CRANFIELD UNIVERSITY

MUHD IKMAL ISYRAF BIN MOHD MAULANA

THE DEVELOPMENT OF BUSINESS CASE FRAMEWORK FOR INTRODUCING THE SET-BASED CONCURRENT ENGINEERING APPLICATION

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

PhD
Academic Year: 2014 - 2018

Supervisor: Dr. Ahmed Al-Ashaab
Associate Supervisor: Prof Essam Shehab
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ABSTRACT

Product development challenges have put such an immense pressure to the companies to become more competitive and efficient in the market. The key demand is sustaining the design through product innovation, produce a quality product, shorten the lead time and in a cost-effective manner. Lean Product Development (LeanPD) through the Set-Based Concurrent Engineering (SBCE) is an approach that has these capabilities, including providing a suitable knowledge environment to support decision making throughout the development process.

SBCE provides an environment where the design space is explored thoroughly which leads to enhanced innovation. This is done by considering an alternative set of solutions after gaining the knowledge to narrow down the solutions until the optimal solution is reached. However, the successful measures of the SBCE applications in practice are still ambiguous. To overcome this, the author believed that having a business case is the way to demonstrate and justify the benefits comes from the application of the SBCE.

This thesis presents a process of developing business case framework for introducing the application of SBCE which enable the justification of the SBCE benefits, hence improve the confidence of having the SBCE in the company. The structure of the framework presents a generic guideline of having a business case in SBCE by justifying the benefits of its application.

Keywords:

Business case, lean product development, set-based concurrent engineering, lean thinking, framework, knowledge creation.

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LIST OF ABBREVIATIONS

A	Area
AHP	Analytical Hierarchy Process
B	Bracket
cm	Centimeter
C	Celsius
C	Cost
CAD	Computer Aided Design
CDOV	Concept, Design, Optimize, Verify
CFD	Computational Fluid Dynamics
DCOV	Define, Characterize, Optimize, Verify
DFA	Design for Assembly
DFM	Design for Manufacturing
DFSS	Design for Six Sigma
DMADV	Define, Measure, Analyse, Design, Verify
ERP	Enterprise Resources Planning
FMA	Functional Means Analysis
FOS	Factor of safety
g	Gram
g	Gravity
HP	High pressure
IDEAS	Identify, Design, Evaluate, Assure, Scale-up
IDOV	Identify, Develop, Optimize, Verify
IIDOV	Invent, Innovate, Develop, Optimize, Verify
IR	Infra-Red
J/kg*K	Joule per kilogram Kelvin
JLR	Jaguar Land Rover
kg	Kilogram
kg/kmol	Kilogram per kilomol
kg/m	Kilogram per meter
kg/m*s	Kilogram per meter second
kg/s	Kilogram per second
K	Kelvin
KVA	Key Value Attributes
L	Length
LeanPD	Lean Product Development
LeanPPD	Lean Product and Process Development
LP	Low pressure
m	Meter

m^2	Meter square
mm	Millimeter
ms^{-1}/ m/s	Meter per second
ms^{-2} / m/s^2	Meter per $second^2$
N	Number of design solution
N	Newton
Nm	Newton meter
Nm^{-2}	Newton per meter square
OEM	Original Equipment Manufacturer
ρ	Density
p	Pressure
psig	Pound-force per square inch gauge
P_f	Value of probability of failure
P_s	Value of probability of success
Pa	Pascal
PA	Pedal arm
PCB	Printed Circuit Board
PD	Product Development
POF	Probability of Failure
POS	Probability of Success
QFD	Quality Function Deployment
RF	Radio Frequency
ROI	Return of Investment
R&D	Research & Development
S	Second
SBCE	Set-Based Concurrent Engineering
SJP	Surface Jet Pump
SMART	Start, Motivate, Apply, Review and Transform
SWOT	Strengths, Weaknesses, Opportunities, and Threats
ToCs	Trade of Curves
TPDS	Toyota Product Development System
TRIZ	Theory of Inventive Problem Solving
u	Velocity
UV	Ultra Violet
W	Weight
$\overline{x}$	Average
z	Level

1 INTRODUCTION

1.1 Research Background and Context

Product development (PD) is crucial for company growth and success in the business, making profit, introduce a variety of models, and the most important is to keep the cost lower. Today, customer demonstrates an appreciation much to the value of the product. The demand for quality, reliable product and affordable price has put on pressure to the manufacturer to make a product that meets these criteria. In other word, the manufacturer has to increase their level of innovations to fulfil the customer needs, if not, they will obliterate from the market. By having the innovation, an organisation will be able to develop a new product with higher quality, lower in cost and shorter lead time. Hence, the product will perfectly win the market at the right place, right time and the right price. To deal with this, the author believed the Set-Based Concurrent Engineering (SBCE) is the methodology that can improve the efficiencies and effectiveness of product development. Kennedy (2008) and Ward and K. Sobek II (2014) claim the SBCE is four times more efficient than a traditional phase gate process.

It is impossible to make a transformation in product development without deliberating the current product development challenges occur in the development process. Most of the company struggle optimising their own product development process to find a solution to address all the challenges (Curwen, Park and Sarkar, 2013). Therefore, designing and developing a product with faster time-to-market, and more cost effectively than competitors is a recipe for success, and Lean Product Development (LeanPD) and Set-based Concurrent Engineering (SBCE) could potentially address the current challenges happen in product development. In particular, the SBCE could provide a benefit to address the challenges in the current product development, for instance rework, knowledge provision, and lack of innovation (Khan *et al.*, 2011). According to Al-Ashaab *et al.* (2013), by implementing the Set-based Concurrent Engineering approach in the company could support the innovation and robustness of the requirement by increasing the confidence level in the selection through the consideration and exploration of sets of alternative solutions.

During Lean Product and Process Development (LeanPPD) European project, Al-Ashaab *et al.* (2013) and Khan (2012) has developed a LeanPPD model which consists of five key enablers; value, knowledge, continuous improvement, chief engineer and SBCE, which is core enabler. The SBCE process model of the LeanPPD project has got five stages; value research, map the design space, concept set development, concept convergence and detailed design (Khan *et al.*, 2011). Prior to this, the application of SBCE is limited to the primary study at Toyota Motor Corporation, where the SBCE were initiated, however the detail outcome from the application are ambiguous, especially the way to justify the tangible benefit from business perspective (Sobek II *et al.*, 1999). Therefore, by having the business case for introducing the application of SBCE, the justification can be made in a tangible way either in monetary or non-monetary aspect. The cases can be varied, for example, time-consuming, cost-related, risk or building the cultural change in the companies. More significantly, this research may be able to enhance companies' PD know-how both in technological and business aspect. Figure 1-1 summaries the research background and context of the thesis which elaborately explains on previous paragraphs.

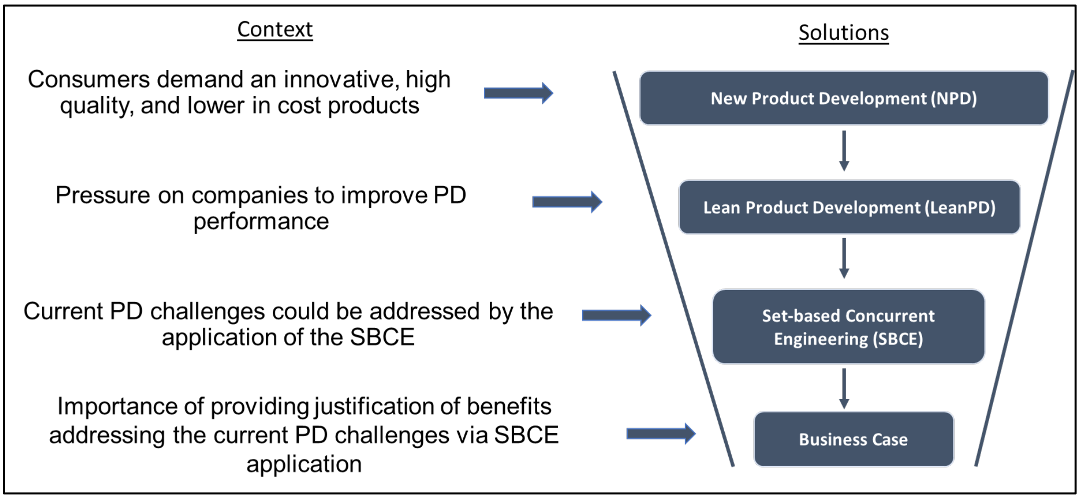


Figure 1-1 The context of the thesis

1.2 Research Questions

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

1. What are the challenges in current PD that would trigger the interest of SBCE application?
2. What is the tangible benefits associated with the introduction of the SBCE Process Model?
3. What is the planning for the manpower and their skill to undertake SBCE application?
4. What business case should be put forward to justify the introducing of the application of SBCE?

1.3 Research Aim and Objectives

The aim is to develop the business case framework for introducing the application of the Set-Based Concurrent Engineering (SBCE) in a company. The case will be in terms of; addressing the current PD challenges and identify the expected tangible measurable deliverables. The business case will also propose the process of cultural change that has to manage to enhance company's PD capabilities, productivities and innovation.

In order to carry out the research, four objectives have been defined as follows:

1. To capture the common practices of PD approaches and current challenges via extensive literature review.
2. To have a comprehensive understanding of the SBCE and their tangible benefits as well as its implementation success factors.
3. To develop the business case to justify the introducing of the application of SBCE in the industry by the following:
    - 3.1. To determine the measurable benefits and other expected benefits gain from the application of SBCE.
    - 3.2. To develop the business case framework for the introduction of the SBCE application.
4. To validate the work via real industrial case studies.

