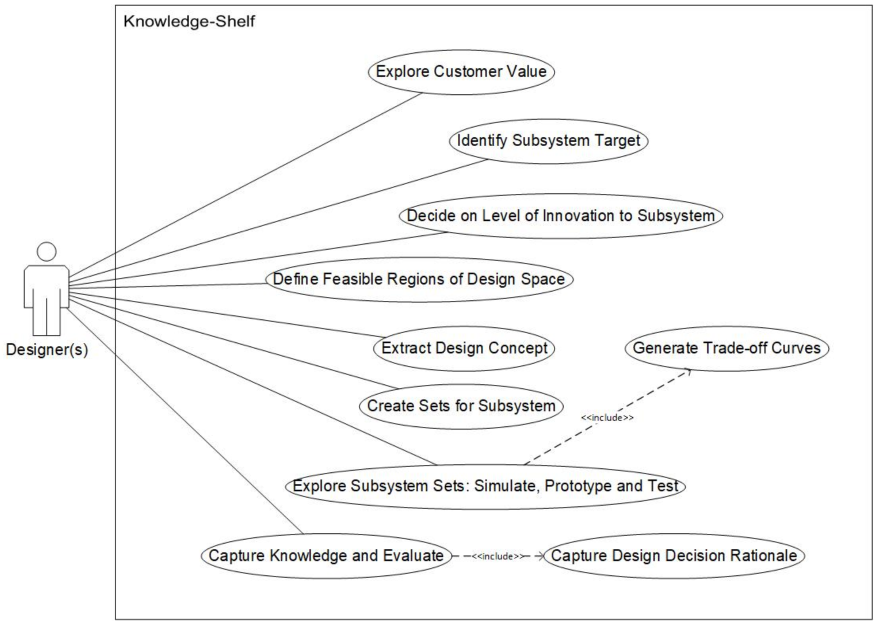


Figure 5-3 UML use case to model the knowledge in the K-Shelf software

The designer in Figure 5-3 is an actor involved in the K-Shelf software. The designer has some association relationship with particular SBCE process which is denoted by a straight line. For example, the designer commenced with the first activity in SBCE process to explore customer value. Subsequently, the designer identifies subsystem target, decide on level of innovation to subsystem, define feasible regions of design space, extract design concept and create sets for subsystem. Including the relationship between two use activities; explore subsystem sets and generate trade-off curves, shows the behaviour that the included use case is part of the including (base) use case. Hence, exploring subsystem sets activity is incomplete without generate trade-off curves activity. In this situation, the generated trade-off curves activity is not optional. Similarly, the capture design rationale activity is included in the capture knowledge and evaluate activity. The 'include' relationship has to be read alongside the direction of the arrow.

The GUI design of the K-Shelf software was developed based on the UML use case. Thus, the K-Shelf software GUI consists of (1) regions – area of a page that serves as a container for selected SBCE activities, and (2) navigation bar – a bar on the left side that serves as a placeholder for SBCE phases. The homepage of the K-Shelf software is shown in Figure 5-4.

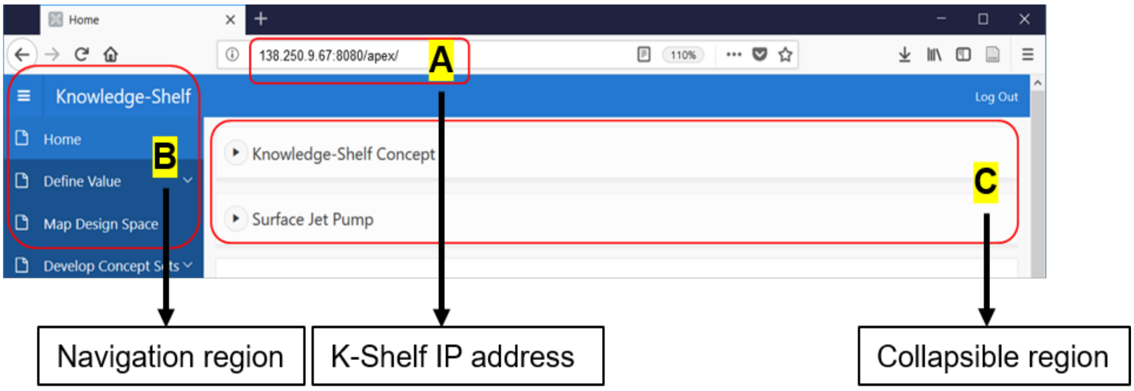


Figure 5-4 GUI of the K-Shelf software homepage

The K-Shelf software is invoked when the users navigate internet browser to particular IP address of web server which is located inside the embedded PL/SQL gateway (EPG) as shown in Figure 5-4A. This homepage has the title *Knowledge-Shelf* in the navigation bar along the top and SBCE phases in the navigation menu along the left side of the page as shown in Figure 5-4B. In the main window of the K-Shelf's homepage, the K-Shelf concept and SJP case study are presented in collapsible regions as illustrated in Figure 5-4C.

5.3.3 Construction

In this phase, the prototypes and beta systems from the design phase are converted into a working model. The construction phase breaks down into application development, coding, database design and integration. It also includes the use of powerful automated tools for transforming process and data models into the final, operational product. All the collected enhancements and modifications are applied during this third phase of the RAD approach. Feedback about what is good, what is bad, what to keep, and what to remove, is given in this phase.

The feedback given during the construction phase is not limited to functionality, but also includes aesthetics, interfacing, etc. The prototyping then continues with all the received feedback taken into consideration. Both prototyping and feedback continue until a final product that fits the client requirements in the most suitable way are developed.

The K-Shelf software constructed with the industrial collaborators works at component level of a product instead of subsystem. For example, the case study of Surface Jet Pump (SJP) that will be demonstrated in Section 6.3 has got several components, one of them is nozzle as illustrated in Figure 6-11. Figure 5-5 illustrates partial class representation of SBCE process and associated class of SJP which is managed in K-Shelf software. The partial class is a feature in Oracle to implement the functionality of a single class into multiple files and all these files are combined into a single class file when the application is compiled. The classes in K-Shelf software represents the conceptual designs of product's systems and subsystems/components as shown in Figure 5-5.

In Figure 5-5, two instances of inheritance concept are established between *SYSTEM* class and *SURFACE_JET_PUMP* class, also between *SUBSYSTEM* class and *NOZZLE* class. The *SURFACE_JET_PUMP and NOZZLE* are child of *SYSTEM* and *SUBSYSTEM* classes, respectively. A child-class inherits the traits of the parent-class. Inheritance facilitates reusability and is an important concept of object-oriented approach. With inheritance, the development of the K-Shelf software can reuse the attributes and methods of the existing class.

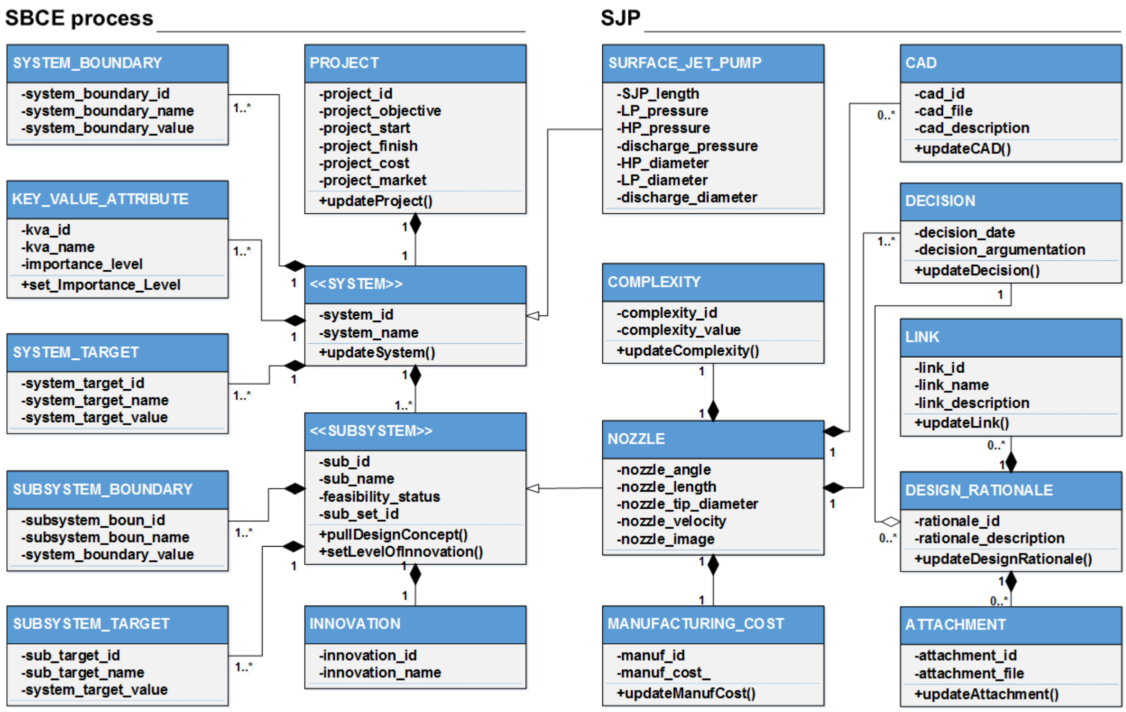


Figure 5-5 Class diagram of SBCE process associated with SJP

The *PROJECT* class represents activity 1.1 to classify project in SBCE process model (refer to Figure 4-11). The *PROJECT* class has six attributes: *project_id, project_objective, project_start, project_finish, project_cost, project_market* and has one method: *updateProject()* as presented in Figure 5-5. The *PROJECT* object type has one-to-one multiplicity relationship with *SYSTEM* object type. This means that each SBCE project has one and only one product at system level, and a system belongs to one and only one project. The *SYSTEM* class is associated with activity 1.2 in SBCE process model to explore customer value activity in SBCE process model. The *SYSTEM* class has two attributes: *system_id* and *system_name*, and one method: *updateSystem()* to return the updated value to *system_name* attribute.

The *SYSTEM* class is composed of *SYSTEM_BOUNDARY, SYSTEM_TARGET* and *KEY_VALUE_ATTRIBUTES* classes which capture system boundaries, system targets and key value attributes of the system respectively. The *SYSTEM_BOUNDARY* class consists of three attributes: *system_boundary_id, system_boundary_name* and *system_boundary_value* which can be used later to define the design space as mentioned in activity 2.3 of SBCE process model to define feasible regions of design space. The Key Value Attributes (KVA) are values that have been classified as high importance and each of them is measured by load of importance in percentage. *The KEY_VALUE_ATTRIBUTES* class has two attributes: *kva_id and kva_name*, and two methods: *updateKva() and updateImportanceLevel()* as shown in Figure 5-5. The database design corresponding to the *SYSTEM* class is constructed in *SJP_SYSTEM* table as shown in Figure 5-6.

SJP_SYSTEM

Table | Data | Indexes | Model | Constraints | Grants | Statistics | UI Defaults | Triggers | Dependencies | SQL

Add Column | Modify Column | Rename Column | Drop Column | Rename | Copy | Drop | Truncate | Create Lookup Table

Column Name	Data Type	Nullable	Default
SYSTEMID	NUMBER(4,0)	No	-
SYSTEMNAME	VARCHAR2(1000)	Yes	-
HPPRESSURE	NUMBER(10,2)	Yes	-
LPPRESSURE	NUMBER(10,2)	Yes	-
DISCHARGEPRESSURE	NUMBER(10,2)	Yes	-
TOTALLENGTH	NUMBER(10,2)	Yes	-
NOZZLEID	NUMBER(4,0)	Yes	-
TUBEID	NUMBER(4,0)	Yes	-
BODYID	NUMBER(4,0)	Yes	-

Figure 5-6 The SJP_SYSTEM table in the K-Shelf software construction

The *SYSTEM_TARGET* class has three attributes: *system_target_id, system_target_name* and *system_target_value*. The system targets are specified to explain how the value attributes will be reached. The *SYSTEM* class is parent for *SURFACE_JET_PUMP* class which then inherit all the attributes and methods. The *SURFACE_JET_PUMP* class owns their specific attributes: *SJP_length, LP_pressure, HP_pressure, discharge_pressure, HP_diameter, LP_diameter* and *discharge_diameter* and does not have any method as shown in Figure 5-5.

A system can have at least one subsystem/component. *SUBSYSTEM* class is composed of *SUBSYSTEM_BOUNDARY* and *SUBSYSTEM_TARGET* classes that act similarly to *SYSTEM_BOUNDARY* and *SYSTEM_TARGET* yet in subsystem level. The *SUBSYSTEM_TARGET* class represents activity 2.1 in SBCE process model to identify subsystem targets. The *SUBSYSTEM* class has four subsystems: *sub_id, sub_name, feasibility_status* and *sub_set_id*. The first two attributes can retrieve returned value from *pullDesignConcept()* method in *SUBSYSTEM* class which is associated to activity 3.1 in SBCE process model to extract/pull design concepts in SBCE process model. The *pullDesignConcept()* method populates set of component designs from previous projects.

SJP_NOZZLE

Table | Data | Indexes | Model | Constraints | Grants | Statistics | UI Defaults | Triggers | Dependencies | SQL

Add Column | Modify Column | Rename Column | Drop Column | Rename | Copy | Drop | Truncate | Create Lookup Table

Column Name	Data Type	Nullable
NOZZLEID	NUMBER(4,0)	No
NOZZLENAME	VARCHAR2(1000)	Yes
ANGLE	NUMBER(5,2)	Yes
INSIDEDIAMETER	NUMBER(5,2)	Yes
LENGTH	NUMBER(5,2)	Yes
TIPDIAMETER	NUMBER(5,2)	Yes
VELOCITY	NUMBER(5,2)	Yes
SYSTEMID	NUMBER(4,0)	Yes
IMAGE	BLOB	Yes
DESIGNPERFORMANCE	NUMBER(2,0)	Yes
MANUFACTURABILITY	CHAR(1)	Yes
COST	CHAR(1)	Yes
DESIGNRATIONALEID	NUMBER(4,0)	Yes

Figure 5-7 The SJP_NOZZLE table in the K-Shelf software construction

The new subsystems are generated outside the K-Shelf software shelf using computer-aided drafting software which includes the process of creating a technical draw. The SolidWorks software was used in this thesis to draft tapered faces of various nozzles with desired angle. Subsequently; designers input them to K-Shelf software as mentioned in activity 3.2 of SBCE process model to create sets for subsystem. The other method in *SUBSYSTEM* class is *setLevelOfInnovation()* which has a mutual with *INNOVATION* class to define the subsystem's level of innovation that associated with activity 2.2 of SBCE process to decide on level of innovation to subsystem. The *SUBSYSTEM* class is parent for *NOZZLE* class which then itself inherit all the attributes and methods. Apart from inherits the *SUBSYSTEM* class, the *NOZZLE* class has also specific attributes: *nozzle_angle, nozzle_lenght, nozzle_tip_diameter, nozzle_velocity* and *nozzle_image* and does not have any method. The database design corresponding to the *NOZZLE* class is constructed in *SJP_NOZZLE* table as shown in Figure 5-7.