1.4 Thesis Structure

On completion of the research, the thesis structure has been constructed which consists of seven chapters as shown in Figure 1-2. At first, chapter 1 describes about the foundation of the research. The sub-section on chapter 1 comprises of the research background and context, research questions, research aim and objectives, and thesis structure. Chapter 2, explains the process of Research Methodology in fulfilling the aim and objectives of the research as well as Research Methodology Adopted which divided into three phases; 1) State-of-the-art, 2) Developing the process of generating business case for the justification of introducing the SBCE, and 3) Industrial collaboration and validation. Chapter 3 (Literature Review) defines the overview of the existing work carried out by the researchers. The literature review covers the current product development (PD) approaches and challenges, state-of-the-art of SBCE, the benefits of SBCE, a review of business case, culture change, critical success factor, and research gap. In chapter 4 (Industrial Perspective), the purpose is to understand the industrial perspective of current PD practices and the challenges faced by the companies. The approaches are through the interview with semi-structured questionnaires, meetings, observations, training, and workshops with the industrial collaborators. Chapter 5 presents the novelty work of developing business case framework for the justification of introducing the SBCE. Three processes were identified in developing the business case framework which are listed below:

1. The adoption of the SBCE Process
2. Towards the development of business case framework: An Overview
3. The construction of business case framework for introducing the SBCE
4. Successful measure for the introduction of SBCE

Chapter 6 in this thesis will explain the application and validation of the framework through the real industrial case studies from several industrial collaborators. Finally, chapter 7 summarised the research through the discussion, contribution to knowledge, research limitation, conclusion and future work.

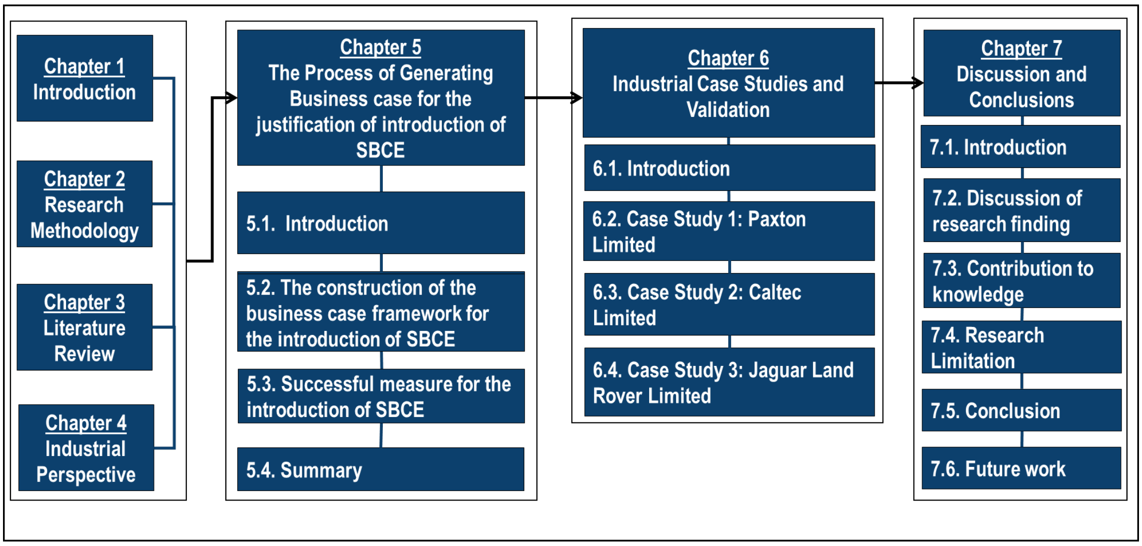


Figure 1-2 Thesis structure

2 RESEARCH METHODOLOGY

2.1 Research Methodology Overview

The foundation of this research was initiated from the research background, research questions and research context, which is explained in chapter 1 (Introduction). In order to achieve a successful research, this chapter clarifies the research methodology that was employed. A Research method is required since it enables researcher to understand, predict and control their environment (Sekaran and Bougie, 2016). Sekaran and Bougie also emphasise that the research methodology has to be well organised, structured, and rigorously employed in order to produce a valid conclusion from the data gathering and analysing. Research paradigm is categorised into four different perspectives which is epistemology, ontology, methodology, and method (Carter and Little, 2007; Scotland, 2012). In reference to research background and context, aim and objectives, this research addresses a justification of introducing the SBCE in real industrial application. Since this research focuses on real industrial application, epistemology is the most suitable one for this research. Audi (2010), mentioned epistemology as the philosophy of knowledge and justification. In addition, Cohen, Manion and Morrison (2007) mentioned that epistemological assumptions rely on the creation, acquisition, and communication of the knowledge.

Deductive research approach employs the research moving from generic to specific where the conclusion follows logically from the availability of the data. Typically, the deductive research approach is used in quantitative research. Quantitative research relatively employs a logical positivism approach by experimental methods to test hypothetical generalisations (Hoepfl, 1997). Bogdan and Biklen (1998) emphasise the qualitative research are based on facts and causes behaviour where the data or information rooting in form of numbers which could be quantified and summarised. This is expressed through mathematical analysis such as analysis of numeric data and statistical process (Charles, 1998).

The inductive research approach is when the research moves from specific observation to generalisation and theory where the conclusion is likely based on principles. Typically, inductive research approach is used in qualitative research. Qualitative research uses a multi method involving an interpretive approach that seeks to understand a real situation or phenomena in context-specific settings and does not attempt to manipulate the phenomenon of interest (Patton, 2002). Corbin and Strauss (1990) mentioned qualitative research is the research that does not use statistical procedure or other means of quantification in producing findings. Qualitative researchers seek instead, illumination, understanding, and extrapolation to similar situations (Hoepfl, 1997). This means, methods like interviews and observations are dominant in the interpretive as well as survey. Researchers in this area have to be in the event to record the changes before and after the event. Patton (2002) also clarifies the credibility of quantitative and qualitative research and they are differentiated as follows;

1) Quantitative research depends on instrument construction
2) Qualitative research depends on the ability and effort of the researcher

However, both need to be tested and demonstrated to gain its credibility. Bryman (2012) illustrates an overall view of research tools and method which represent research paradigm, research approaches, research types, and research method as shows in Figure 2-1.

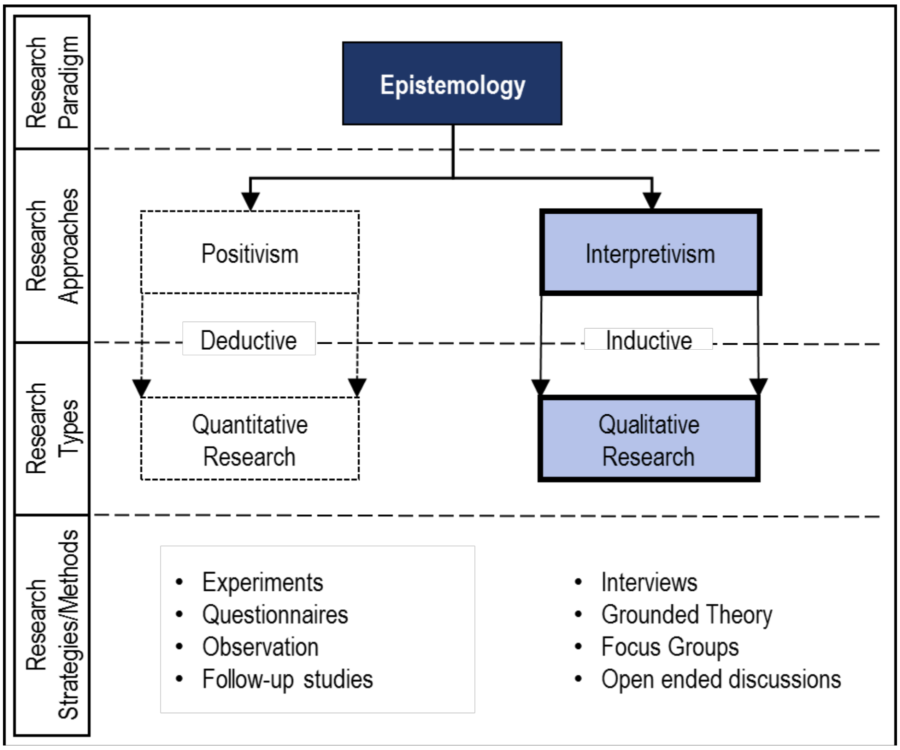


Figure 2-1 Overall view of research tools and method

In order to fulfil the aim and objectives of the research, an appropriate research methodology has been structured aiming to develop and capture the best practices for justifying the introduction and implementation of SBCE as well as to validate the developed approach. The following paragraph explained the method to be used in this research which separated into 3 stages.

- **Method for Stage 1**

a. Literature review: In order to carry-out the research, first step is to understand the current situation from the literature review. Bryman (2012) highlighted literature review as an engagement of knowledge in order to develop an argument based on understanding of the work of others in the same interest. A literature review can provide up-to-date information regarding the research area, hence make a clear understanding the gap in the research (Gray, 2014). The first stage is to understand the research area where the information is gathered via textbook from the library and the e-book. The second stage, the aim is to understand the research contribution made by scholars through the academic research publication of instance, journal papers, conference papers where the database are from the Scopus, Mandeley, EBSCO, Science Direct, Elsevier, IEEE Xplore and Emerald Insight.

b. Semi-structured interview: A semi-structured interview is a method to obtain data grounded from the individual or group experience in the related organisation (Galletta, 2013). Cohen (2006) describes that semi-structured interview can be classified into several techniques; by observation, informal and unstructured interview, and open-ended question to gather information and understanding of the research.

c. Research Collaboration: According to Katz and Martin (1997) research collaboration is encouraged with the aim of developing collaboration among researchers or industry for the expansion of knowledge. In this research, the collaboration will be carried among the Ph.D. researchers from the research group, LeanPPD Project and the industries.

- **Method for Stage 2**

a. Primary data analysis: Primary data analysis can be interpreted as an original data analysis in a research study (Glass, 1976). The primary data are collected purposely for the specific research problem at hand, using procedures that fit the research problem best (Hox and Boeije, 2005). It is typically can be identified via statistical comparison using a statistical method (Mancuso *et al.*, 2011). Rabianski (2003) stated primary data is specific information gathered for the purpose to reach research goal. A primary data analysis can be collected from the interview session, observations, workshop, case study, and validation.

b. Secondary data analysis: Secondary data analysis can be interpreted as the utilisation of previous data collection to address the problem (Brewer, 2007). The secondary data could be obtained from source of internet, data files, email, and other official archives (Hox and Boeije, 2005).

- **Method for Stage 3**

  a. Case study: A case study is a strategic qualitative research method and commonly used in sociology and industrial relations (Baharein and Noor, 2008). Yin (2003) describes the case study as "an empirical inquiry that investigates a contemporary phenomenon within its real-life context". He also says that the case study is preferred when "how" and "why" questions are raised. In order to conduct a case study, six steps will be followed: plan, design, prepare, collect, analyse, and share (Yin, 2003).

  b. Validation: A validation is a process to develop a fitness of the research purpose by conducting a pilot project or a case studies (Inglis, 2008).

2.2 Research Methodology Adopted

The methodology defined in this research is divided into three phases; state-of-the-art, developing the business case, and validation. Each phase has an individual key task, method and deliverable as shown in Figure 2-2. The details are explained in the following point.

Phase	Key Tasks	Method	Deliverable
1. State of the art	1.1. Capture and understand the current product development approaches and challenges 1.2. Understand the SBCE and their tangible benefits 1.3. Capture and benchmark from the best practices for its success factors 1.4. Requirement of culture change in the SBCE context	• Literature review • Semi-structured interview • Research collaboration	• Identification of PD approaches • Identification of current PD challenges • Identification of SBCE benefits • Identification of success factors and culture change from best practices • Research gap
2. Developing the business case framework for justification of introducing the SBCE	2.1. Analysing data collection from literature review and interviews. 2.2. Designing and developing business case framework for introducing the SBCE application	• Primary data analysis • Secondary data analysis • Understanding the research gap	• Assessing the LeanPD • Understanding and verifying the current PD challenges • Demonstrate the SBCE application • Business case framework for introducing the SBCE application in the industry
3. Validation	3.1. Justifying the work with several industrial collaborators	• Real industrial case studies	• Validate the business case framework with several industrial collaborators

Figure 2-2 Research methodology process

Phase 1: State of the art

- Key tasks for Phase 1

1.1. The current product development approaches and challenges will be captured via literature review and semi-structured interviews.

1.2. The SBCE appreciation and the tangible benefits will be captured in the literature review, semi-structured interviews, and case study with several industry partners. The critical success factors for SBCE will be proposed through the process of benchmarking with other big initiatives program such as Lean Manufacturing, Enterprise Resource Planning, and Lean Six Sigma in the literature review. The needs of culture change also will be captured, understand, and analyse through the literature review.

Phase 2: Developing the business case

- Key tasks for Phase 2

2.1. The primary data collection and analysis will aim to determine the expected tangible benefit, define the key factor of culture change in SBCE, and propose the new critical success factors for SBCE applications towards the development of the SBCE business case model.

2.2. Develop a business case for SBCE using the result from the analysis of primary data and also considering the research gaps that found in the literature review.

Phase 3: Validation

- Key tasks for Phase 3

3.1. The work will be carried out via real industrial case study with several industrial partners where the experienced practitioners and researchers will validate the work.

3 LITERATURE REVIEW

3.1 Scope of Literature Review

The scope of the literature review is structured into five categories which are the product development, SBCE, success factors, culture change, and business case. Each of the categories has been described below in order to fulfil the research aim and objectives. Figure 3-1 illustrates the scope of the literature review and present in some details in the following paragraph:

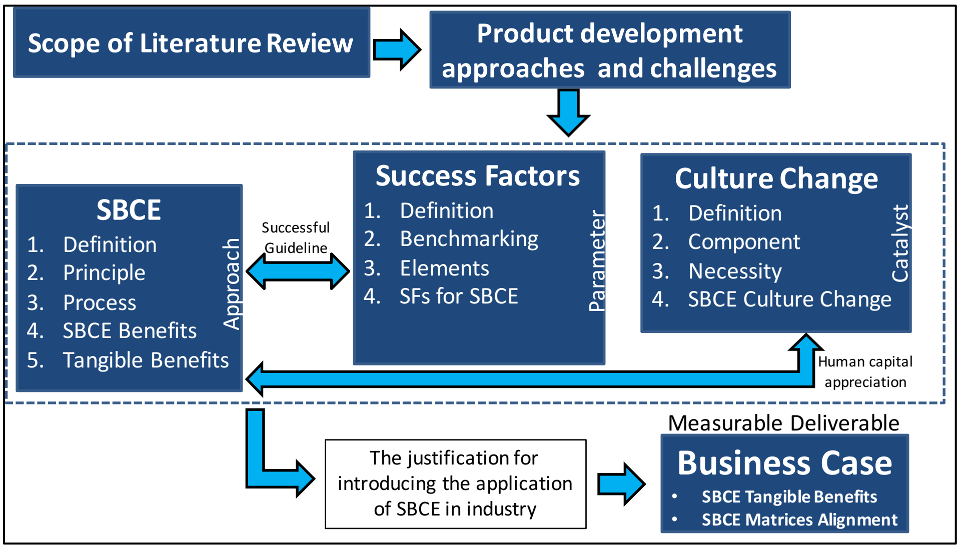


Figure 3-1 Scope of Literature Review

Product Development (PD) approaches and challenges: The foundation of the research is based on the approaches and challenges in current product development. The main focus on the current PD approaches is to understand what the relevant good practices could be used as a benchmark for the successful introduction and implementation of SBCE. It is also to understand what is the significant different between the current PD approaches and SBCE. Secondly, is to capture and understand what are the current PD challenges which could be unravelled by implementing the SBCE. This need to be addressed in order to enhance company's product development capabilities, productivities and innovation. Both PD approaches and challenges will be captured in the literature review and industrial applications. The SBCE has the potential to address the challenges, however, the SBCE by practice in the industry are still at low (Kerga *et al.*, 2014). Thus, a tangible justification is required to trigger the interest of having SBCE in industry and at the same time it reflects the company's performance.

Set-Based Concurrent Engineering (SBCE): The SBCE as an approach that will drive the research by capturing three elements;

a) To understand the SBCE development, principles, process, and activities.
b) To capture the SBCE benefit that has potential to address current product development challenges via extensive literature review and industrial applications.
c) Identifying the SBCE tangible benefits in term of addressing current PD challenges via extensive literature review and industrial applications.

Success Factors: This is a parameter to delineate success factors in the SBCE. The success factor works by providing some success guidelines in introducing the SBCE application. By having this, it can monitor the performance, level up the confidence level and interest to have the SBCE applications in the companies;

a) To learn the success factor from the other big initiative program, for example; ERP, Lean, and Six Sigma.
b) To identify the appropriate success factors for SBCE by doing a benchmarking from the other initiatives.
c) To propose the SBCE success factors as a guideline for the companies to success in introducing the application of SBCE.

Culture Change: The culture change is a catalyst to ensure smooth buy-in process and human capital appreciation towards long term achievement;

a) To understand the definition and necessity of culture change need for the introduction and implementation of any big initiatives.
b) To explore the best practice of culture change.
c) To define the key factor of culture change needed in introducing the SBCE.

Business case: The business case will deliver the justification of introduction the SBCE in a tangible way. At the same time, it will align with the company's matrices, for example; product performance, cost, and, risk to provide a clear measurable deliverable which will give direct impact on a company's performance, hence enhancing the PD capabilities, productivities and innovation.

3.2 Common Product Development Approaches

There are many of PD approaches have been introduced in order to improve the product development process. The most common approaches are Design for Six Sigma (DFSS) and Stage-Gate Process. However, there are a limitation or challenges which could dawdling the process of developing a product in the companies. The purpose of this section is to understand what the most common PD approaches practiced by the companies as well as an explanation of their limitations. One of the common product development approaches used by companies is Design for Six Sigma (DFSS). DFSS is a subset of Six Sigma that focuses on preventing problems and improvement of the product (Nicolaescu, Kifor and Lobonţ, 2015). Six Sigma and DFSS is a comprehensive statistics-based methodology that aims to achieve zero defect in the process and product (Henderson and Evans, 2000; Hammer, 2002). General Electric corporation delineated the DFSS as an approach that only focus on prediction of design quality and design improvement during the early design phases which use a statistical analysis in the process (Treichler *et al.*, 2002). The organisational structure in the DFSS seems to be too complex as well as tools and method which consume a time for the user to understand before implementation (Ericsson and Lillieskold, 2012). The level of description in the DFSS process are way too detailed which cause a difficulty for top management in the organisation when come to the decision-making stage. They also pointed that DFSS is likely suitable only for the improvement on the existing product and process by understanding why it fails and identify the root cause of the problem. (Creveling, Slutsky and Antis Jr., 2003) described the main challenge in using DFSS in the product development is to choose the right tool at the right time throughout the product development cycle.

Nathan (2004) has defined some of the limitations in the DFSS application at Ford Motor Company. Firstly, the process of the DFSS has no well-structured version to be followed, which result a variety of DFSS approaches version being developed such as IIDOV, CDOV, IDOV, DMADV, DCOV and IDEAS[2]. This caused a problem to Ford to choose which one of the approaches are suitable or should create a new version of DFSS for the company. Secondly, DFSS has its limitation in identifying the design boundaries during the conceptual design stage. This is due to the capabilities of the DFSS, which focuses more on the improvement of the quality. Nathan (2004) also outlined that DFSS is lacking in tackling the uncertainty about the key customer requirement and usage variability that will affect product performance. This limitation happens as DFSS does not equipped with the method for obtaining and cascading customer requirement down to component level.