The component’s complexity and its manufacturing cost are also determined and recorded as presented in *COMPLEXITY* and *MANUFACTURING_COST* classes. As the design progresses, design decisions are made, the set is gradually narrowed based on the knowledge gained and the rationale of the weak or infeasible solutions are also captured as illustrated in the relationship between *DECISION* and *DESIGN_RATIONALE* classes. Apart of decision argumentation and design rationale description, *LINK* and *ATTACHMENT* classes are elaborated to provide further reference to the design decision rationale being made as shown in Figure 5-5.

5.3.4 Cutover

The last phase includes the finalisation of the aesthetics, features, functions, interface, and everything else related to the K-Shelf software. Interfaces between the various independent modules require proper testing. The cutover phase includes testing of GUI compatibility in various devices and platforms. For example, the K-Shelf software can be accessed through handheld device to support designer’s mobility in the company site as shown in Figure 5-8.

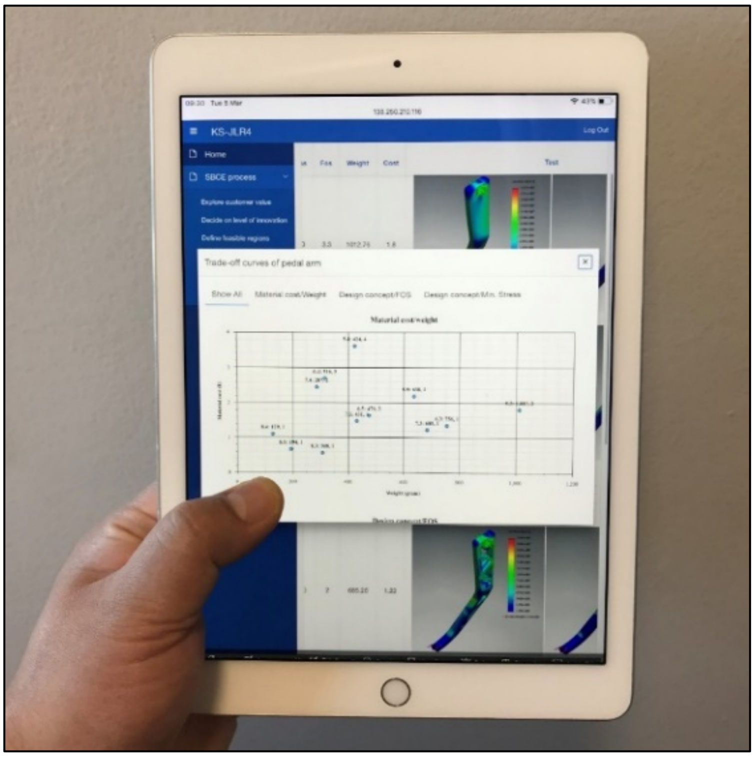


Figure 5-8 The K-Shelf software

Chapter 6: Validation of the K-Shelf

6.1 Introduction

This chapter presents the application and the validation of the K-Shelf concept and software demonstrator addressed in Chapter 4 and Chapter 5, respectively. Figure 6-1 illustrates the structure of this chapter.

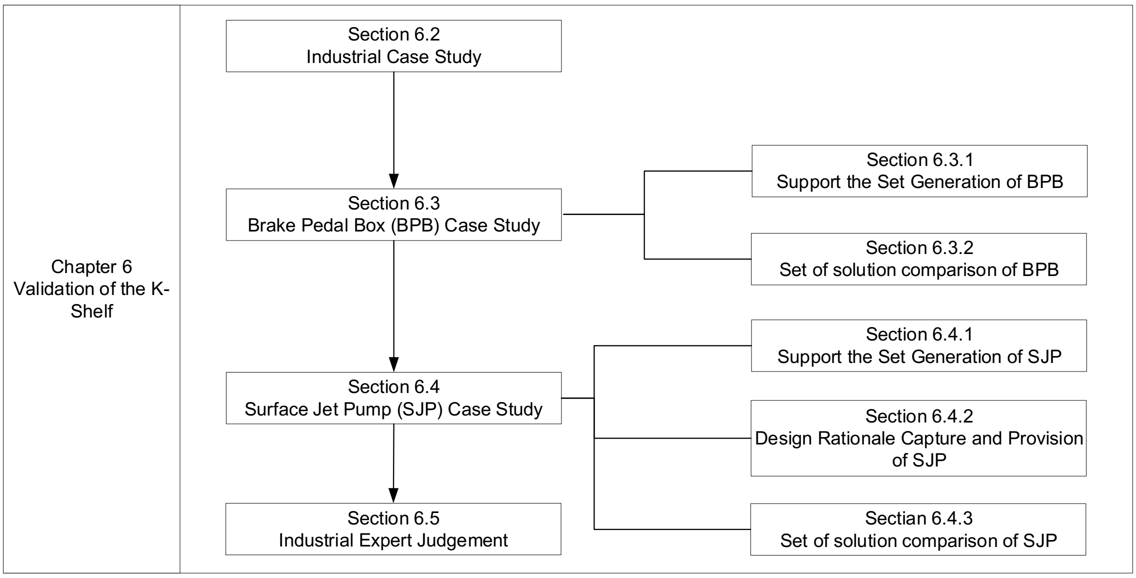


Figure 6-1 Chapter 6 structure

Section 6.2 provides an outline for each of the case studies that were used to develop and validate the K-Shelf concept and software demonstrator. Section 6.3 explains an application of K-Shelf software through an automotive case study – Brake Pedal Box (BPB). Section 6.4 presents the application of K-Shelf software with an oil and gas solution case study – Surface Jet Pump (SJP). The BPB case study validates two of K-Shelf capabilities; supporting the set generation and comparison set of solutions. Furthermore, the SJP case study validates supporting the set generation, capturing design rationale and comparison set of solutions. The members of LeanPPD research group comprises of three PhD researchers who contributed to and were involved in conducting this case study are presented in Appendix C. Finally, experts' judgements are presented in section 6.5.

6.2 Industrial Case Studies

Two industrial collaborators gave the author the opportunity to undertake the case study in an industry driven research as follows:

1. Jaguar Land Rover Limited (JLR)
   JLR the biggest car manufacturing in the United Kingdom, where the business activities consist of design, development, manufacture, and sales of the vehicle. JLR has been a subsidiary of TATA Motors since they founded it for the acquisition of Jaguar Cars Limited and Land Rover from Ford in 2008. Currently, the company has thirteen vehicle models in the market under the JLR marque.
2. Caltec Production Solutions (CALTEC)
   CALTEC is an oil and gas engineering solution company that design and manufacture Surface Jet Pump (SJP) which purpose to revive the production of oil and gas from the dead wells. CALTEC's parent company, PETROFAC, is a global provider of oilfield services, operating on a global basis with over 18,000 employees. CALTEC currently holds 14 major design patents related to SJP.

A system can be divided into a hierarchy of sets of elements that include subsystems, components, subcomponents and parts. A Subsystem is a system in its own right, except it normally will not provide a useful function on its own, it must be integrated with other subsystems to make a system. Brake Pedal Box (BPB) of JLR and Surface Jet Pump (SJP) of CALTEC were two systems being used in the following case studies.

6.3 Brake Pedal Box (BPB) Case Study

The K-Shelf concept was applied in a case study at JLR. The K-Shelf was also implemented to demonstrate K-Shelf capabilities in addressing the PD challenges faced by the Chassis Engineering Department at JLR. This section validates the K-Shelf concept which is explained in Section 4.3.

The brake pedal box is one of the most important parts in a car which functions to assist a car driver to have control over the car while driving. Figure 6-2 shows the elements of the brake pedal box: 1) Bracket, 2) Pedal arm, 3) Pedal Pad and 4) Bushing. The most important characteristics of the brake pedal box desired are safety, reliability, and stiffness of the brake pedal box.

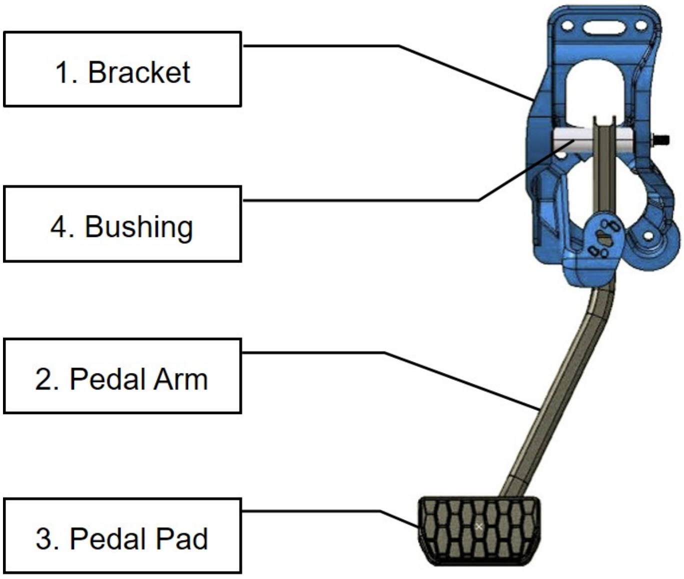


Figure 6-2 The system level of brake pedal box

The SBCE process model has a set of activities that must be carried out. The selected SBCE activities addressed in this research have been listed earlier in Figure 4-11. The following paragraphs explain the application of the Knowledge-Shelf capabilities in the BPB case study that refers to Knowledge-Shelf scenarios explained in Section 5.3.

6.3.1 Support the Set Generation of BPB

6.3.1.1 SBCE Activity 1.2: Explore Customer Value in BPB Case Study

The use of the K-Shelf software significantly improves the SBCE application in JLR, which previously done in a paper exercise (Maulana, 2018) i.e. the process to identify Key Value Attribute (KVA) as illustrated in Figure 6-3.

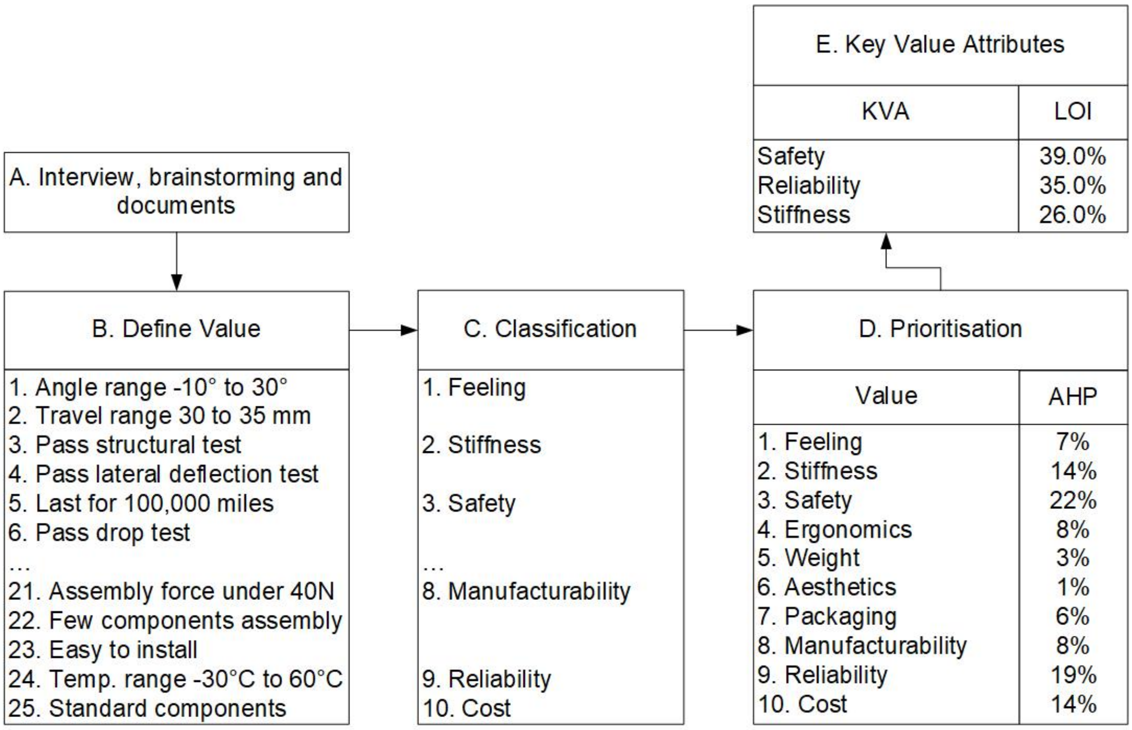


Figure 6-3 Process of Identifying key value attributes of brake pedal box in a paper exercise

As shown in Figure 6-3B, the first list of 25 value attributes was generated through brainstorming, analysing the customer requirement documents and interviewing the personnel in charge of the brake pedal box. Subsequently, these 25 values attributes were classified into 10 categories for easier handling of the analysis as shows in as shown Figure 6-3C. For example, values 21 to 23 were classified as single value attribute tagged as 'Stiffness'. In this same way, the rest of the values were classified based on the similarity of their objectives. In Figure 6-3D, AHP was used to identify the relevance of classified value attributes and the top three designs with the highest relevance scores were chosen as shown in Figure 6-3E.

The K-Shelf software populates the KVAs and their relevance as shown in Figure 6-4. The K-Shelf software in BPB case study has additional feature on the top of the webpage, a progress wizard to assist designer is presented according to selected SBCE activities. Without removing the navigation on the left pane, designer can see how further he is progressing in a current project and can return to the last session when he re-login to the K-Shelf software. For example, in Figure 6-4, KVA in BPB case study is found inside activity 1.2 of SBCE process model – explore customer value (refer to Figure 4-10). To add new KVA or delete existing one, designer have to press *Add Row* or *Delete* button. Subsequently, designer can insert both KVA and associating relevance values. To proceed to the next SBCE activity, designer need to press *Apply Changes* button. KVA and its relevance value automatically stored in to the database.