Franza and Chakravorty (2007) emphasised the DFSS using DMADV approach. They mentioned about the importance of gathering data to generate as many as possible creative solutions to end up with promising solutions. The stage has been categorised into two; 1) generate solutions and 2) prioritise solutions via problem solving method. The final solutions then will be verified through several engineering tests using a physical prototype. During the process, information regarding the customer requirement was gathered. However, due to numbers of customer requirement, Franza and Chakravorty (2007), found a time consuming to address each of the requirements. Therefore, the decisions are to focus only on the first requirement. This happens due to lack of structure way to do prioritisation of the customer requirements. Thus, resulting a redundancy and iteration between analyse, design, and verify stage before finalising the promising solution.

Another product development approach that currently uses among companies is a Stage-Gate process. Cooper and Kleinschmidt (1993) outlined that the stage-gate model as a process to facilitate projects from idea to product launch. Conventionally, manufacturing companies conducted product development using an idea-to-launch such as Stage-Gate process (Griffin, 1997; Haque, 2003; Cooper and Edgett, 2012). Miranda De Souza and Borsato (2016) have mentioned that Stage-Gate is categorized as a point-based product development. Cooper (2008) explained Stage-Gate is a process of conceptual and operational mapping in the development of a new product from idea to launch which aims to improve product development effectiveness and efficiency. In the Stage-Gate, the process is separated into five gates and stages which is 1) scoping, 2) build a business case, 3) development, 4) testing and validation, and 5) launch. Each gate has a “go-no-go” protocol, where a series of test will be conducted for the product to go to the next stage; it means the product must pass the tests or otherwise it will start the process again. Stage-Gate has higher costs as the process advances due to increasing level of commitment. Moreover, if there is a feedback which shows a need of major redesign, the product will possibly cease from moving on to the next stage or maybe stop from further development.

3.3 Product Development Challenges

Towards developing a business case for the SBCE, it is important to understand the challenges faced by the companies in their current product development approaches. Therefore, literatures on product development challenges captured from various articles and thesis are explained in the next paragraph.

Challenge 1 “Lack of communication”: The lack of communication happens when there is a collaboration breakdown within a department or business unit (Khan, 2012). This situation could jeopardize the entire product development system, including process and knowledge creation since the previous communication is not taken into account for current development (Ward and Liker, 1995; Al-Ashaab *et al.*, 2009, 2013; Raudberget, 2010; Rocha, Souza and Filho, 2014). This lack of communication could affect in providing a clear guideline for designers and engineers to be followed in the product development process.

Challenge 2 “Higher lead time (speed and time-to-market)”: Higher lead time is bad for the competitiveness where company’s growth depends on the speed for the development of new product to respond the customer demand (Al-Ashaab *et al.*, 2013; Rocha, Souza and Filho, 2014; Ammar *et al.*, 2017). Arundachawat *et al.* (2009) stated that an overlapping design task could contribute a higher lead time in the product development phase yet cause a design rework. It is also will increase the numbers of unnecessary meeting and work delay which also consume a higher number of lead time in product development (Ward and Liker, 1995; Liker *et al.*, 1996; Raudberget, 2010).

Challenge 3 "Uncertainty Situation; exaggerated design or engineering change": Al-Ashaab *et al.* (2013) outlined one of the main areas for improvement in current product development is an enormous design change in product development stage. Moreover, Arundachawat *et al.* (2009) defined the cause of rework are possibly occurring from uncertainty of design change due to imperfect information given since at an early stage of product development. For instance, if the designers developing a solution with a less input data given, it might cause an uncertainty situation in design stage, which cause a design change by having a several iteration process to fulfil the customer need (Liker *et al.*, 1996). Khan (2012) and Ward and Liker (1995) emphasised that the key reason for the lack of punctuality in the engineering project cause of the unplanned design changes. Moreover, the uncertainty design changes could drag the product development process into catastrophes which cause a disruption in the overall schedule of the project and unpredictability in the downstream activities (Endris, Khan and Arias, 2012).

Challenge 4 "Knowledge are underutilized to the right people at the right time": Another challenge that has been identified in the literatures is where the knowledge is underutilised to the right people at the right time. Such of this challenge happen due to the inaccessibility of knowledge, the unwillingness to share knowledge or a lack of awareness about the existence of knowledge (Berends, Vanhaverbeke and Kirschbaum, 2007). Khan *et al.*(2011, 2013) emphasises the importance of correct knowledge to be received in the right place at the right time in the product development process. This is by ensuring the knowledge is pull at an early stage of the product development process. The knowledge includes: tacit knowledge, trade-off curves, check sheets, technical design standards and rules, and A3 problem solving (Khan, 2012).

Challenge 5 "Low in knowledge exploration and lesson learnt": Knowledge explorations seem to become a challenge in the product development process (Berends, Vanhaverbeke and Kirschbaum, 2007). Knowledge exploration is challenging as knowledge and learning are subject to path dependencies. Path dependency means that future developments strongly depend upon past developments (Garud and Karnoe, 2001; David, 2007). Knowledge explorations facilitate the new fields of technological knowledge, building up expertise in new markets and the creation of new competences (Berends, Vanhaverbeke and Kirschbaum, 2007). New technological capabilities are needed, or at least the stretching of existing capabilities (McDermott and O'Connor, 2002). Khan (2012) mentioned one of the important techniques in providing the knowledge is from the lesson learnt which can be captured in many ways, such as published books, official document, articles and so forth. Contrary, lesson learnt is not used effectively in the product development due to several obstacles such as overburdened by the quantity of work and rework activities in development stage (Khan *et al.*, 2013). However, some of the company captured lesson learnt from previous projects or benchmarking activities by teams who are responsible to make the suggestion which the information then will feed back into the product development process. Others, depending on individual incentives as it was an ad hoc task due to lack of support for knowledge reuse or lack of knowledgeable employees (Raudberget, 2010).

Challenge 6 "Product quality": The next product development challenges are to improve quality of the product. Oppenheim (2004) has mentioned that, one of the values considered in product development is product quality. Hoppmann *et al.* (2011) deliberated quality as an important factor to the company to be more competitive in the market. Kennedy (2003) and Morgan and Liker (2006) stated in their work that the impact of tackling the product quality issues at early of development stage is more significant rather than in the production stage. They also mentioned that failure to consider the quality of the product in product development stage could possibly cause a high rate of early failure in the after-market and causing a lengthy effort of rework as well as short product life span (Morgan and Liker, 2006).

Challenge 7 "Higher cost": Researchers believed that the higher cost is the most challenge in the current product development. Most of them agreed the cost due to design rework triggering the impact of the higher cost (Ward and Liker, 1995; Endris, Khan and Arias, 2012; Al-Ashaab *et al.*, 2013; Rocha, Souza and Filho, 2014). The cost will keep increasing as the project progress until nearly the launch of the product. One of the reasons is due to lack of exploring the alternative design solutions and feasibility study using the proven data and knowledge at an early stage of designs (Ward and Liker, 1995; Sobek II *et al.*, 1999; Raudberget, 2010; Khan *et al.*, 2011; Endris, Khan and Arias, 2012; Khan, 2012; Al-Ashaab *et al.*, 2013; Rocha, Souza and Filho, 2014; Ammar *et al.*, 2017).

Challenge 8 "Rework": Khan (2012) and Al-Ashaab *et al.* (2013) pointed that rework is typical product development challenges usually derives from the late design change practice during the development of products. Design rework considered as negative iteration, which normally occurred when considering only one single design solution in design activities (Arundachawat *et al.*, 2009; Khan *et al.*, 2011). In the rework, as the design progressed to meet certain criteria, it will keep changing and force the design to undergo the rework cycle (Liker *et al.*, 1996; Endris, Khan and Arias, 2012; Khan, 2012; Ammar *et al.*, 2017). These reworks activities will create an overburden work environment which led to higher lead time in the product development process.

Challenge 9 "Low innovation": Low of innovation is the next challenges happen in the current product development. Khan *et al.* (2013) pointed that most of the designers spent eighty percent of the working time performing their routine task rather than focusing on product innovation. This is due to the nature of the traditional product development that will only consider one best design solution during early design stages which resulting lower innovation, while SBCE encourage the innovation by considering a set of possible design solutions (Liker *et al.*, 1996; Raudberget, 2010; Cai and Freihet, 2011; Khan *et al.*, 2011; Endris, Khan and Arias, 2012; Al-Ashaab *et al.*, 2013). Table 3-1 summarised the current PD challenges captured in the literature:

Table 3-1 Current PD challenges captured in literatures

	References \ Challenges	Lack of communication	Higher lead time (speed and time-to-market)	Uncertainty situation, too many engineering change to meet customer demand	Knowledege are under utilized to the right people, and the right time	Low in knowledge learning or lesson learnt	Low product quality	Higher cost	Rework	Low innovation
1	Al-Ashaab et al., 2013	x	x	x		x		x	x	x
2	Al-Ashaab et al., 2009	x								
3	Ammar et al., 2017		x					x	x	
4	Arundachawat et al., 2009		x	x					x	
5	Berend, Vanhaverbeke and Kirschbaum, 2007				x	x				
6	Cai and Freihet, 2011									x
7	Endris, Khan and Arias, 2012			x			x	x	x	x
8	Ford and Sobek, 2005						x			
9	Hoppmann et al., 2011						x			
10	Kennedy, 2003						x			
11	Khan et al., 2013				x	x				
12	Khan et al., 2011				x			x	x	x
13	Khan, 2012	x		x	x	x	x	x	x	
14	Liker et al., 1996		x	x					x	x
15	Morgan and Liker, 2006						x			
16	Oppenheim, 2004						x			
17	Raudberget, 2010	x	x			x		x		x
19	Rocha, Souza, and Filho, 2014	x	x					x		
20	Sobek et al. 1999							x		
21	Ward and Liker, 1995	x	x	x			x	x		
	Total	**6**	**7**	**6**	**4**	**5**	**8**	**9**	**7**	**6**

3.4 State-of-the-arts of the Set-Based Concurrent Engineering

3.4.1 A review of SBCE within LeanPD work

The literature emphasises on the importance of SBCE within the lean product development application (Morgan and Liker, 2006; Kennedy, 2008; Ward *et al.*, 2012; Khan *et al.*, 2013). This is because SBCE represents the definition of the process that will be followed to develop a product. Therefore, it is important to review the LeanPD related literature in order to understand the statute of the SBCE development within the acclaimed LeanPD models and frameworks.

The authors' definition of LeanPD: the application of lean thinking in product design, engineering and development. It focuses on value creation, provision of a "knowledge environment", continuous improvement and set-based concurrent engineering process that encourage innovation and collaboration. LeanPD provides a process model and associate tools that consider the entire product life cycle. It provides knowledge-based user centric design and a development environment to support value creation to the customers in term of innovation and customisation, and quality as well as sustainable and affordable products. Based on the LeanPD definition, the authors believe that in order to have a good LeanPD model or framework that will enhance the performance of product development the following should be included; 1) That it is based on clear lean principles, 2) A well-defined elements where at least one of them describes a development process, 3) A good description of the tools and methods that will enable the applications of the lean principles, 4) Clear implementation guidelines of the model or framework and finally 5) There is a case study to demonstrate the value of the model or framework.

The following is a critical review of the LeanPD literature who acclaimed the development of a certain model or framework. Morgan and Liker (2006) presented a detailed description of the 13 principles that shaped the Toyota product development system as illustrates in Figure 3-2. They formed a conceptual model called the “Toyota lean product development system” model. The model is divided into three sub-systems; process, people as well as tools, and technology where the 13 principles are presented and explained accordingly. Morgan and Liker stated clearly that the model does not explain the way lean product development works in reality. A case study has been conducted at Ford Body and Stamping Engineering (Liker *et al.*, 2015) where the first step was to get the people, culture, and organisation right with an “attitude change” and a serious “focus on customer” mentality. Similarly, the 13 principles were addressed. The product development process was enhanced and activities that were identified as a waste were eliminated using value-stream mapping. This helped to perform several tasks simultaneously for longer periods and delay key decisions until later in the process where customer consideration is closer, and the data are more accurate. This helped to achieve a good level of SBCE application.

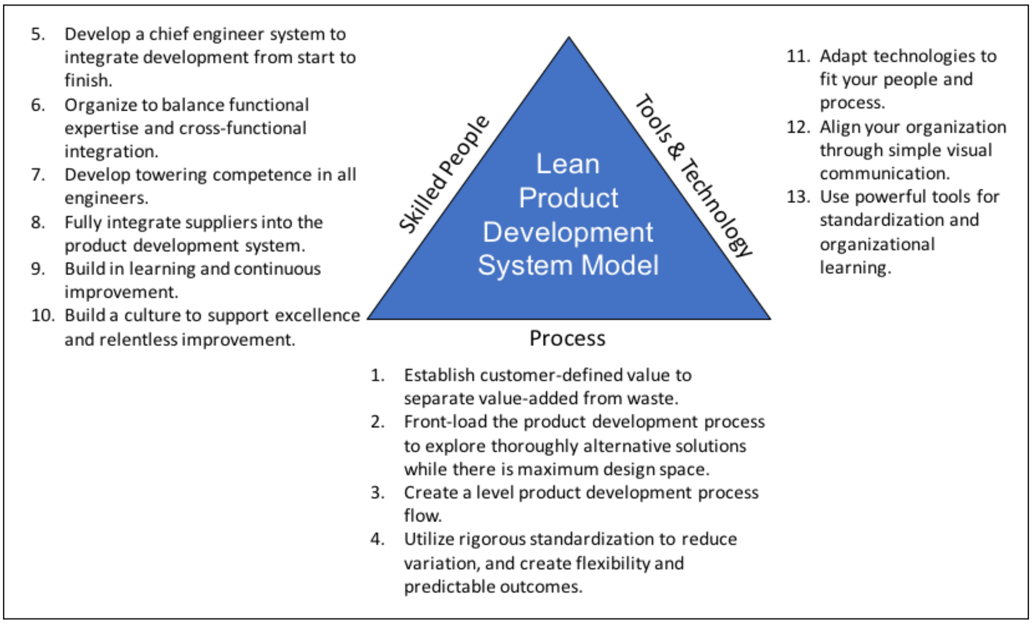


Figure 3-2 Toyota Lean Product Development System Model and 13 principles (Morgan and Liker, 2006)

Kennedy (2003, 2008) is also common references used in the LeanPD related literature. Although the two books are in the style of a so called "business novel" and the work does not contribute much to theory, the method, tools, and mechanisms of LeanPD are however uniquely described. In addition, Radeka (2012) also has described several companies' experience achieving a significant result by emphasising the method and implementation of the LeanPD, however, it did not explain in detail about the SBCE in her work.

Several works claimed to have developed a different LeanPD framework (Anand and Kodali, 2008; Hoppmann *et al.*, 2011; Letens, Farris and Van Aken, 2011; Nepal, Yadav and Solanki, 2011; Wang *et al.*, 2012). All the developed frameworks have been graphically represented in the form of tables which have several elements. These elements have been proposed based on the review of other LeanPD and product development literature. The researchers of these LeanPD frameworks have appreciated the foundation of LeanPD to be the Toyota product development system (TPDS) and incorporated some elements of TPDS into the five lean principles from Womack, Jones and Roos (1990) combined with other ideas from traditional product development to formulate their frameworks.

None of the work provided any detail of the SBCE application, however, they referenced the work of (Morgan and Liker, 2006; Ward, 2007).

The author believes developing or implementing one or two isolated elements of LeanPD does not make a truly LeanPD application. In order to develop a product development model that is fit to consistently perform in a rapidly changing market and environment, a changeless core is required. Thus, the focus should be on value creation, provision of a knowledge environment, continuous improvement and processes that encourage innovation and collaboration. Therefore, SBCE is a very important enabler to any truly LeanPD applications. The following sub-section presents the evolving concept of SBCE.

3.4.2 Review of SBCE related work

Ward and Liker (1995) discovered that the real success of Japanese manufacturers originated from the Toyota Product Development 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. Sobek II *et al.* (1999) put the following definition forward; design participant practice SBCE by reasoning, developing, and communicating about a set of solution in parallel. As the design progressed, they gradually narrow their respective set of solution based on the knowledge gained. As they narrow, they commit to staying within the sets so that the others can rely on their communication. The principle of SBCE was described in the conceptual framework which breaks into three broad principles; maps the design space, integrate by intersection, and establish feasibility before commitment (Sobek II *et al.*, 1999). Morgan and Liker (2006) stressed that SBCE is significant as it become part of the Toyota product development system under the principle of “front-load the product development process to explore thoroughly alternative solution while there is maximum design space”. They also pointed out that Toyota used the trade-off curves and decision matrices to communicate and evaluate set of design solution. However, they have not provided a detailed SBCE process model.

Ballard (2000) hypothesised that the application of SBCE would reduce a negative iteration in the design. He suggested a number of strategies for reducing negative iteration in design by: 1) Restructuring the design process, 2) Reorganising the design process, 3) Changing how the design process is managed, and finally 4) Overdesign (design redundancy) when all else fails. Ford and Sobek (2003) developed a system dynamics model to simulate a product development process in which four alternative automobile systems (e.g. cooling) are simultaneously designed. The central premise of real options theory is that, if future conditions are uncertain and changing the strategy later incurs substantial costs, then having flexible strategies and delaying decisions can increase project value when compared to making all key strategic decisions early in the project. Kerga *et al.* (2014) has proposed and developed a roadmap which intends to lead and simplify the start of SBCE implementation, the SBCE Innovation Roadmap. They claim that SBCE insufficiently provides designers on knowledge as to how to identify, prioritise and plan improvement areas on a product under development. However, their work did not show any real SBCE process model or a reference to use any existing one. The overall idea is to use commonly well-known tools; QFD and TRIZ in order to integrate customer requirements into a technical quality characteristic and support the search efforts to find innovative solutions.

Moreover, work also has been done to help to drive SBCE through engineering relationship. This includes the incorporation of fuzzy set theory/logic and the automated analysis of design parameters by means of mathematical algorithms (Nahm and Ishikawa, 2006; Telermen *et al.*, 2006; Avigad and Moshaiov, 2010; Inoue *et al.*, 2010; Moreno-grandas *et al.*, 2010; Qureshi *et al.*, 2011). These studies are also concerned with, decisions under uncertainty, design optimisation and incorporating designer preferences.

Levandowski, Michaelis and Johannesson (2014) outlined their work by incorporating SBCE with the software application providing designers a tool to re-use design knowledge of the products by using a function-means modelling and trade-off curves. These studies are to ensure feasibility in the entire design space before committing to a design by validating it in two levels; 1) design spaces created within each system, and 2) discrete design spaces resulting from a combination of several systems.

Correia, Stokic and Faltus (2014) developed a software model to optimise SBCE communication and knowledge sharing. The software tools present the main information about communication mechanisms with relation to SBCE baseline model from (Khan *et al.*, 2011). These works also pointed to an expected key benefit as follows; reduction of lead time, reduction of cost in the product and process development, efficient communication, and design quality improvement.

There are limited numbers of SBCE case studies. Madhavan *et al.* (2008) developed what they refer to as a set-based approach to multi-scale design by means of modelling and simulation at Schlumberger. They reported two benefits; creating a greater variety of solutions and a lower risk of not finding any feasible solution and having to go through expensive iterations. Raudberget (2010) conducted a number of case studies to test principles of SBCE, based on the work of (Sobek II *et al.*, 1999). Participating design teams were encouraged and optimistic after initial applications. Case studies were conducted on mechanical engineering products or subsystems from three automotive companies and one company from the paper industry. Case study participants noted improvements in product cost and performance, level of innovation, project risk, and a reduction in engineering changes.

Al-Ashaab *et al.* (2013) performed a case study on the SBCE model at Rolls-Royce aerospace industry to transform one of the current product development process into a lean environment. This transformation was achieved in two main stages: 1) Integrating the principles of SBCE into an existing product development model which include defining the activities and associated tools, and 2) Implementation of the developed model in a research-based industrial case study of a helicopter engine. The case study deliberates on how a company can integrate the principles of SBCE within its own product development process as a step towards lean transformation in product development, and how this step can influence the product development process.