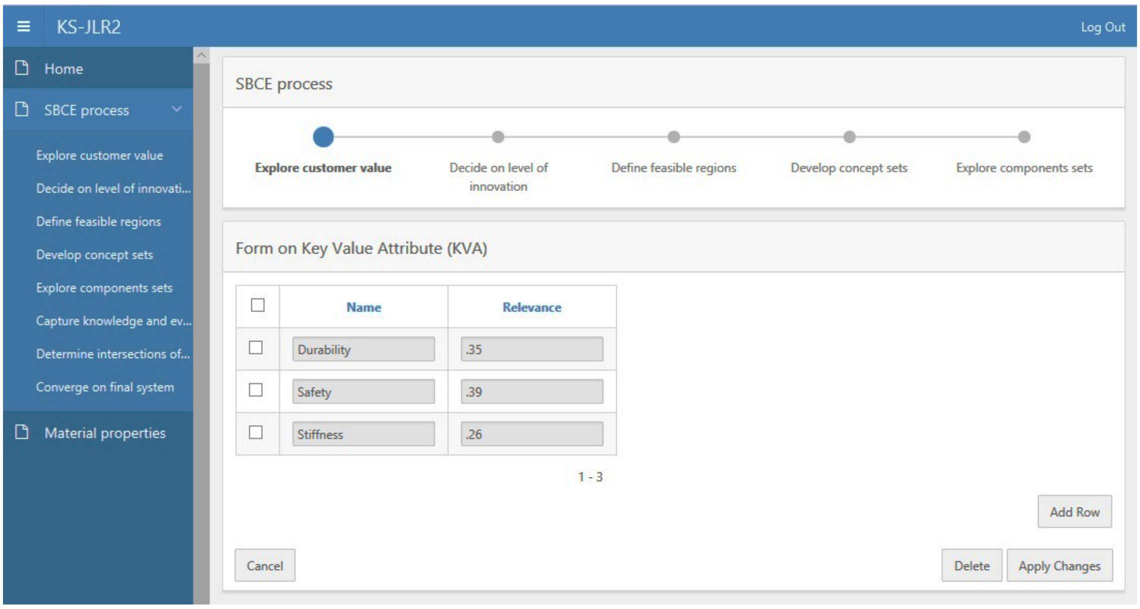


Figure 6-4 Customer value exploration of BPB in the K-Shelf software

6.3.1.2 SBCE Activity 2.2: Decide on Level of Innovation in BPB Case Study

Each of the components of the brake pedal box was analysed individually and it was decided whether it is worth developing them and to what level it should be, therefore level of innovation was used at this phase. Figure 6-5 illustrates the K-Shelf GUI of brake pedal box components and their respective level of innovation. A high level of the innovation was required for the bracket since there was a lot of flexibility in its design in terms of geometry and material. Furthermore, medium level of innovation was required for the pedal arm while the pedal pad and bushing are needed “no changes” in the design. Worth noting that *Explore Customer Value* in SBCE process region was ticked in green, while *Decide on Level of Innovation* in SBCE process region is active indicated by solid circle in blue.

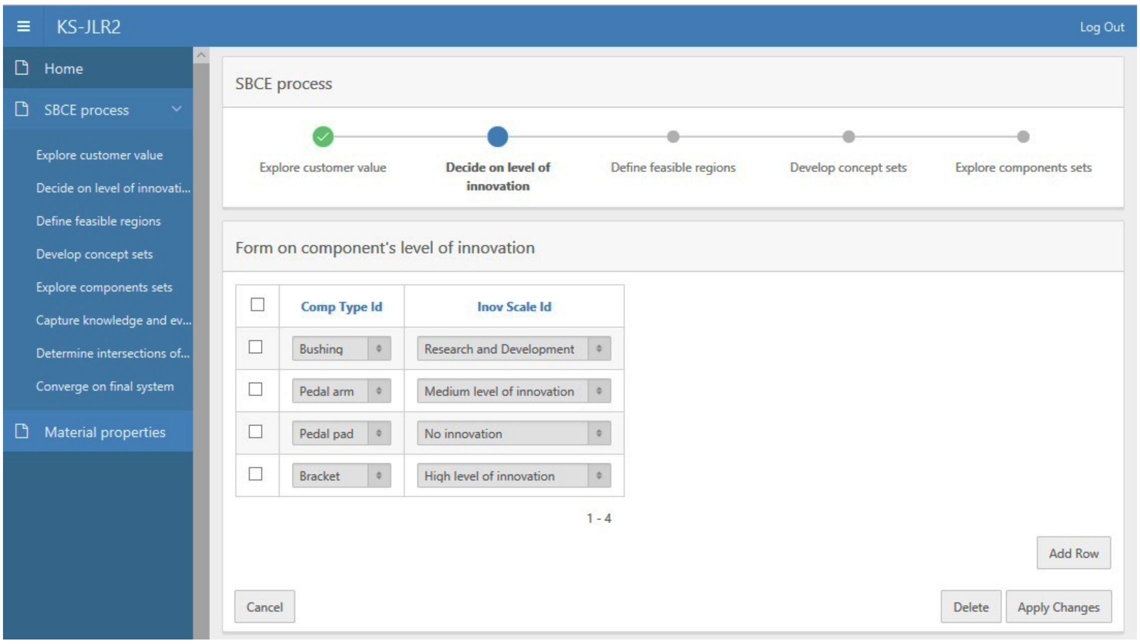


Figure 6-5 Level of innovation decision of BPB in the K-Shelf software

6.3.1.3 SBCE Activity 2.3: Define Feasible Regions of Design Space in BPB Case Study

To have clear objectives for the design and then to evaluate those different design alternatives, it is important to define feasible regions. Defining the feasible regions of design space also helps to reduce waste caused by over-engineering. Some characteristics and targets have been decided based on the given specification document and the tests which will be carried out. The targets set for the different elements will determine several feasible regions for several characteristics, these are shown in Figure 6-6.

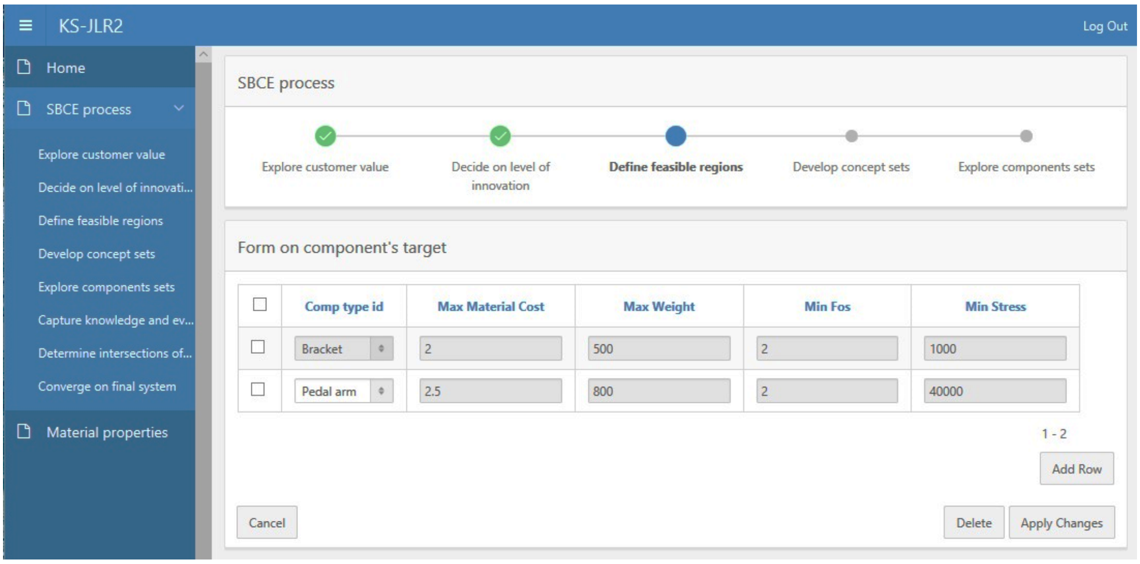


Figure 6-6 Feasible Region Definition of Brake Pedal Box in the K-Shelf Software

6.3.1.4 SBCE Activity 3.2: Create Sets for Subsystem in BPB Case Study

A research of existing designs and different design approaches was performed to inspire the generation of alternatives for the different components. All the efforts were put forward in the creation of alternative designs for the bracket and the pedal arm.

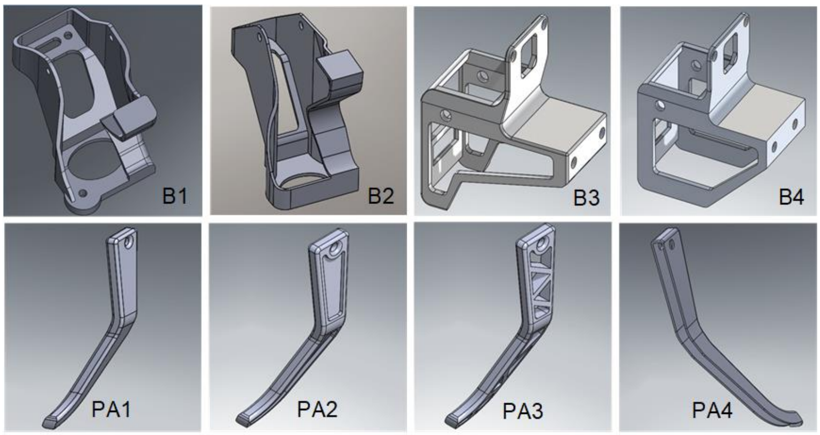
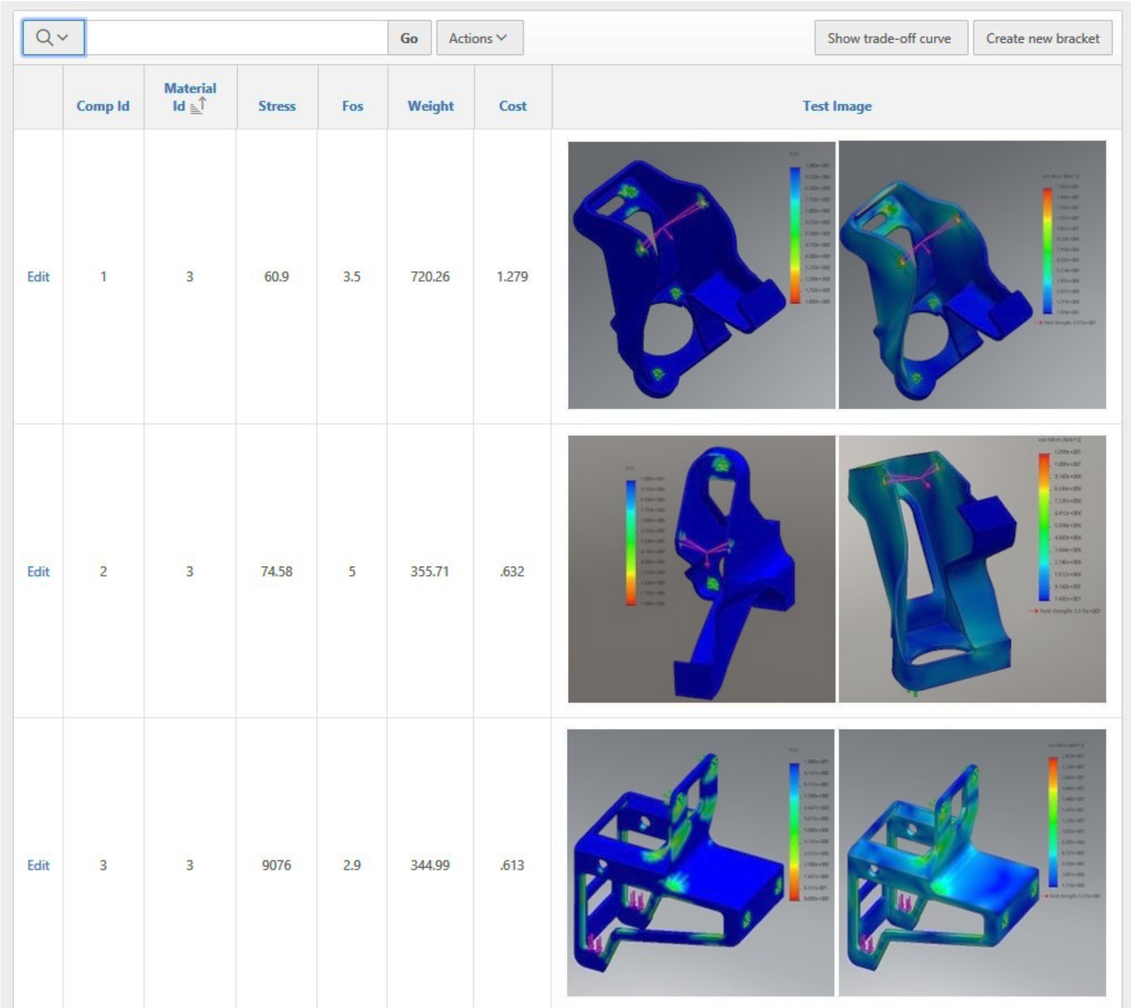


Figure 6-7 Generated set of bracket and pedal arm

As shown in Figure 6-7, four designs were found for both the bracket (B1-B4) and the pedal arm (PA1-PA4). Three different materials were considered for each of them; aluminium alloy 6061, magnesium alloy, and glass filled nylon fibre. These materials were selected due to their characteristic ability to address the KVA which is safety, reliability, and stiffness. Pairing of both bracket and pedal arm with material option gives 4 x 3 = 12 possible designs for each of them. When combined, it gives 12 x 12 = 144 different possible design solutions for the brake pedal, and therefore, potential solutions.



	Comp Id	Material Id	Stress	Fos	Weight	Cost	Test Image
Edit	1	3	60.9	3.5	720.26	1.279	
Edit	2	3	74.58	5	355.71	.632	
Edit	3	3	9076	2.9	344.99	.613	

Figure 6-8 Create sets for BPB bracket in the K-Shelf software

The purpose of this activity is to analyse the conceptual solutions to ascertain their reliability. The simulation analysis was carried out outside of the Knowledge-Shelf using SolidWorks software to create virtual prototypes of the parts that had the desired level of innovation i.e. the bracket and pedal arm. For example, by using SolidWorks from the outside of K-Shelf, the stress analysis was carried out for the bracket in Figure 6-8 and pedal arm as shown in Figure 6-9.