3.4.3 The Principle of SBCE

The principles of SBCE have been identified in several literature sources as it has evolved (Ward and Liker, 1995; Sobek II *et al.*, 1999; Morgan and Liker, 2006; Ward, 2007). These principles are classified into three categories by Sobek II *et al.* (1999) which are 1) map the design space, 2) integrate by intersection, and 3) establish feasibility before commitment. As the principles evolve, Khan *et al.* (2011) and Khan (2012) defined another two additional categories which is strategic value research and alignment, and create and explore multiple concepts in parallel illustrated in Table 3-2

Table 3-2 SBCE Principles (Khan et al., 2011 and Khan et al., 2013)

Category	Principle
1. Strategic value research and alignment	a. Classify projects into a project portfolio (Morgan and Liker, 2006; Ward, 2007) b. Explore customer value for project X (Morgan and Liker, 2006; Ward, 2007) c. Align each project with the company value strategy (Ward, 2007) d. Translate customer value (product vision) to designers (via concept paper) (Sobek II *et al.*, 1999; Morgan and Liker, 2006)
2. Map the design Space	a. Break the system down into subsystems (Ward, 2007) b. Identify essential characteristics for the system (Ward, 2007) c. Decide on what subsystems/components improvements should be made and to what level (selective innovation) (Ward, 2007) d. Define feasible regions based on knowledge, past experience and the Chief engineer, and consider the different perspectives/functional groups (Sobek II *et al.*, 1999)
3. Create and Explore multiple concepts in parallel	a. Pull innovative concepts from R&D departments (Ward, 2007) b. Explore trade-offs by designing multiple alternatives for subsystems/components (Sobek II *et al.*, 1999) c. Schedule time for innovation and problem solving while the set of alternatives is broad (Morgan and Liker, 2006; Ward, 2007) d. Ensure many possible subsystem combinations to reduce the risk of failure (Ward, 2007)

	e. Extensive prototyping (physical and parametrical) of alternatives to test for cost, quality, and performance (Ward and Liker, 1995; Sobek II *et al.*, 1999; Morgan and Liker, 2006; Ward, 2007) f. Perform an aggressive evaluation of design alternatives to increase knowledge and rule out weak alternatives (Sobek II *et al.*, 1999; Ward, 2007) g. Information goes into a trade-off knowledge base that guides the design (Ward, 2007) h. Communicate sets of possibilities (Ward and Liker, 1995; Sobek II *et al.*, 1999; Morgan and Liker, 2006)
4. Integrate by intersection	a. Look for intersections of feasible sets, including compatibility and interdependencies between subsystems (Sobek II *et al.*, 1999; Morgan and Liker, 2006; Ward, 2007) b. Impose minimum constraints: deliberate use of ranges in specification and initial dimensions should be nominal without tolerances unless necessary (Sobek II *et al.*, 1999) c. Seek conceptual robustness against physical, market, and design variations (Sobek II *et al.*, 1999; Ward, 2007) d. Concurrent consideration of lean product design and lean manufacturing (Sobek II *et al.*, 1999)
5. Establish feasibility Before commitment	a. Narrow the sets gradually while increasing detail: functions narrow their respective sets based on knowledge gained from analysis (Ward, 2007) b. Delay decisions so that they are not made too early or with insufficient knowledge (Sobek II *et al.*, 1999; Ward, 2007) c. Design decisions should be valid for the different sets and should not be effected by other subsystems (Sobek II *et al.*, 1999) d. Stay within sets once committed and avoid changes that expand the set (Sobek II *et al.*, 1999) e. Control by managing uncertainty at process gates (Sobek II *et al.*, 1999) f. Manufacturing evaluation of the final sets and dictation of part tolerances (Sobek II *et al.*, 1999) g. Manufacturing begins process planning before a final concept has been chosen and thus act on incomplete information (Sobek II *et al.*, 1999) h. Delay releasing the final hard specification to major suppliers until late in the design process (Ward, 2007)

3.4.4 The SBCE process model

The Lean Product and Process Development (LeanPPD) European project developed a model that consists of five elements; Value focus, knowledge-based environment, continuous improvement culture, chief engineering leadership and SBCE (Khan *et al.*, 2013). SBCE is considered as the core enabler as it represents the process that guides the development of a product in a lean environment (Al-Ashaab *et al.*, 2016)

After structuring and analysing the SBCE principles, the SBCE baseline model has been developed to align with these principles listed in Table 3-2. As a graphical representation of the idea, (Khan *et al.*, 2011) developed a baseline model for SBCE, as illustrated in Figure 3-3 to summarise its characteristic entirely, including exploration of multiple alternatives, delaying specification, minimal constraint policy (delayed commitment), extensive prototyping and convergence upon the optimum design. Furthermore, it delineated that the customer and supplier are involved from start to finish in the process of product development to establish a robust and efficient communications. It is also empowering the suppliers to develop their own SBCE which benefited to reduce supplier tracking and enhance the innovation.

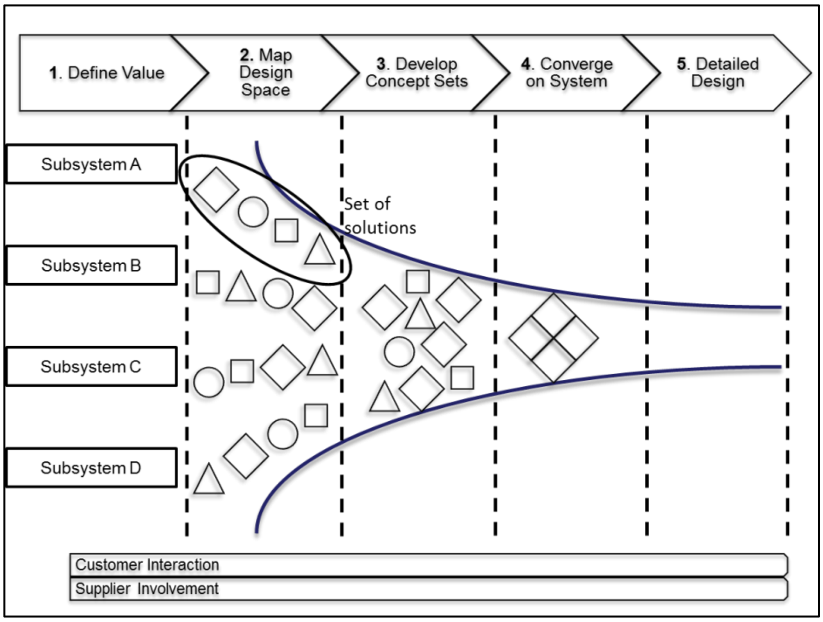


Figure 3-3 The SBCE baseline model (Khan *et al.*, 2011)

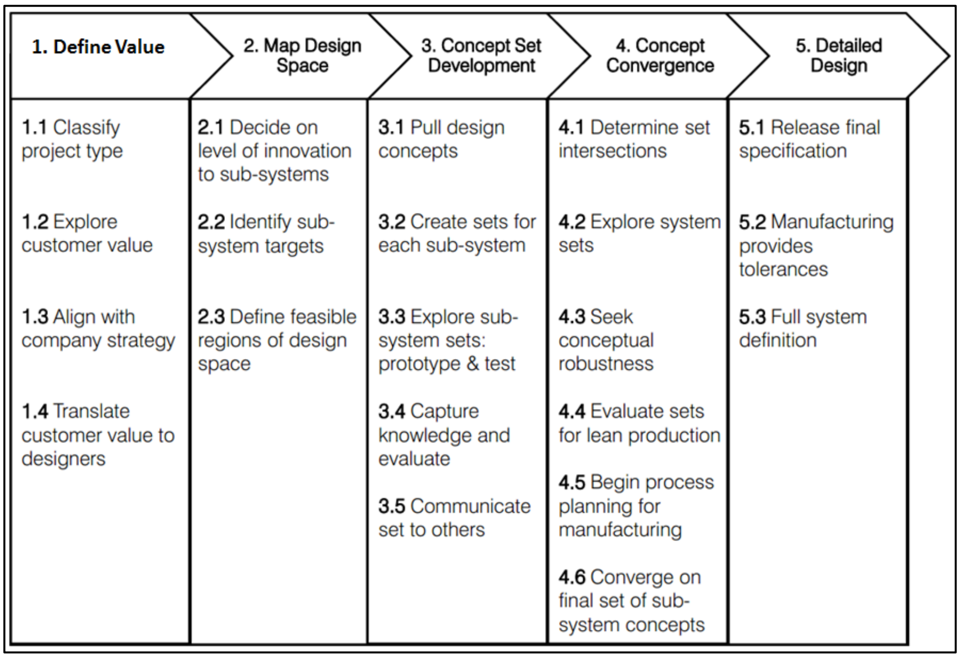


Figure 3-4 The SBCE process model (Khan *et al.*, 2011; Al-Ashaab *et al.*, 2013)

Each category list in Table 3-2 has been represented as a key stage of the SBCE baseline model, namely; 1) Define value, 2) Map Design space, 3) Develop concept set, 4) Converge on System and 5) Detail design. In addition, most of the SBCE principles listed in Table 3-2 have been translated into activities to form the SBCE process model shown in Figure 3-4. The principle "Explores customer value for project X" has been translated as activity 1.1 "Classify project type". The principle "aligns each project with the company value strategy" has been translated into activity 1.2 "Explore customer value". A similar approach is seen in the rest of the SBCE activities shown in Figure 3-4. Moreover, this process model has been described in a step-by-step activity to enhance communication and ensure the implementation of SBCE are followed correctly at the first time as illustrated in Table 3-3. The development of the SBCE process model has been done in consultation and with input from all the industrial partners of the LeanPPD project, namely: Rolls-Royce, Volkswagen, Visteon, Sitech, and Indesit.

Table 3-3 The SBCE methodology for activities (Khan, 2012)

Phase	Activity
Phase 1. Define Value	Methodology for activity 1.1: 1. Create project classification matrix using a table or spreadsheet 2. Create project name and schedule 3. Determine customer/intended market 4. Classify the level of innovation by colour-labelling the system design architecture and identify level of innovation required in each subsystem/module 5. Estimate/determine man-month effort and cost investments, and calculate ROI 6. Input additional parameter information
	Methodology for activity 1.2: 1. Customer value (needs and desires) should be internalised by technical project representatives using customer request documentation, requirements, market research methods, and meetings with customer representatives 2. Customer value should be decomposed into attributes and structured/represented by creating a product value model 3. System targets (requirements) should be defined in order to clarify how the value attributes will be achieved; special emphasis may be directed towards how the product will be a unique offering in contrast with competitive products.
	Methodology for activity 1.3: 1. Identify strategic PD goals from company documentation (company strategy, engineering strategy, and R&D strategy documents) 2. Create a matrix through which strategic goals may be structured and the impact of current projects may be analysed: goals vs. projects 3. Analyse current projects against strategic PD goals to determine the strategic impact of each project on PD and populate this data via the matrix created 4. Evaluate each future project against strategic PD goals using the same matrix and determine new goals where appropriate
	Methodology for activity 1.4 1. A product concept definition template can be used by internal technical personnel to translate customer value to engineers; customer value may be represented visually using videos, photographs, sketches, diagrams etc. in addition to the necessary requirements, text and maths - this can be achieved using additional web-based techniques if necessary; the template should cater for

	different departments/functional groups as they will develop their subsystems/work based primarily on this document 2. The product concept definition template combines the knowledge created in phase 1 in a single document; it may be that multiple versions are created for different audiences (e.g. senior managers) from the same information
Phase2. Map Design Space	Methodology for activity 2.1 1. The product concept definition should be used by subsystem participants/teams to understand the strategic objectives, system targets, and the level of innovation required for their particular subsystem 2. Based on the product concept definition subsystem participants/teams can further classify the level of innovation required for each component or sub subsystem; using a subsystem architecture template that depicts the modular breakdown of the subsystem architecture the level of innovation for the different product components or sub-subsystem may be labelled
	Methodology for activity 2.2 1. System targets will be analysed in order to determine modifications to components or sub-subsystems that could help to achieve them 2. Based on the product concept definition and innovation classification diagrams, lower-level targets (requirements) will be identified for sub-subsystems and components (e.g. reduce component weight by x%) 3. Subsystem targets will be reviewed by the technical leader at the system level in order to ensure the correct flow down of system targets 4. A subsystem concept definition template can be used to capture and communicate subsystem targets in addition to the innovation classification
	Methodology for activity 2.3: 1. Each subsystem participant or team should identify and document design constraints on their subsystem: what can/cannot/should not be done. This information can be extracted from lessons learnt logs, design standards, best practise guides and checklists 2. Each subsystem participant or team should identify (“map-out”) possible options for their subsystems, sub-subsystems and components. Feasible regions may include different fundamental concepts, components, arrangements, properties or geometry; R&D departments should be engaged in order to understand state of- the-art technologies 3. Representatives for the other subsystems may be referred to at this stage to develop a pre-emptive understanding of interdependencies

	4. Manufacturing engineers should be consulted to understand their current/future production capabilities and constraints before developing any of the potential options. Manufacturing engineers can be requested to provide the relevant information in a simple visual format to aid the designers (checklists, diagrams etc.) 5. Subsystem design constraints, manufacturing constraints and capabilities, interdependencies with other subsystems, possible options and related information should all be documented in the subsystem concept definition template which is used as the basis for the development of subsystem concept sets
Phase3. Concept Set Development	Methodology for activity 3.1: 1. Subsystem criteria should be defined based on value attributes, system targets, constraints etc. 2. Alternative subsystem and component design documentation/files should be extracted from previous projects, R&D departments, and competitor products based on the subsystem concept definition 3. Knowledge-based engineering system (or product data/lifecycle management software) can be used as a central database from which information concerning previous projects and competitor products is captured and reviewed 4. Alternative options may be mapped against subsystem criteria using matrices in order to filter some of the alternatives
	Methodology for activity 3.2: 1. Based on the subsystem concept definitions, design teams can compose initial sets of design solutions for each of the subsystems which will include the extracted design concepts from activity 3.1 2. Idea generation techniques (e.g. brainstorming) and innovation frameworks (e.g. TRIZ) can be used in order to provoke creativity and facilitate innovation 3. Conceptual solutions can initially be sketched with minimum constraints: the deliberate use of ranges in specification, and initial dimensions should be nominal without tolerances unless necessary 4. Where feasible, CAD software may be used to represent the conceptual ideas

	Methodology for activity 3.3: 1. A plan should be produced for testing each sub-system/component alternative in order to ensure that the knowledge created through testing enables weak solutions to be exposed and increases confidence in the design; the plan can focus on rapid and low-cost techniques if necessary 2. The plan referred to here as 'subsystem knowledge creation plan' should be translated into a document template which defines the test outputs and representations that would support the comparison of sets and other decision making 3. The different options should be explored and analysed through simulation, rapid prototyping, mathematical modelling etc. to determine their feasibility, benefits, and potential costs and the results should be incorporated in the same template
	Methodology for activity 3.4 1. The knowledge created through testing should be represented in the relevant graphical formats: limit curves for representing breaking points (and safe zones) for a single design option, and trade-off curves to compare the set of alternative subsystems/components against subsystem design criteria (e.g. cost and expected performance) 2. A SWOT analysis may also be conducted for the evaluation of options
	Methodology for activity 3.5 1. Conceptual solutions may be represented using an A3 template or MS Power Point presentation. The presentation should include the background, current condition, proposal, sketch/CAD drawing, and SWOT analysis 2. A 'design set (integration) event' can be used as a milestone, where design teams come together to present their sets to each other 3. The set will also be presented using comparative tools such as trade-off curves, and function means analysis 4. Design teams will evaluate sets based on their constraints and will provide recommendations to each other; ideally, any subsystem design decision after this point should neither affect other subsystems nor be affected by other subsystems 5. Based on the evaluation, some of the alternative options may be discarded from the sets
	Methodology for activity 4.1: 1. Populate a design concepts matrix with subsystem/component sets in order to illustrate the

Phase 4. Concept Convergence	possibilities for intersection/integration of the various sets into systems 2. Identify any dependencies 3. Determine which system combinations are possible and/or feasible using the concept intersection matrix 4. 4. Analyse the effect of subsystem or component selection on the system targets 5. Discount system combinations that are infeasible based on knowledge from previous projects, dependencies, and potential/expected conflicts
	Methodology for activity 4.2: 1. A plan should be produced to test system combinations in order to ensure that the knowledge created enables weak system alternatives to be exposed and increases confidence in the design; The plan can focus on rapid and low-cost techniques, and check sheets can be used to track the tests 2. The plan referred to here as the 'system knowledge creation plan' should be translated into a document template which includes recommended representations for test results that would support the comparison of sets and other decision making 3. The different options should be explored and analysed through simulation, rapid prototyping, mathematical modelling etc. to determine their feasibility, benefits, and potential costs and the results should be incorporated in the same template 4. The knowledge created should be represented in the relevant graphical formats: limit curves for representing breaking points (and safe zones) for a single design option, and trade-off curves to compare the set of alternative subsystems/components against design criteria (e.g. cost and expected performance)
	Methodology for activity 4.3: 1. Identify adverse impacts that may arise from physical variation and noise factors such as manufacturing tolerances, aging, usage patterns, environmental conditions, etc. 2. Brainstorm potential market influences and customer requirements/specification changes which may impact the final design solution 3. Consider the effects of potential market influences and customer requirements/specification changes to the final design solution 4. Brainstorm potential effects that may result from any unexpected changes 5. Analyse the effect of the potential changes to the final design solution using a matrix 6. Analyse the system combinations and rank each solution based on the analysis

Methodology for activity 4.4:

1. Manufacturing engineers may determine criteria with which system alternatives may be evaluated for manufacturability and assembly
2. Lean production criteria should be developed so that system alternatives can be evaluated to determine the effect of the different system combinations on wastes in manufacture
3. A 'lean production event' or workshop may be held to evaluate system combinations for manufacturability and lean production with both design teams and manufacturing engineers present
4. Criteria can be weighted, and design options may be evaluated by means of a matrix; check sheets can be used to focus the evaluation

Methodology for activity 4.5:

1. Identify design criteria which are related to the manufacturing and assembly process (including criteria from design for manufacturability (DFM) and design for assembly (DFA)
2. Develop manufacturing process webs
3. Develop assembly process webs
4. Filter process alternatives based on design criteria, filtered design alternatives, etc.
5. Identify knowledge required to evaluate manufacturing and assembly process chains
6. Explore and evaluate candidate manufacturing process chains against cost, time and quality parameters
7. Explore and evaluate candidate assembly process chains against cost, time and quality parameters
8. Use a decision matrix to rank/compare alternative manufacturing and assembly process chains

Methodology for activity 4.6:

1. Individual system design solutions may be presented using an A3 template of MS PowerPoint presentation. The presentation should include the background, current condition, proposal, sketch/CAD drawing, and SWOT analysis
2. Potential systems will be presented for comparison using trade-off curves, and decision matrices
3. A design concepts matrix can be used in order to assess the fulfilment of system targets
4. The manufacturing processes for potential systems can be evaluated with the designs in order to discount infeasible options, or options that are not cost effective before commitment
5. After narrowing the options based on the knowledge gained from analysis, a final system will be converged upon; the final system combination will not be changed except in

	unavoidable circumstances and will be finalised at a 'design freeze (integration) event' where the final design will be presented/discussed
Phase 5. Detailed Design	1. Release final specification: The final specifications will be released once the final system concept is concluded; this is important because by communicating that the specification will be released after all of the activities in phases 1 to 4, it will be more likely that the specification and commitment will be delayed 2. Define manufacturing tolerances: Manufacturing will negotiate part tolerances with design teams; this is another aspect of delaying commitment in design 3. Full system definition: Further detailed design work will follow; it is assumed that companies may continue with their detailed design processes for assurance and qualification of design solutions which is normally industry and product-specific

3.4.5 The benefits of SBCE

This section explains the SBCE benefits from the literature which could address the current product development challenges faced by industries. The benefits have been agreed by several researchers which are; avoidance of highly rework cost, efficient communication, enable the innovation and creativity, encouraged organisational knowledge and learning, and reduction of failure risk (Raudberget, 2010; Khan *et al.*, 2011). According to Khan *et al.* (2011), SBCE is an approach that can address the challenges faced by the current product development. The challenges have been identified by the author from the case study of five companies and summarise into five typical challenges as explain in Figure 3-5.