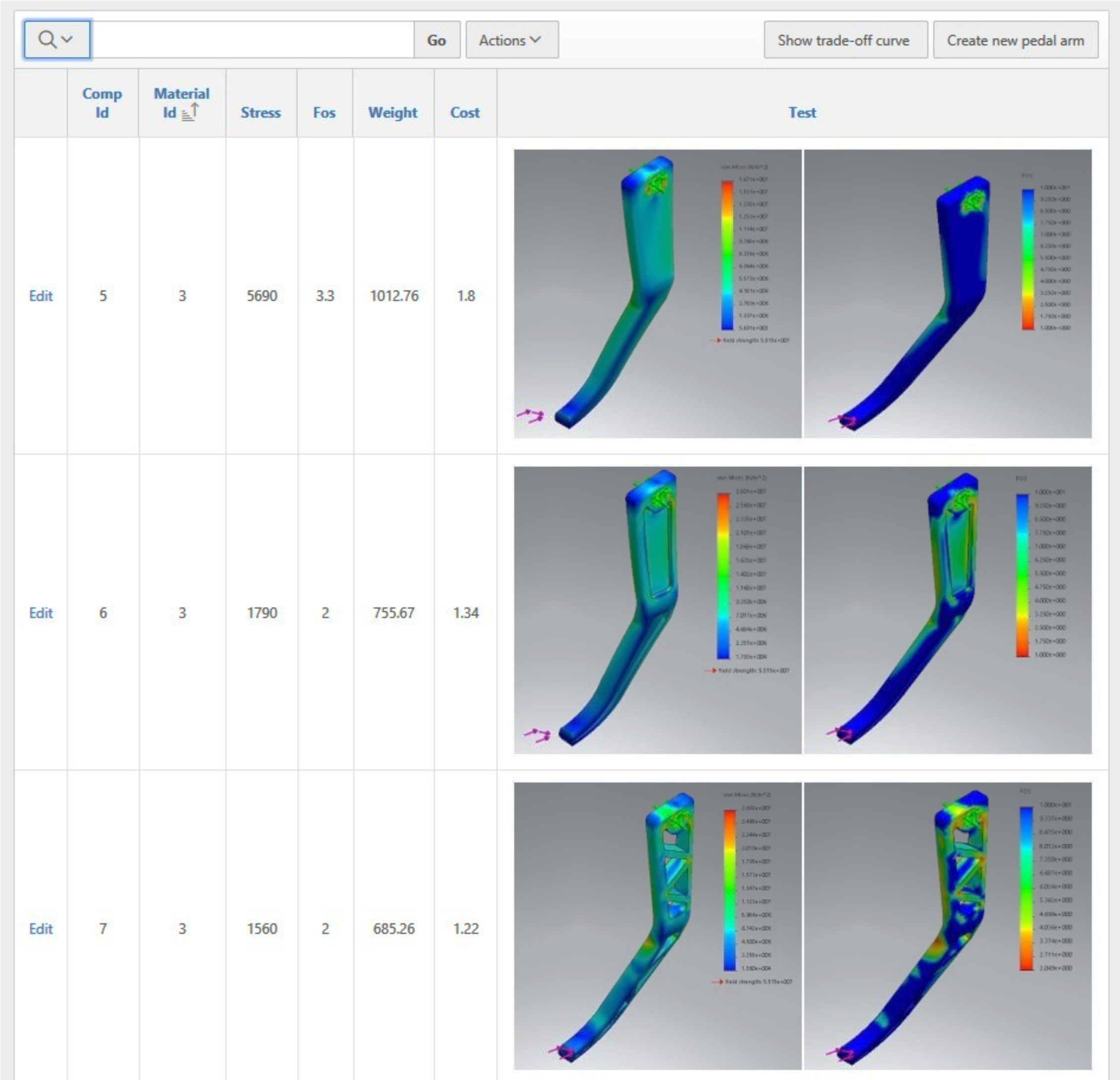


Figure 6-9 Create sets for BPB pedal arm in the K-Shelf software

Stress analysis figures in the K-Shelf software are basically the results from the simulation of any given physical phenomenon using a numerical technique namely Finite Element Analysis (FEA). The FEA figures are used to predict how a component reacts to real-world forces. These figures were uploaded by the designer to their corresponding components. The Finite Element Method (FEM) principle is used to reduce the number of physical prototypes and optimise bracket and pedal arm components in their design phase to develop better products faster. The K-Shelf software is not designed to provide FEA interpretation, however, designer did not have any problem to interpret them during the case study. It was easy for the designer to refer to the scale and numerical of the property to read the FEA result of a single component. Furthermore, to compare set of components and assist the designer to narrow down the set, the K-Shelf software has a feature to visualise TOC. Set of solution comparison will be explained in Section 6.3.2.

6.3.2 Set of Solution Comparisons of BPB

6.3.2.1 SBCE Activity 3.4: Capture Knowledge and Evaluate in BPB Case Study

From the result of the simulation, TOC were used to aggressively narrow down the solutions (Araci et al., 2017). For example, in the K-Shelf software, TOCs of bracket components were generated based on the information obtained in simulation as summarised in which is stress, factor of safety, material cost, and weight. The stress values and factor of safety value were gathered from the simulation data while the material weight and cost data are calculated using weight and cost of material as shown in Table 6-1.

Table 6-1 Set of bracket components simulation result

Design		Minimum Stress	Minimum FOS	Weight (grams)	Material cost (£)
B1	Alum	6.090e+01	3.5	720.26	1.279
	Nylon	2.034e+02	3.5	349.46	2.564
	Mag	2.034e+02	3.5	453.50	1.549
B2	Alum	7.458e+01	5	355.71	0.632
	Nylon	6.799e+01	5	172.59	1.266
	Mag	7.328e+01	5	223.97	0.765
B3	Alum	9.076e+03	2.9	344.99	0.613
	Nylon	1.294e+04	2.9	167.39	1.228
	Mag	1.294e+04	2.9	217.22	0.742
B4	Alum	3.893e+03	3	481.04	0.854
	Nylon	5.020e+03	3	233.40	1.035
	Mag	5.020e+03	3	302.874	1.713

Figure 6-10 illustrates the TOCs for the bracket. At this stage, the focus is to identify the component that could satisfy each of the TOCs values. A combination that does not satisfy any of the TOCs will be discarded.

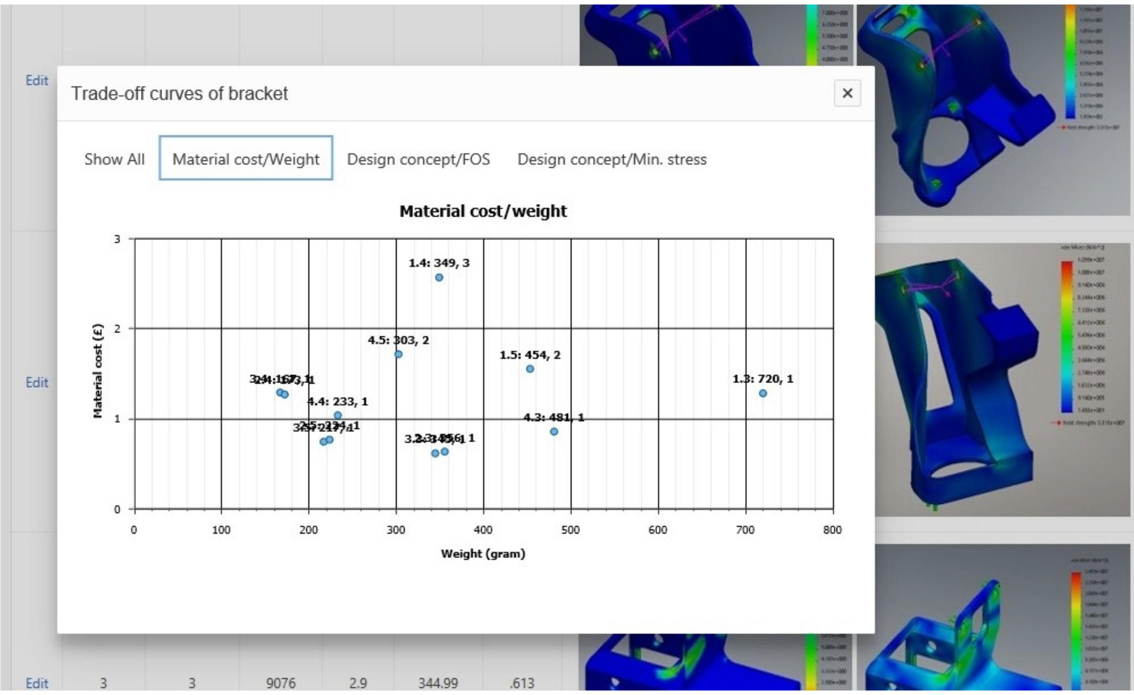


Figure 6-10 Trade-Off Curve of Material Cost and Weight for Bracket

6.4 Surface Jet Pump (SJP) Case Study

The Knowledge-Shelf concept was implemented during the case study of SJP in collaboration with CALTEC. The Knowledge-Shelf software was also deployed to demonstrate its capabilities. The aim of the case study is to present the right knowledge environment to enable SBCE application in the early phase of SJP conceptual design activity.

SJP is a device used to increase production rate and to revive dead wells in oil and gas industry. The general function of SJP is to boost the pressure of low pressure (LP) fluids, which is needed at different stages of the production process. Compared to traditional methods of increasing pressure with the use of compressors, SJP are highly cost-effective solutions that provide the same performance. SJP utilises kinetic energy from a high pressure (HP) source to increase the pressure of the LP fluid as illustrated in Figure 6-11A.

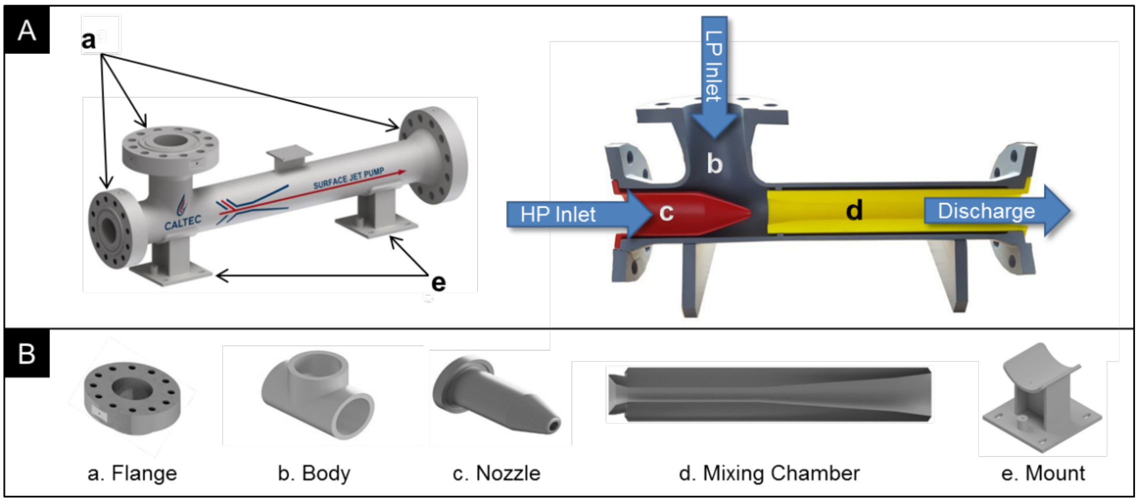


Figure 6-11 CALTEC Surface Jet Pump

The key components of SJP are listed and shown in Figure 6-11B which are comprise of (a) flange for manifolds attachment; (c) nozzle for the motive HP fluid; (d) mixing chamber for transfer of energy and momentum between HP and LP fluid streams; (b) body to integrate the components and provide suitable flow direction of the fluid. The next paragraphs explain the application of Knowledge-Shelf capabilities to enable SBCE application in the SJP case study.

6.4.1 Support the Set Generation of SJP

6.4.1.1 SBCE activity 1.2: Explore Customer Value in SJP Case Study

Customer values must be clearly understood in order to identify SJP system target which focuses on the improvement of the SJP design performance. The use of K-Shelf significantly improves the SBCE application in CALTEC, which previously done in a paper exercise (Maulana, 2018) i.e. the process to identify KVA as illustrated in Figure 6-12. Figure 6-12B shows the first list of 38 value attributes generated through brainstorming, analysing the customer requirement documents and interviewing the personnel in charge of the SJP as illustrated in Figure 6-12A. Subsequently, these 38 values attributes were classified into seven categories for easier handling of the analysis as shows in as shown Figure 6-12C. For example, values 35 and 36 were classified as single value attribute tagged as ‘Design Performance’. In the same way, the rest of the values were classified based on the similarity of their objectives. In Figure 6-12D, AHP was used to identify the relevance of classified value attributes and the top three designs with the highest relevance scores were chosen; design performance, manufacturability and cost as shown in Figure 6-12E.

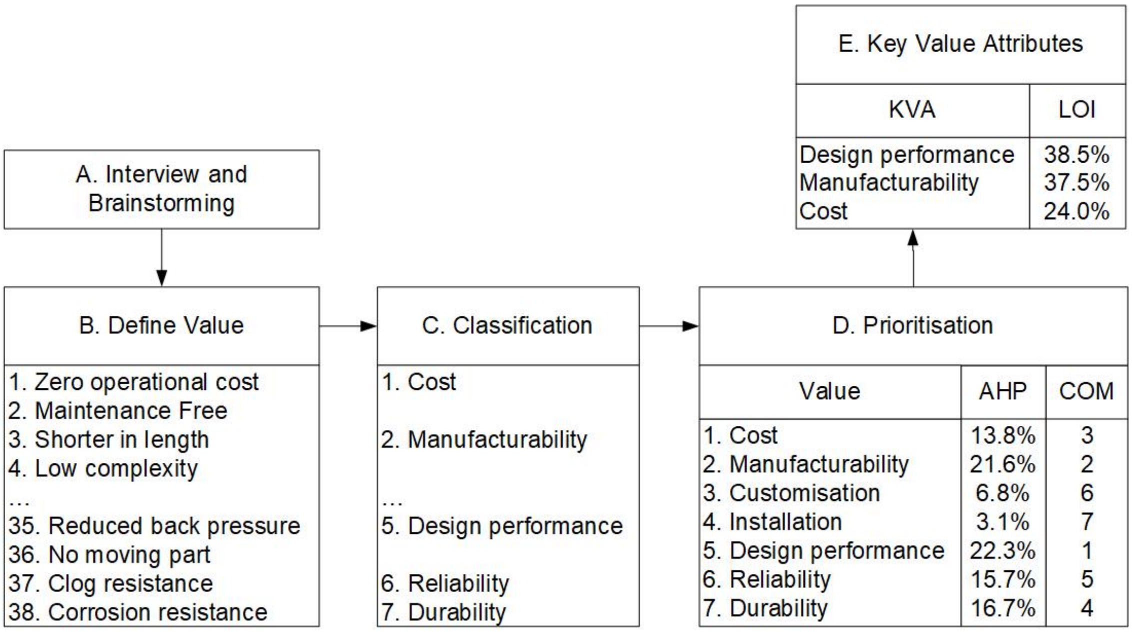


Figure 6-12 Process of identifying Key Value Attribute in a paper exercise

The K-Shelf software enables designer to transform the obtained paper-based customer values to be formally represented and classified in a database for future reuse. Manual input of customer values can be avoided because designer can upload them in spreadsheet format as illustrated in Figure 6-13. This application refers to upload and explore customer value scenario as illustrated in Figure 6-13. Upon the completion of customer values upload, K-Shelf software populated classified customer values along with AHP percentages, company prioritisation and let the designer to select desired key value attributes. The load of importance values is calculated using the following calculation:

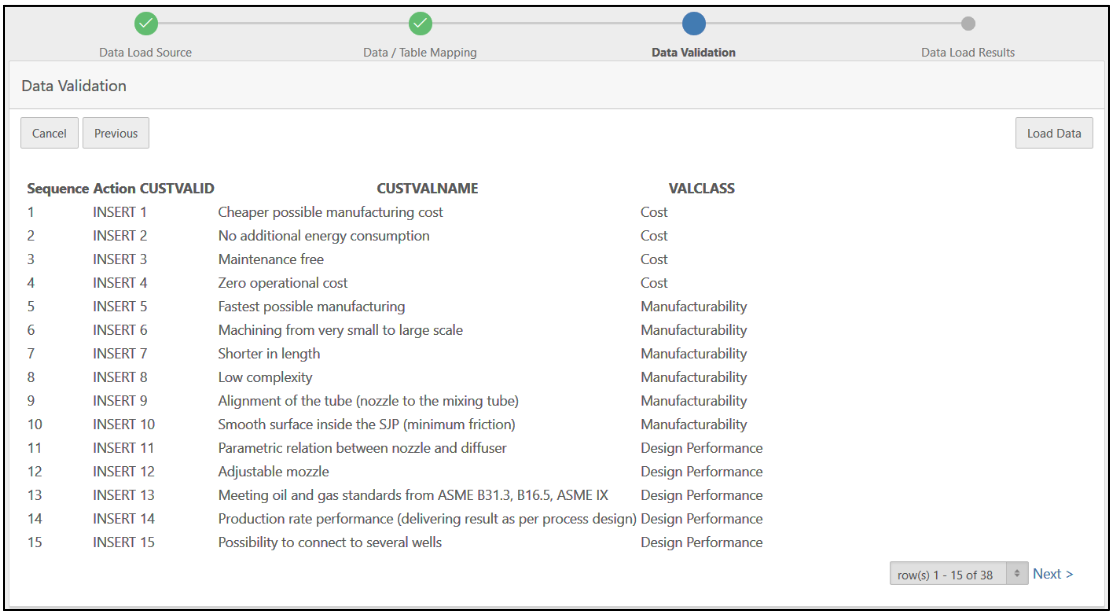
Equation 6-1 Load of importance equation

$$Load\ of\ importance = \frac{AHP_p}{\sum_{i=1}^{3} AHP_p} \times 100\%$$

Where;

AHP_p = AHP priority percentage (e.g. design performance = 22.3%).

$\sum_{i=1}^{3} AHP_p$ = Total sum of top three highest AHP priority percentage based on company prioritization order.



Data Load Source · Data / Table Mapping · **Data Validation** · Data Load Results

Data Validation

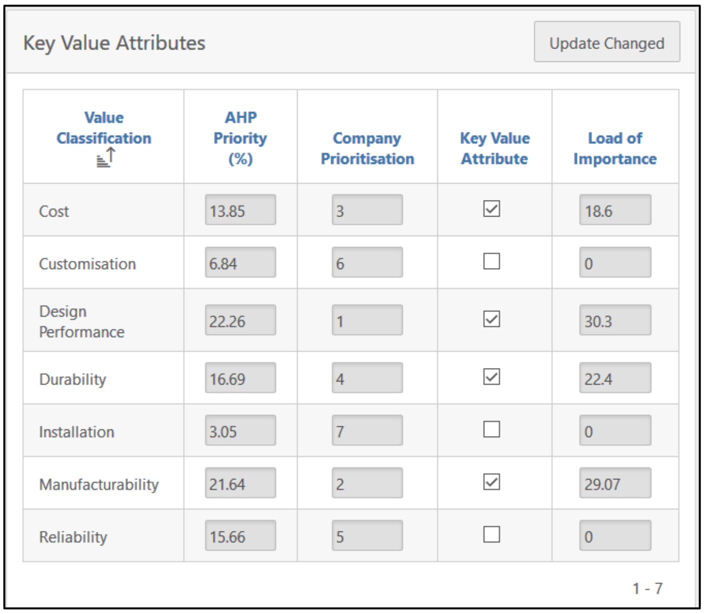
Cancel | Previous | Load Data

Sequence	Action	CUSTVALID	CUSTVALNAME	VALCLASS
1	INSERT	1	Cheaper possible manufacturing cost	Cost
2	INSERT	2	No additional energy consumption	Cost
3	INSERT	3	Maintenance free	Cost
4	INSERT	4	Zero operational cost	Cost
5	INSERT	5	Fastest possible manufacturing	Manufacturability
6	INSERT	6	Machining from very small to large scale	Manufacturability
7	INSERT	7	Shorter in length	Manufacturability
8	INSERT	8	Low complexity	Manufacturability
9	INSERT	9	Alignment of the tube (nozzle to the mixing tube)	Manufacturability
10	INSERT	10	Smooth surface inside the SJP (minimum friction)	Manufacturability
11	INSERT	11	Parametric relation between nozzle and diffuser	Design Performance
12	INSERT	12	Adjustable mozzle	Design Performance
13	INSERT	13	Meeting oil and gas standards from ASME B31.3, B16.5, ASME IX	Design Performance
14	INSERT	14	Production rate performance (delivering result as per process design)	Design Performance
15	INSERT	15	Possibility to connect to several wells	Design Performance

row(s) 1 - 15 of 38 Next >

Figure 6-13 Customer value load in the K-Shelf software

The K-Shelf software presents the region of KVA as shown in Figure 6-14.



Key Value Attributes — Update Changed

Value Classification	AHP Priority (%)	Company Prioritisation	Key Value Attribute	Load of Importance
Cost	13.85	3	☑	18.6
Customisation	6.84	6	☐	0
Design Performance	22.26	1	☑	30.3
Durability	16.69	4	☑	22.4
Installation	3.05	7	☐	0
Manufacturability	21.64	2	☑	29.07
Reliability	15.66	5	☐	0

1 - 7

Figure 6-14 Key Value Attribute Update in the K-Shelf software

The values that remain unchecked e.g. customisation, installation and reliability were assigned as values of consideration. Designer confirms every change by pressing update button in the top right of key value attributes region.

The system targets should be specified in order to explain how the value attributes will be reached. System targets should be analysed at the subsystem level to confirm their correct translation on subsystem targets. K-Shelf software facilitates designers to insert system targets name with the association to its customer value classification using a combo box as demonstrated in Figure 6-15.

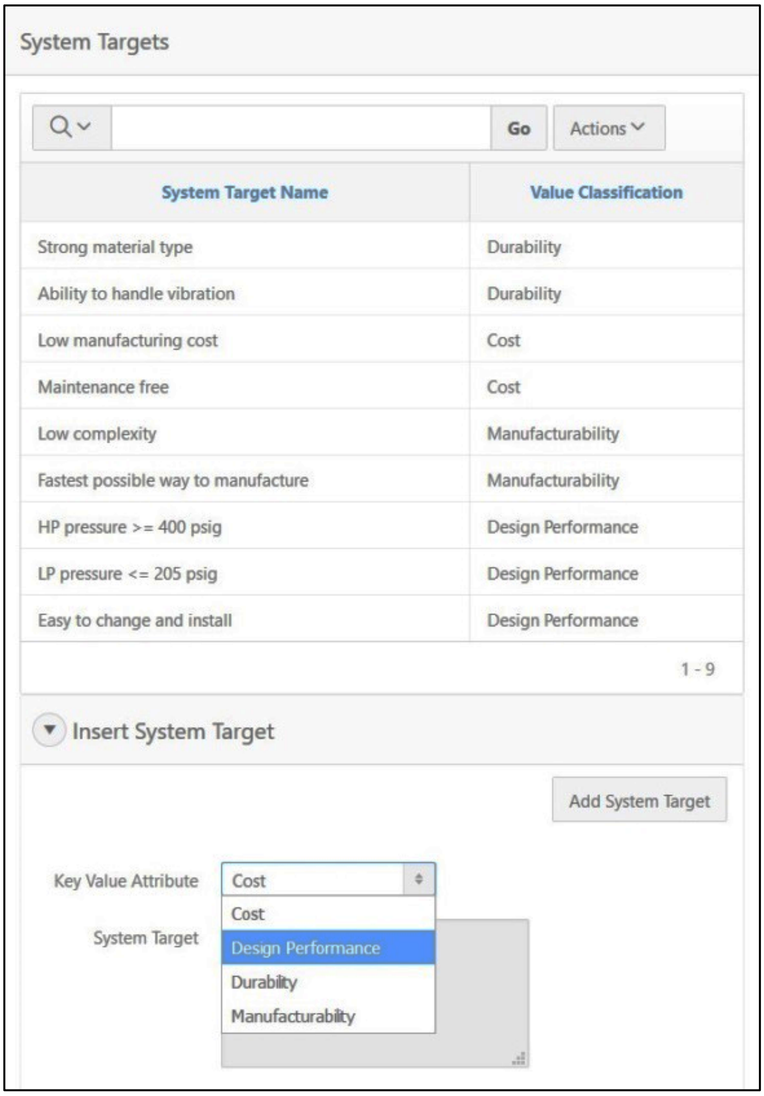


Figure 6-15 Defining System Target in K-Shelf software

6.4.1.2 SBCE Activity 2.1: Identify Component Target in SJP Case Study

Feasible target for each component is defined to prevent over engineering and supporting the development of innovation. Some of the system targets were adapted onto component targets. The rest were defined as a new target to ensure that it meets key value attributes (KVA); design performance, manufacturability and cost. The component targets for the nozzle are listed as follows:

1. The nozzle is replaceable
2. Low complexity of the geometry
3. No moving parts
4. Maintenance free
5. Faster manufacture method
6. Low manufacturing cost

Component targets are recorded in a similar way as system target as illustrated in Figure 6-15. The only difference is that in *System Target* region, system targets were added against KVA while in *Subsystem/Component Target* region, component targets are added against components e.g. nozzle, mixing tube, mount, body or flange.

6.4.1.3 SBCE Activity 2.2: Decide on Level of Innovation to Subsystems/Components in SJP Case Study

Activity 2.2 of SBCE process in which to decide on level of innovation (see Figure 4-11) is translated to K-Shelf software as *Feasible Regions of Design Space* region as shown in *Subsystem/Component Level of Innovation* region as shown in Figure 6-16A. The SJP system structure is divided into components comprise flanges, nozzle, body, mixing tube and mounts. Since the nozzle and body determines the performance of the SJP system, hence the nozzle and body level of innovation were set as high level. The function of the body is to provide a suitable flow direction of the fluids as well as to integrate each of the components in the SJP. The mixing tube has been classified as a medium innovation. Inside the mixing tube, HP and LP fluids from oil and gas well are mixed together to obtain the discharge pressure. In order to increase discharge pressure, mixing tube needs a medium level of design changes to enhance system performance.

Mounts are defined as “Low innovation” to ensure proper absorption of the vibration. Flanges are coded as “no change in the design”. User needs to press *Update Changes* button to commit changes of any level of innovation revision.

6.4.1.4 SBCE Activity 2.3: Define Feasible Regions of Design Space in SJP Case Study

The design space is defined as the boundaries for designers and engineers to explore and communicate with many alternative conceptual design solutions. The component boundaries for the nozzle is corresponding to the defined level of innovation as illustrated in Figure 6-16C and have been identified to generate alternative design solutions as well as to create an appropriate design space for the other subsystems to fit together without any adjustments for the body and flanges. Component boundaries for the nozzle were derived from the SJP handbook from Beg and Sarshar (2014) as follows:

1. Nozzle angle ≤ 17.5°.
2. Inside diameter ≤ 131 mm.
3. Nozzle length ≤ 445 mm.
4. Nozzle tip diameter ≤ 41.28 mm.

Activity 2.3 of SBCE process in which to define feasible regions of design space (refer to Figure 4-11) is translated to K-Shelf software as *Feasible Regions of Design Space* region as shown in Figure 6-16B. Components that have high level of innovation, for example the nozzle in Figure 6-16C is enquired with predefined boundary questions as illustrated in Figure 6-16D.

Boundary of the SJP’s system is filled up in a text entry field that accept conditional statement e.g. “discharge pressure ≥ 300 AND total length ≤ 2000” as illustrated in Figure 6-16E. The AND operator used in the conditional statement performs a logical conjunction. If one of the two statements are false, then the *System Boundaries* region in the K-Shelf software will not display any SJP system from previous project. However, the K-Shelf software keeps these boundaries into the database and inform the users if there is any previous project that fits the boundaries. In this case, there were two comprised previous project obtained from the industrial collaborator as illustrated in Figure 6-16F. The capability of the

K-Shelf software to identify subsystem or component as a part from previous project that falls into certain boundary demonstrates the provisioning of knowledge to the designer. Type of knowledge addressed by the author in this research are design rationale and TOC.

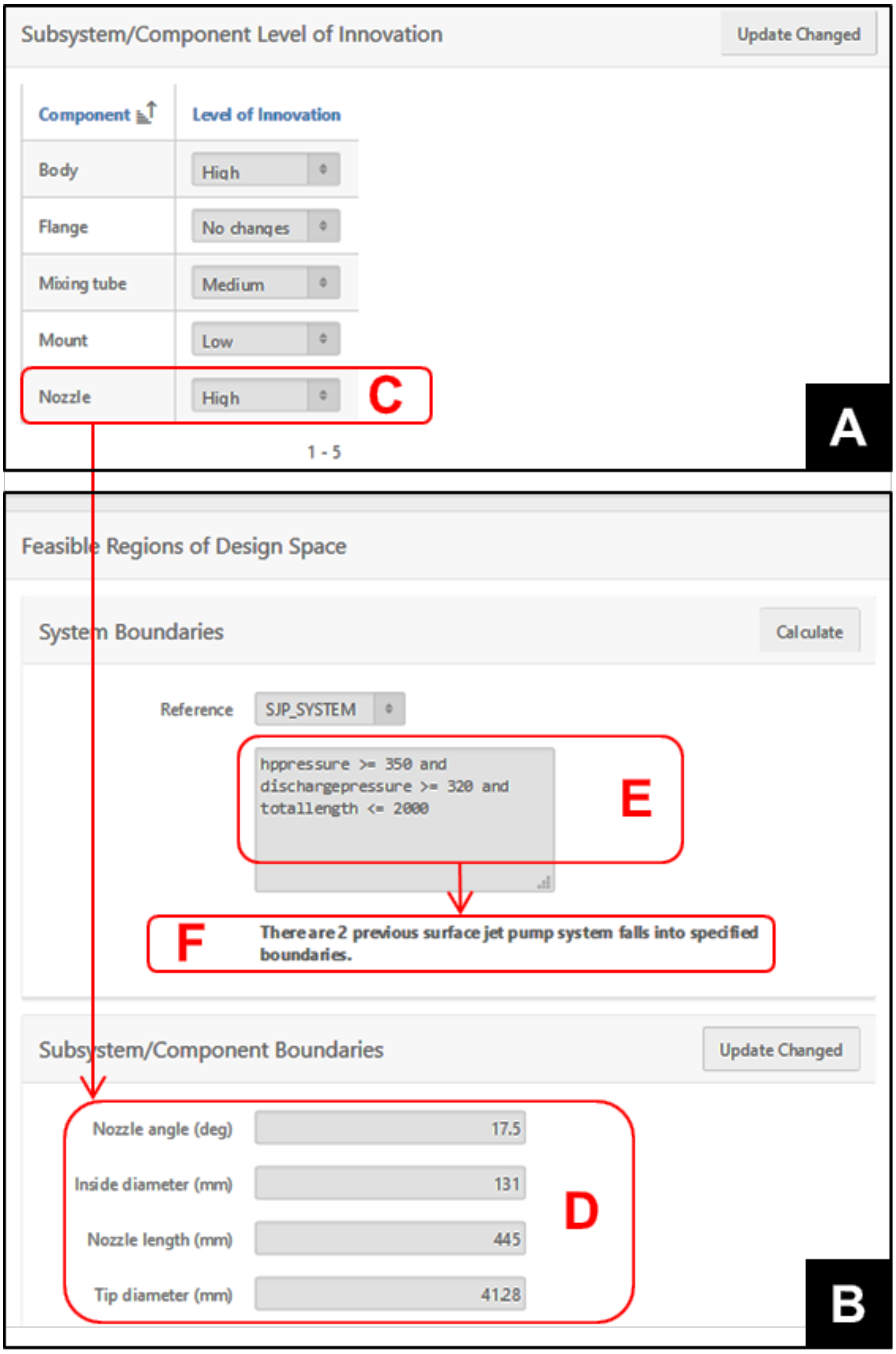


Figure 6-16 Defining Level of Innovation and Feasible Region in the K-Shelf

6.4.1.5 SBCE Activity 3.1: Extract (Pull) Design Concept in SJP Case Study

The K-Shelf software provides a tool for designer to extract or pull SJP's component design concepts which is translated from Activity 3.1 in SBCE process model (refer to Figure 3-3). Activity 3.1 of SBCE process to extract (pull) design concepts in SJP case study is presented in the K-Shelf as *Design Concept Extraction* region discloses the identified SJP's previous project that falls into specified boundaries as aforementioned in Figure 6-16F. The component of nozzle, body and mixing tube of this previous design became the basis of design that is named as original components in this case study. The system boundaries, component targets and component boundaries were considered during generation of the alternative design.

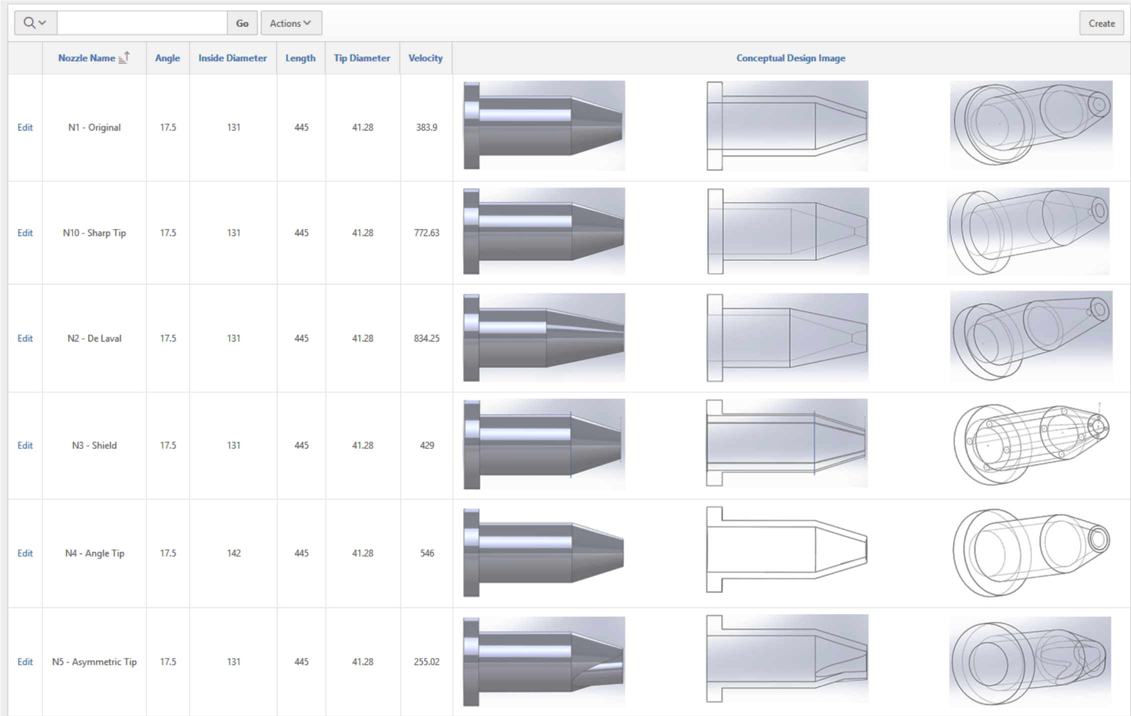
6.4.2 Design Rationale Capture and Provision of SJP

6.4.2.1 SBCE Activity 3.2: Create Sets for Components in SJP Case Study

The K-Shelf software provides a tool for designer to create sets for components in SJP case study which is translated from Activity 3.2 in SBCE process model (see Figure 4-11). Activity 3.2 in SBCE process model is presented in the K-Shelf software in the form of a tabular region, as shown in Figure 6-17. In this region, all of the component design concepts from previous project that falls into specified boundaries are presented. At the same time, newly generated component design concepts can be inputted by the designer by pressing *Create* button in the top right of this region as shown in Figure 6-17.

Conceptual design images were produced outside of the K-Shelf software. All of nozzle images in Figure 6-17 were drafted and rendered using ANSYS software. In the first row of *Component Generation* region is the basis of nozzle design, namely *N1 - Original* as shown in Figure 6-17. This original design is acquired from previous project. In this case study, the designer managed to design nine new nozzle designs, hence in total ten nozzles were considered. The nozzles are: N1 - Original, N2 - De Laval, N3 - Shield, N4 - Angle Tip, N5 - Asymmetric, N6 - Bi-Nozzle, N7 - Multi Jet, N8 - Parabolic, N9 - Riffle and N10 - Sharp Tip where six of them are shown in Figure 6-17. The body and mixing chamber components were also developed; there were two new bodies and one new mixing tube.

During Activity 3.2 of SBCE, 60 potential solutions were generated as the result of multiplication of ten nozzles, three bodies and two mixing tubes.



Go Actions Create

	Nozzle Name	Angle	Inside Diameter	Length	Tip Diameter	Velocity	Conceptual Design Image
Edit	N1 - Original	17.5	131	445	41.28	383.9	
Edit	N10 - Sharp Tip	17.5	131	445	41.28	772.63	
Edit	N2 - De Laval	17.5	131	445	41.28	834.25	
Edit	N3 - Shield	17.5	131	445	41.28	429	
Edit	N4 - Angle Tip	17.5	142	445	41.28	546	
Edit	N5 - Asymmetric Tip	17.5	131	445	41.28	255.02	

Figure 6-17 Create Sets for Nozzle Component in the K-Shelf

6.4.2.2 SBCE Activity 3.3: Explore Subsystem Sets in SJP Case Study

To explore component sets during SJP case study, the K-Shelf software provides a tool for designer to explore possible alternative components which is translated from Activity 3.3 in SBCE process model (refer to Figure 3-3). Activity 3.3 in SBCE is presented in the K-Shelf software in the form of a region, namely Possible Alternative Components as shown in Figure 6-18. In this region, all possible alternative component design concepts are presented as the combination of nozzle, mixing tube and body conceptual designs.

Designer selects the most appropriate conceptual design based on three criteria in the KVA; design performance, manufacturability and cost. Some conditional expressions were applied in the *Possible Alternative Components* region. For example, feasible nozzles will be carried on SJP development if at least two criteria were selected and only if design performance criterion was selected as highlighted. As shown in Figure 6-18, five nozzles met the criteria comprises N1, N2, N4, N7 and N10. In terms of design performance, designer refers to the result of analysis of SJP's flow motions that were carried out using Computational Fluid Dynamic (CFD) software – ANSYS. The results of CFD analysis are stored in the K-Shelf database and populated in the K-Shelf software as image in Join Photographic Expert Group (JPEG) format.

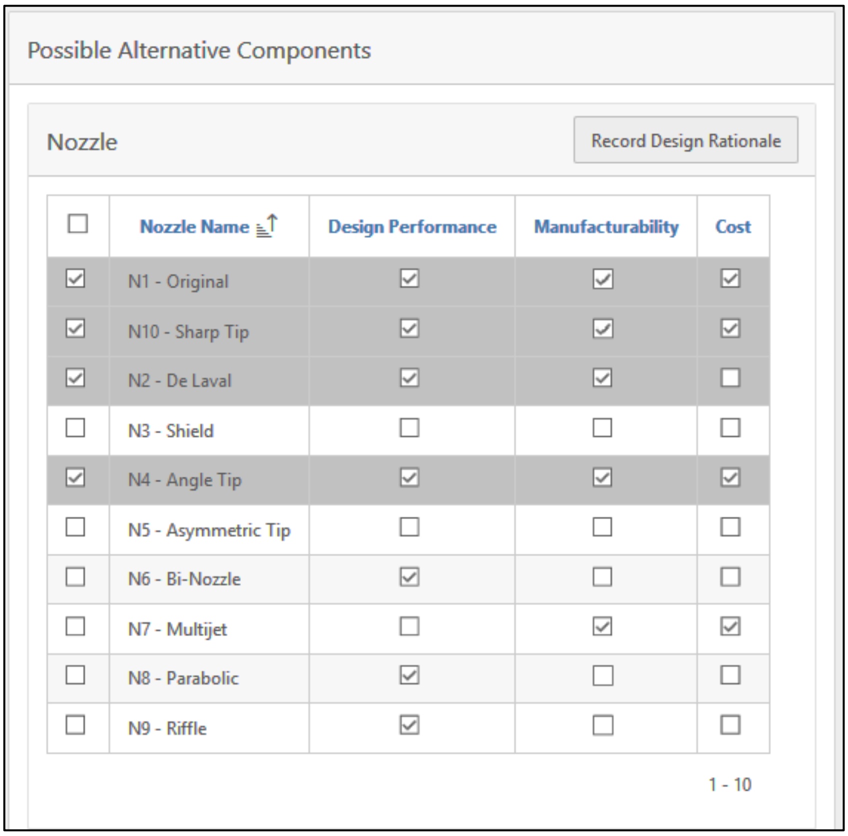


Figure 6-18 Explore Subsystem Set Activity in Knowledge-Shelf

Design Rationale region in the K-Shelf software is triggered when the designer presses *Record Design Rationale* button in the top left of *Possible Alternative Components* region as shown in Figure 6-18.

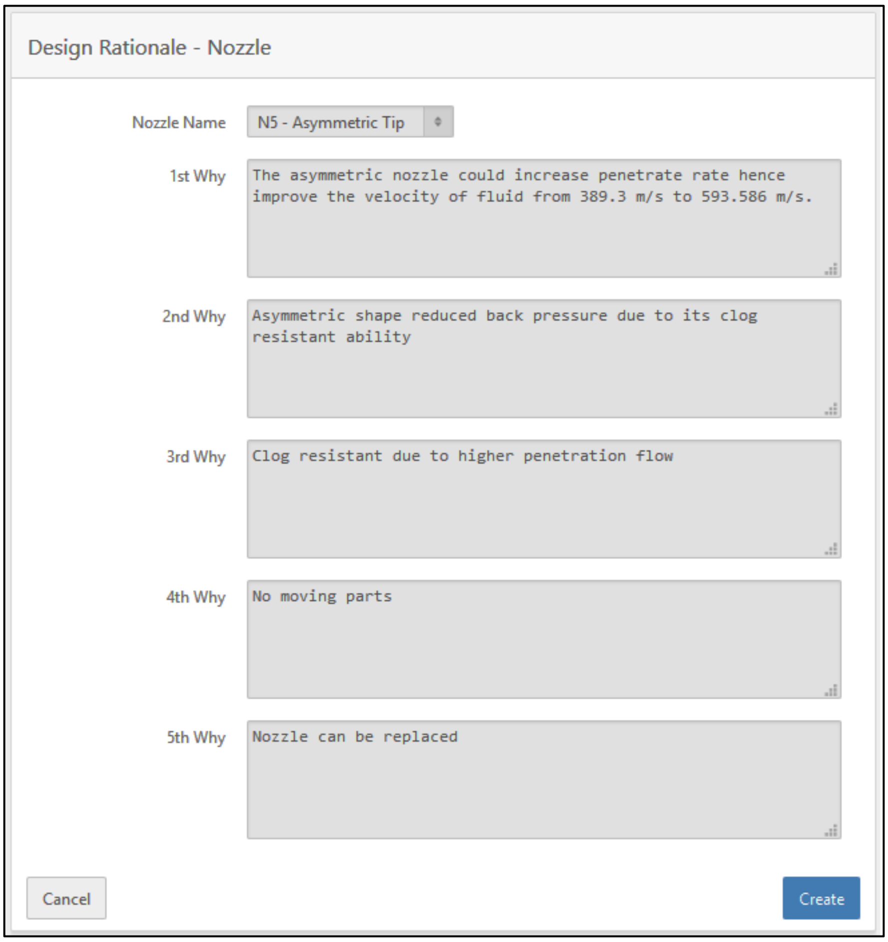


Figure 6-19 Design rationale Capture of Nozzle Component in the K-Shelf

Design decision rationales behind a particular decision made by designer were captured in the K-Shelf software region. For example, design rationale of asymmetric nozzle (N5) was captured dynamically inside *Design Rationale* region as shown in Figure 6-19. The K-Shelf software facilitates designer to capture components' design rationale regardless of their feasibility, both of feasible and infeasible components.

Once the designer presses *Record Design Rationale* button as shown in Figure 6-18, design rationale capturing dialog will be initiated. For instance, nozzle N5 design rationale was captured in an iterative interrogative 5 Whys dialog to record the cause-and-effect relationship underlying a particular decision as shown in Figure 6-19. The SJP design rationales were based on empirical data acquired during the case study or argumentation among design participants.

6.4.3 Set of Solution Comparisons of SJP

6.4.3.1 SBCE Activity 3.4: Capture Knowledge and Evaluate in SJP Case Study

In Section 6.4.2.2, the conceptual solutions were evaluated. The analysis has been focused on the flow motion of nozzles to determine the HP and LP values which give an impact to the performance of the SJP. The nozzle analyses were performed outside the K-Shelf software by using the ANSYS software. For example, CFD results for nozzle N10 is shown in Figure 6-20 with the following CFD simulation parameters:

1. Flow rate = 10.33 kg/s.
2. Nozzle outlet pressure = 196 psig.
3. Nozzle inlet temperature = 88 °C.
4. Molar weight = 24.89 kg/kmol.
5. Specific heat = 2,340 J/kg*K.
6. Dynamic viscosity = 1.03971e10 kg/m*s.

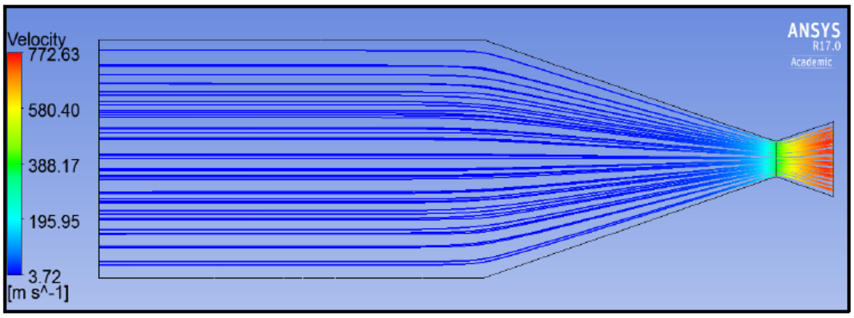


Figure 6-20 Example of CFD simulation result for nozzle N10

However, the analysis at this stage is done only for the nozzles as it is the only component that could be analysed separately. Design variations are needed in order to obtain the highest velocity in the nozzle. This could generate a vacuum pressure state, which helps to boost the pressure of LP fluid or gas to an intermediate pressure level. From the 60 potential SJP configurations, not all are suitable to become the final solution of the SJP. Therefore, TOC were used to narrow down the subsystem solutions based on the CFD simulation results, manufacturing complexity and manufacturing cost of the solutions.

In order to narrow down the 60 system configurations, during the paper-based SBCE application, a manual plotting technique was performed to compare manufacturing complexity and manufacturing cost to nozzle downstream velocity (Maulana, 2018). As it could be seen in Figure 6-21, it is difficult for the designer to identify set of nozzles that falls within feasible region.

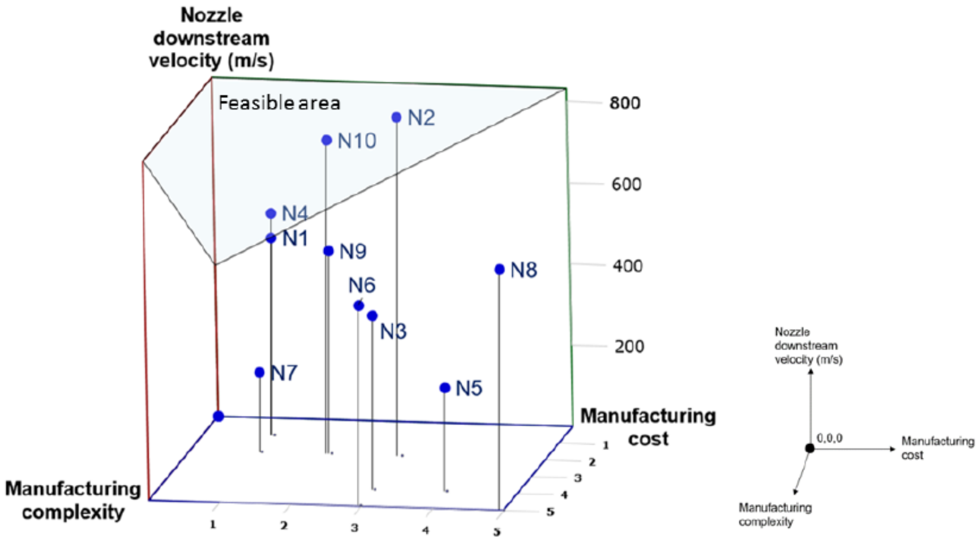


Figure 6-21 Comparison of manufacturing complexity and manufacturing cost to nozzle velocity

Another capability included in the K-Shelf software is the provision of diagrams and representation that support the comparison of different design solutions. One particular diagram that has been highlighted as essential for SBCE is the TOC which presents the behaviour of multiple solutions along critical performance axes for the purpose of comparison. TOCs were generated using components' information as illustrated in Figure 6-22. In order to plot nozzle physics-based TOC, following indicators were used:

1. Nozzle downstream velocity (m/s) as a parameter related to design performance.
2. Manufacturing cost scaled from 1 to 5, where 1 is the cost of the original design and 5 is the highest cost.
3. Manufacturing complexity scaled from 1 to 5, where 1 is the manufacturing complexity of the original design.

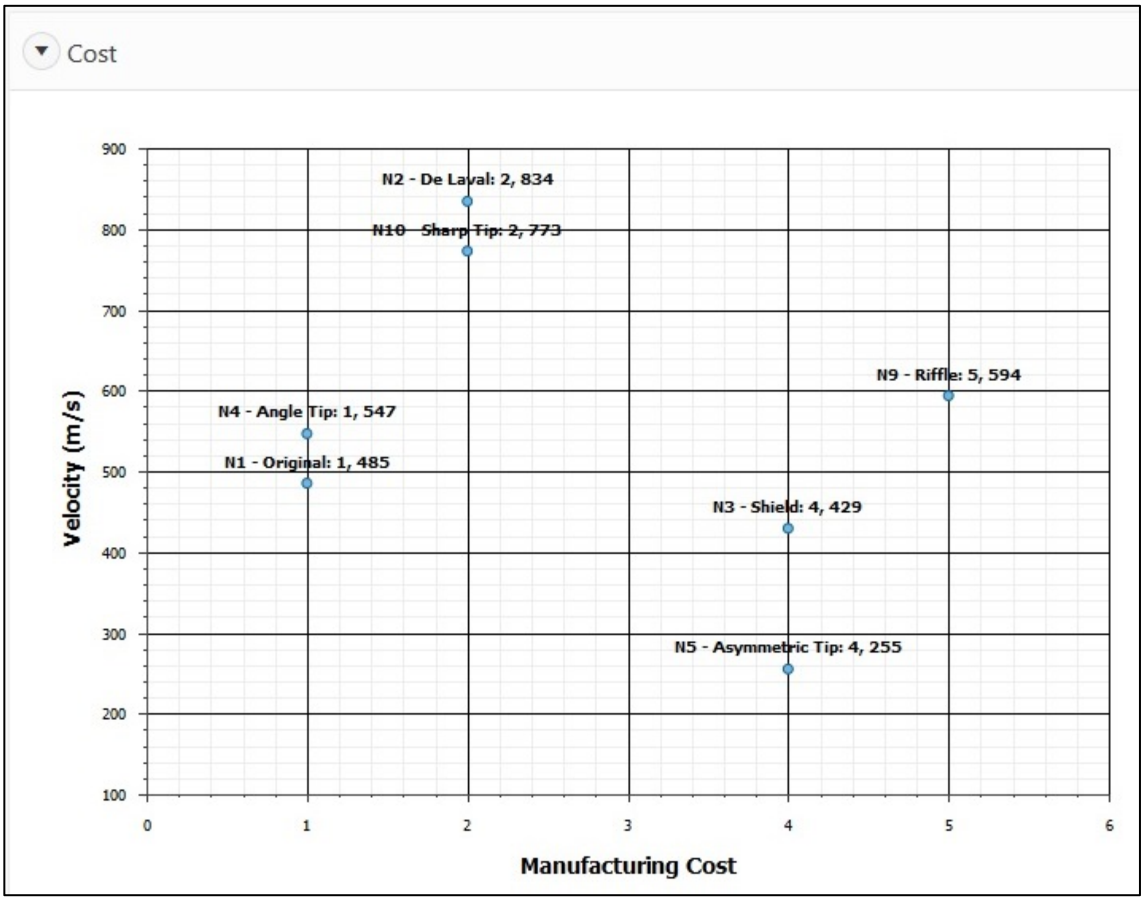


Figure 6-22 TOC of Nozzle Manufacturing Cost and its Velocity

K-Shelf is designed to support comparison among set of solution which is needed in order to assist the narrowing of set of solutions. During SBCE process, multiple solutions are explored simultaneously. Possible solutions might include numerous designs, different technologies, or a range of parameter values. The K-Shelf supports this exploration, by capturing information about multiple solutions and allowing the user to navigate across options and explore them with appropriate views throughout the SBCE process. As it could be seen in Figure 6-22, there are four design solutions of the nozzle in the feasible area. These are N1, N2, N4, and N10 which are illustrated in Figure 6-19. Hence, with the capability of the K-Shelf software to compare the set of solution, the number of the nozzle designs was narrowed down from 10 to 4.

6.5 Industrial Expert Judgement

Two experts, who have specialised in PD and each have several years of experience, were identified to capture their feedback and comments on the following aspects:

1. The concept of K-Shelf
2. The demonstration of K-Shelf software, emphasised in the process of supporting the set generation of components, capturing design rationale knowledge and set of solution comparisons.

Each expert judgement session commenced with a brief definition of the K-Shelf concept and overview of the K-Shelf software, as described in Section 4.3.2.1, Section 6.3 and Section 6.4. Subsequently, a discussion was held where feedback and comments from the experts were received and captured. Expert opinions on the capabilities of the K-Shelf were captured and documented in Section 6.5.1 Section 6.5.2.

6.5.1 Expert Judgement 1

The first expert for this research is a technology director in oil and gas solution company, 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 was asked to comment regarding the K-Shelf concept and capabilities demonstration via the K-Shelf software. He found the K-Shelf software helps provide speed and cost effectiveness in decision-making. It provides, in a short time with minimal amount of effort, the decision-makers with:

1. Information on previous R&D projects to completely eliminate the probability of doing the same R&D project more than once.
2. Recording of the decision-making process for that R&D, therefore gaining the knowledge by experience the way the R&D team had.

3. Complete data of the R&D project that includes among other things: design, performance, cost and resources needed for manufacture.

He also expressed his endorsement for this software to be applied in various company including his own.

6.5.2 Expert Judgement 2

The second expert for this research is a senior of powertrain test operations manager in a leading car manufacturing in the UK. The expert thinks that in PD within a big company where many products are developed simultaneously, it is imperative to be able to capture the knowledge gained. While developing different products, a number of designs are evaluated. Some of these designs, despite being good are discarded due to them not being viable for the current product. This could be due to the design or technology not being market ready or perhaps the product not being the best application for the said design. Usually these designs would be discarded and not captured.

The expert thinks that the capability of the K-Shelf software which dynamically capturing design rationale capture is very important. During the next PD cycle, the designers go through the same cycle of PD. This possibly creates repeated work which could be avoided if only the design rationale knowledge was captured in the first instance. The expert also highlights the capability of the K-Shelf to provide the designers with TOC visualisation to compare the conflicting parameters. This feature will facilitate the understanding of the current project among the team members. Although TOC is not totally a new approach, however, the integration of TOC in a web-based knowledge environment is a breakthrough.

In terms of the practicability aspect of the K-Shelf software, the expert expressed his opinion as below: With the help of the K-Shelf, the designs would have been captured during the first phase of PD, then shelved due to it not being of use for that product. This is where the advantages and resourcefulness of the K-Shelf kicks in. Then during the development of a different product, the design can be revisited and ultimately used. Not only would this save the company time but potentially millions of pounds.

Chapter 7: Discussion and Conclusion

7.1 Introduction

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

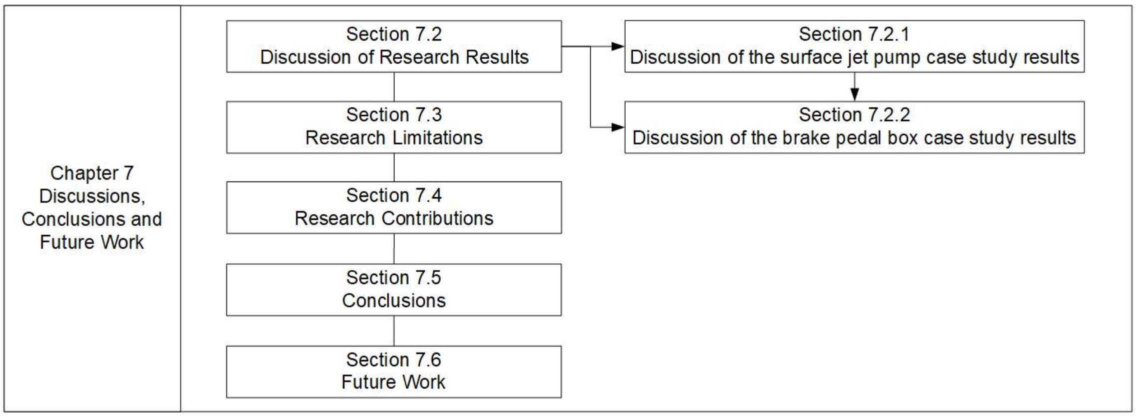


Figure 7-1 Chapter 7 structure

7.2 Discussion of Research Results

This section is constructed mainly for a discussion of research findings on each of the case studies that have been performed. Each of the case studies will be summarised and key findings highlighted. SBCE requires a reliable knowledge environment that is created both from already existing knowledge or created at the source and the point in time in which decisions are made. In this context, the author developed a concept of knowledge environment, namely K-Shelf to enable SBCE application through knowledge provision. The K-Shelf has three capabilities; support the set generation of conceptual design, capture design rationale and compare set of solutions. These capabilities are described in section 4.4.

From interactions with industrial collaborators and interviews using a semi-structured questionnaire, the need emerged to develop a knowledge environment to assist designer throughout SBCE process. According to the practitioners, the establishment of a right knowledge environment can reduce the resources required during the product development process significantly. Although representing the knowledge environment is important for the practitioners, it was obvious that the literature did not address this need. Therefore, the author developed K-Shelf, a knowledge environment 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 BPB case study result

The K-Shelf concept was applied in Brake Pedal Box (BPB) case study to demonstrate its capabilities to support the set generation of conceptual design and compare set of solutions. The aim of the BPB case study is to present a demonstration of the K-Shelf concept and capabilities to enable SBCE application. The K-Shelf software assist designers throughout SBCE process with knowledge provision in term of TOC visualisation to compare the conflicting parameters of BPB designs.

The implementation of the K-Shelf software that is shown in Section 6.3 helped JLR to develop novel design concepts within the SBCE environment. In the same time, the K-Shelf helped JLR to have sustainable knowledge environment and practices in developing, deploying and protecting company strategic knowledge resources – visualisation of TOC. A number of findings were derived in the SJP case study:

1. Design decision rationale and TOC visualisation are retained in company's database for future reuse.
2. The visualisation method does help the company to understand easily and effectively during the evaluation of design options.

7.2.2 Discussion of SJP case study result

The SJP case study showed the implementation of the K-Shelf concept through the SBCE process model to support the set generation, capture design rationale and compare set of solutions. The aim of the SJP case study is to present a demonstration of the K-Shelf concept and capabilities to enable SBCE application. The K-Shelf software assist CALTEC designers throughout SBCE process with knowledge in term of design decision rationale capturing and TOC visualisation to generate a new design to enhance the efficiency of SJP. The knowledge obtained from SBCE application in CALTEC have been captured, in term of design rationale knowledge. Knowledge visualisation through the provision of TOC has also been delivered. A number of findings were derived in the SJP case study:

1. The implementation of the K-Shelf software that is shown in Section 6.3 helped CALTEC to develop novel design concepts within the SBCE application. In the same time, the K-Shelf concept helped CALTEC to have sustainable knowledge environment and practices in developing, deploying and protecting company strategic knowledge resources; design decision rationale and visualisation of TOC.
2. The SJP case study shows the application of SBCE process model in the real scenario. This case study has benefited the company by shifting its current PD process from a paper-based SBCE process to the K-Shelf software as their knowledge environment. The K-Shelf software assists the designers to explore the possible design within the design space without any difficulties from the current product development practices. The K-Shelf software provided the designers with design rationale knowledge and TOC visualisation to help them made the right design.
3. The K-Shelf concept along with the introducing of SBCE application has improved the probability of project success increased from 33% to 96% success rate. The design failure also improved from 0.8 to 2.4 successful design.
4. The K-Shelf proved during the case study:
    - Design rationale knowledge and TOC visualisation are retained in company's database for future reuse.
    - Mechanism of capturing design rationale using 5 Whys approach is easy to understand by the designer in the industrial collaborators.

- The visualisation method does help the company to understand easily and effectively during the evaluation of design options.

7.3 Contribution to Knowledge

The following presents the author's key contributions to the scientific body of knowledge:

1. The K-Shelf concept developed including detailed description of its capabilities to provide a suitable knowledge environment to enable an effective SBCE application.
2. Filling the gap of research in SBCE by exploring and explaining the underlying mechanism of how knowledge provision enables an effective SBCE application with the support of K-Shelf.
3. The advanced perspective and principles of design decision rationale capture in a structured manner to be used for future reuse in SBCE application.
4. The K-Shelf software developed to demonstrate K-Shelf capabilities implemented in a proposed information technology environment.
5. Two K-Shelf industrial case study applications, providing empirical evidence regarding the transformation towards a knowledge environment to enable an effective SBCE application.

7.4 Research Limitation

During the journey to completing the research, it is a common for a researcher to encounter some research limitations. The same situation occurred in this research which listed below:

1. Research scope

   Research scope has been setup for developing a knowledge environment to enable an effective SBCE application focused only on selected activities e.g. explore customer value, identify subsystem targets, define feasible regions, extract design concepts, create sets for subsystems and explore subsystem sets. The remaining SBCE activities are not considered in this research but it is important to be aware of them if a full implementation of SBCE is to take place.

2. Research approach

   Since the qualitative research was used in this thesis, it will inherit bias which is unavoidable. However, the author took a necessary step to ensure the negative consequence of bias could be reduced. This is done by adopting the triangulation method which involves the literature review, interviews, communication with industrial collaborators, case study validation, and expert judgement. Results from these methods were then gathered and analysed to reach the reliable conclusions.

3. Data establishment

   Data establishment was quite challenging during the process of K-Shelf software prototyping. However, this issue could be eliminated once the data is established and stored for the future project.

4. Data accessibility

   As the research involves industrial collaboration, some of the data are restricted and confidential, resulting in a limitation while carrying-out the research i.e. the company only provides one previous project to be explored and limited access to their existing IT infrastructure.

5. Time limitation

   The time limitation is one of concern in a PhD research. The time spent in the industrial case studies are relatively short and at some point, there is an obstacle that affects the available time due to other commitments from the industrial collaborators.

6. Skill constraints

   In the perspective of the case studies, it was noted that there is a need for specific skills and knowledge on each of the products. However, constraints on knowledge and skills have been addressed while performing the case studies.

7.5 Conclusions

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

1. The result from the research suggests that the implementation of a right knowledge environment will enhance SBCE application significantly. It has not escaped our notice that a great number of works of knowledge-based engineering in product development are successful. However, these works were mainly relying on domain knowledge of particular aspects e.g. process, resources, etc.
2. The knowledge in SBCE is distinct in respect of there is more than one designs put forward. As the design progresses, the set of design is gradually narrowed based on the knowledge gained and design decision rationale are captured. While the design decision rationale of one of these designs is not suitable for the project under consideration, it might be useful for parallel project or future project. Thus, design decision rationale needs to be captured and saved for future use. There is no work addressing this issue as of yet; therefore, the concept of knowledge-shelf is important for improvement of the SBCE application.
3. Because of the challenging aspect of SBCE, the K-Shelf is developed with some capabilities that e.g. supports set of design generation, support set of design comparison, and captures design decision rationale. These capabilities are related to each other and have been demonstrated to industrial collaborator to evidence the significance of knowledge-based environment in supporting the SBCE application.

7.6 Future Work

The author recommends that further research be undertaken to investigate the following:

1. Full implementation of the K-Shelf capabilities to enable SBCE application. In this thesis, particular SBCE activities were selected to demonstrate the K-Shelf concept.

2. The possibility to shift the mechanism of capturing design rational knowledge from free-text to a more structured format i.e. ontology
3. Further industrial applications of the K-Shelf should be investigated not only at different sectors, but also on complex integrations.

Publication

1. Published paper

   Suwanda S, Sobun NS, Al-Ashaab A, Khan MS, Rehman A and Beg N (2016) The development of K-Shelf to support the generation of a set-based design of Surface Jet Pump, WSEAS Transactions on Fluid Mechanics, 11 Article No. 20 159-165.

2. Article in press

   The Development of Knowledge-Shelf to Enable an Effective Set-Based Concurrent Engineering Application paper has been accepted for publishing in the International Journal of Internet Manufacturing and Services, Inderscience Publisher.

3. Poster

   The author has been awarded 2nd place at the PhD poster presentation day, Manufacturing Doctoral Community, Cranfield University, 25th April 2018.

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Appendices

Appendix A Semi-Structured Questionnaire

Knowledge-Shelf industrial requirements

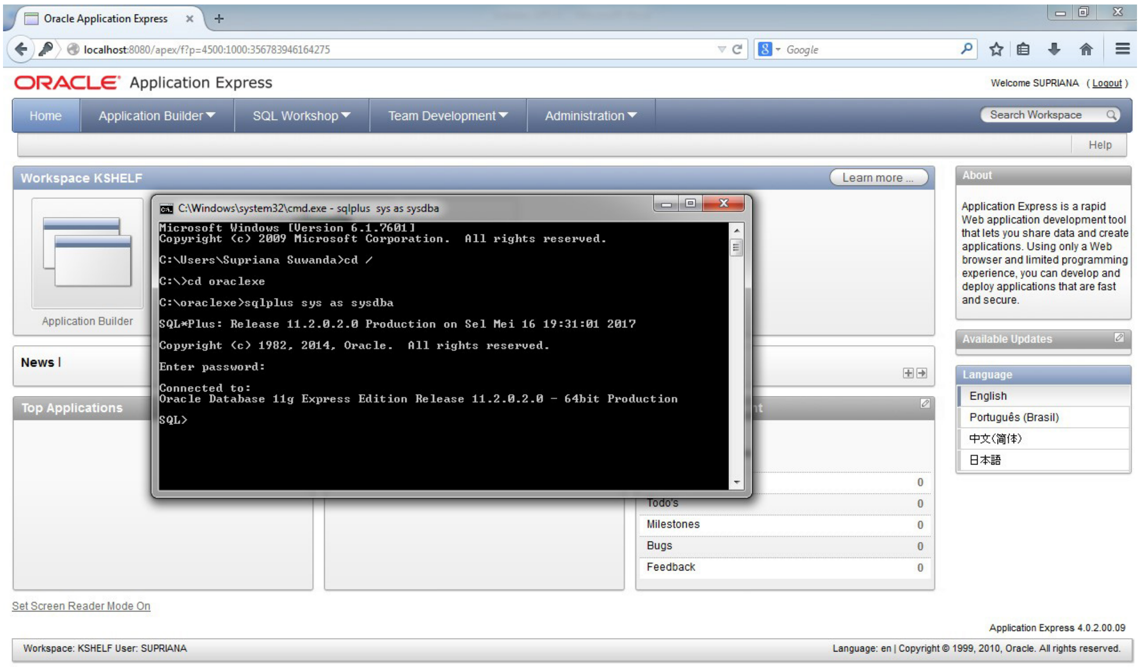
Purpose: Capture the industrial requirements related to development and implementation of Knowledge-Shelf capabilities to enable Set-Based Concurrent Engineering (SBCE) application.

Questions	Industrial requirements	Relevance		Feasibility		Constraints
		Company A	Company B	Company A	Company B	
1	**Knowledge content**					
1.1	Capture the knowledge about the working environment of the product.	5.0	5.0	3.7	3.8	A.1 The environment that the product is used in may be different to that perceived in early design. A.2 Identify what needs to be capture could be a constraint.
1.2	Capture the knowledge to support customer value definition by understanding.	5.0	5.0	3.0	3.5	
1.3	Capture the knowledge according to the level of innovation of the new product.	4.7	5.0	3.3	2.6	A.3 External factors can change regardless of differencies in time product solution. B.1 Problem regarding the format of knowledge; too many spreadsheet formats.
1.4	Capture the knowledge of the generic system/subsystem architecture and its alternative configurations.	5.0	5.0	3.7	2.0	B.2 Huge amount of data so it will be difficult to organise it
1.5	Capture the working parameters of the different system/subsystem functions to support wide range of simulations of alternative concepts.	4.0	5.0	3.3	3.8	B.3 The more data you generate, the more data you have to analyse
1.6	Capture the functional knowledge of system/subsystem and view/constrains of different group (design, manufacturing, assembly etc.) to support identification of alternative design solutions.	4.7	5.0	3.7	3.2	A.5 The different graph may not have the capabilities for rapidly analysing the attempeted design solutions. A.6 Not just the results, the rationale needs to be captured.
1.7	Capture and structure previous projects in order to have a standardised project knowledge repository to support new projects (e.g. CAD files, BOM, lesson learnt, specification, etc.)	5.0	5.0	4.7	3.8	
1.8	Capture and store existing design concept solutions from previous projects of system/subsystems, research and development, and other internal documents.	4.3	4.6	4.0	4.0	A.7 This could be difficult for old data and processes.
1.9	Capture and structure the filtering criteria to evaluate the alternative system/subsystem solutions and to rule-out those which are infeasible.	5.0	4.6	4.3	3.2	A.8 Low TRL technologies may be more optimistic than can be realised
1.10	Store all alternative system/subsystem solutions and capture the reasons why they were identified as feasible or infeasible.	5.0	5.0	5.0	3.2	
1.11	Capture the knowledge generated during simulation, prototype and test. This knowledge should be stored in a database (knowledge-base software, PLM, PDM, knowledge repository, etc.)	5.0	5.0	4.3	2.6	A.9 It may not be possible to achieve in one project. The experts can help while we move towards a more complete database.
1.12	Provide the knowledge required to perform the convergence process until the final system solution is identified.	5.0	4.0	4.3	4.0	
2	**Knowledge structure**					
2.1	Enable the knowledge capturing/extracting, filtering, structuring, storing, searching, provision, updating.	5.0	5.0	4.0	4.0	
2.2	Enable a logical structure to make the knowledge provision process quick	5.0	5.0	4.0	4.2	
3	**Knowledge format and provision**					
3.1	Support K-S users to store the knowledge captured during the process from the early stages.	5.0	4.4	3.7	2.2	A.10 Must not create a workload overhead to the users.
3.2	Make the knowledge available in a proper format to support K-S users in the decision making.	5.0	5.0	5.0	4.2	A.11 Difficult to predict the required format for the way stored knowledge should be presented
3.3	Allow K-S users to use different formats according to functional and process needs.	5.0	4.0	2.3	4.0	A.12 What are considered as the design rules also result in mechanistic behaviours innovation becomes.
4	**Dynamic knowledge capture**					
4.1	Support the capture of new/novel/current knowledge generated during the activities performed in parallel at every stage of the current process.	5.0	4.8	3.7	1.8	A.13 What can be captured, may be just the procedure, not the knowledge.
4.2	The captured knowledge should be stored in a way that it is easily accessible in current and future projects.	5.0	5.0	4.0	3.2	A.14 Sometimes the procedure/process can be captured rather than the content.
5	**Knowledge sources**					
5.1	The knowledge stored in the K-S shall come from different sources.	5.0	5.0	2.7	2.0	A.15 There has been over three decades knowledge systems with little progress in providing a usefull efficient tool.

Appendix B Oracle APEX Configured for K-Shelf

Oracle APEX installation script executed in C:\oraclexe\sqlplus sys as sysdb:

1. *create tablespace apex*
2. *logging*
3. *datafile 'c:\oraclexe\oradata\apex.dbf'*
4. *size 512m*
5. *autoextend on*
6. *next 64m maxsize 10G*
7. *extent management local;*
8. *sqlplus sys as sysdba*
9. *@apexins.sql apex apex temp /i/*
10. *@apex_epg_config.sql c:\oraclexe*



Appendix C PhD Researchers of the LeanPPD Research

Case study	Name	Role
JLR	Supriana Suwanda	Developing K-Shelf concept and software demonstrator to support the set generation and to support the solution comparisons in the SBCE application.
	Muhd Ikmal Isyraf Mohd Maulana	Justification of introducing the SBCE as a new PD approach.
CALTEC	Supriana Suwanda	Developing K-Shelf software demonstrator to support the set generation, capture the design rationale and to support the solution comparisons in the SBCE application.
	Zehra Canan Araci	Generating knowledge-based TOC to support decision-making and communication
	Muhd Ikmal Isyraf Mohd Maulana	Investigating the benefits of applying the SBCE process model.