Challenge	How SBCE Addresses the Challenge
Rework	Problematic design options are ruled out by developing and evaluating multiple alternatives in parallel
Sub-optimal Designs	Customer value is internalised and communicated holistically to all designers
Knowledge Crisis	An effective and coherent knowledge life-cycle facilitates the capture, representation and provision of the right knowledge to the right people at the right time
Lack of Innovation	Specific time and resources are scheduled for innovation, and multiple options must be considered as part of the process
High Unit Cost	By reducing rework, focusing on customer value, and improving communication and the process of PD, unit cost is reduced

Figure 3-5 SBCE and typical challenges face in PD (Khan *et al.*, 2011)

Meanwhile, Raudberget (2010) state that some of the current PD benefit can be utilized in the SBCE such as project cost, product cost, project lead time, project risk, unwanted engineering change, and warranty cost. Nevertheless, with an extensive literature review, more SBCE tangible benefit can be clarified to meet the research requirement. Table 3-4 illustrates the SBCE benefits from the literature and presented in some details in following paragraph.

Table 3-4 SBCE benefits matrix captured in literature

SBCE Benefits / References	Reduce rework	Efficient communication	Increase Innovation	Increase knowledge creation	Reduction of failure risk	Reduce lead time	Reduce cost	Improve product quality	Reduce uncertainty situation	Well-defined activities and tools
Al-Ashaab et. al, 2009		x		x		x	x			x
Al-Ashaab et. al, 2013	x	x	x	x	x	x	x			x
Arundachawat et. al, 2009	x					x			x	
Cai and Freihet, 2011			x		x		x			
Endris, Khan and Arias, 2012			x				x	x		x
Khan et. al, 2011	x	x	x	x			x			
Khan, 2012	x	x	x	x	x	x	x	x	x	x
Liker et. al. 1996		x								x
Raudberget, 2010		x	x		x	x	x		x	
Sobek II et. al, 1999	x					x			x	
Ward and Liker, 1995		x	x	x		x	x	x	x	
Tally	5	7	7	5	4	7	8	3	5	5

Reduction of cost is the most significant SBCE benefit captured in the literature. Al-Ashaab *et al.* (2013), Khan *et al.* (2011), and Khan (2012) agreed that the cost reduction gaining from the avoidance of the rework process in later design stages. Likewise, late design change will cause a major rework since the physical product has been finalized and ready to be in the market, thus, any changes made at this point are costly to the company (Ward and Liker, 1995; Endris, Khan and Arias, 2012). For that reason, the SBCE process can diminish the cost of late design stage rework by generating a set of design solutions at the earliest stage, eliminate the weaker solutions during the process, capturing the advantages from all the solutions until reaching the final optimum solution (Sobek II *et al.*, 1999; Cai and Freihet, 2011). According to Ward (2007), exploring the alternative design solution using a proven data and knowledge at the early stage will result a robust solution which could reduce the total overall cost of product development.

A product development lead time can be reduced through the elimination of the design rework (Sobek II *et al.*, 1999; Arundachawat *et al.*, 2009). Al-Ashaab *et al.* (2013) stated that SBCE demonstrated the reduction of lead time by creating well-defined activities, clear guide of tools to use, integrated documentation, and embracing the innovation yet increase the confidence level in the selection of concept through the exploration of a set of possible solution. Hence, it will reduce the number of lengthy review meetings so that, work faster and more efficient (Ward and Liker, 1995; Liker *et al.*, 1996).

In general, SBCE could promote a well-structured collaboration of different functional teams through an efficient communication (Cai and Freihet, 2011). According to Ward and Liker (1995) and Al-Ashaab *et al.* (2013), the SBCE can develop an efficient communication in the product development process where the whole communication is defined in the set of the possible solutions; as the set narrow, the early communication is still reliable but tend to be more detailed and precise as the project progress based on the knowledge gained. Moreover, communicating within the set of the possible solution can lead generating a robust and optimised design, and reduce the amount of the rework process (Sobek II *et al.*, 1999).

Khan *et al.* (2011) and Raudberget (2010) mentioned that level of innovation can be increased using the SBCE by exploration of the knowledge and create multiple concepts in parallel. The concept is by encouraging team members to discuss the alternatives through the creation of valuable knowledge from each other and fuse the optimum ideas (Cai and Freihet, 2011). Moreover, Endris, Khan and Arias A.B. (2012) has stated that the innovation level can be improved by adopting the SBCE which using a proven data and knowledge at early development stages. As a result, designers and engineers have a possibility to generate more innovative and robust solution compared to the point-based product development (Ward and Liker, 1995).

One of the benefits of using the SBCE is to reduce the failure risk by meeting customer requirement and improve product value (Cai and Freihet, 2011). Al-Ashaab *et al.* (2013) stated that risk of failure can be reduced by eliminating the weaker solution and let the final optimum solution go into the final phase. It is not just eliminating the weakest solution, but also learns the advantages from all the solution, combine the idea, and develop the best solution (Sobek II *et al.*, 1999). For instance, rejecting the worst solution is less critical compared selecting the third best alternatives for development instead of the best (Raudberget, 2010).

3.4.6 Changing the Mind-set: Build up the Culture

In many organisations, culture change is the most important to influence people to change, especially when new approach being introduced. Indeed, crux for a successful project driven from the embracing of culture change in the organisation (Kotter, 2013). It is also an indicator to identify whether the project will success or fail in the long term (Searcy, 2012). Typically, when an important change occurs, most of the people in the organisation are anxious of the unknown and they do not understand the need for change which resulting a resistance in culture change (Coronado and Antony, 2002). Eckes (2001) identify four different factors of change resistance in different perspectives such as technical, political, individual, and organisation. Some of the organisations that have succeeded in managing change have identified that the best way to tackle resistance-to-change is through increased and sustained communication, motivation and education (Eckes, 2001).

In the SBCE, culture change is one of the factors that need to be considered as the processes involving peoples to implement it (Raudberget, 2010; Khan *et al.*, 2011). Moreover, since the SBCE has different practices compared to the traditional product development, the needs of culture change management are crucial for the staff to undertake the SBCE particularly in the development of SBCE skills and decision making (Raudberget, 2010). Smith (2003) explains that culture change is a change of acting, recognising, thinking and developing by individual or group in the organisation. Regardless the complexities of the organisation, the acknowledgement of cultural change are subjective and different from each other. Each person in the organisation has a different view, experience, and belief, yet a different angle of thinking (Lawrence and White, 2013). Morgan and Liker (2006) described the culture change as a process of sharing the values and having a collective belief in the organisation, yet the strong culture came from the how much values is shared and believed. To change the culture, it must be blended with the corporate culture, yet required a robust management strategy in order to embrace the different way of doing business (Charles, 1998). Table 3-5 indicates the appropriate culture change needs in the new initiative program.

Table 3-5 Culture change needs in organisation captured in literature

Culture Change / References	Organisational Support	Boderless communication	Empowerment	Reward and recognisition	Education and training	Realizing the benefits	Discipline
Kotter, J., 2013	x	x	x	x			x
Lawrence, P. et. al, 2013	x				x		x
Martin, E.S, 2003	x	x		x			x
Morgan, J., 2006	x	x	x	x	x		x
Parks, C.M, 2002			x		x	x	x
Searcy, D.L, 2012	x		x		x	x	
Tally	**5**	**3**	**4**	**3**	**4**	**2**	**5**

Hence, changing the culture is not only an individual responsibility, but comprises entire people in the organisation from the blue-collar workers up to the management of the company (Searcy, 2012). In addition, cultural change can be managed by defining a clear direction, conducting more training, and provide more workshops (Lawrence and White, 2013). Figure 3-6 illustrates the component of the change program.

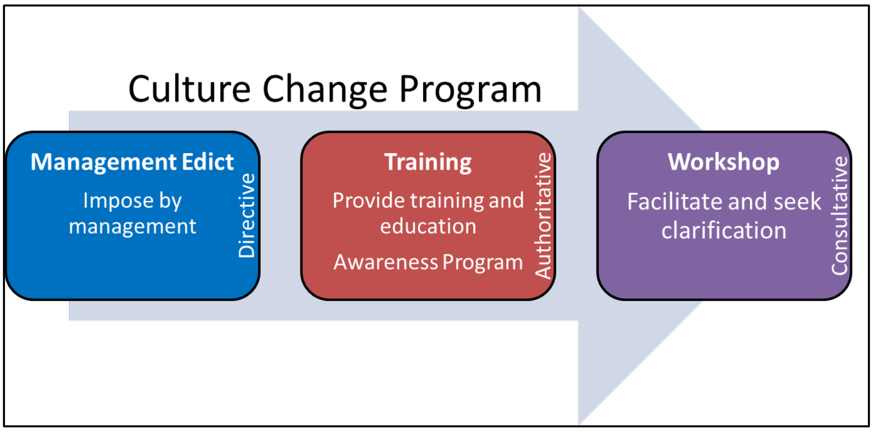


Figure 3-6 Component of change program (Lawrence and White, 2014)

3.4.7 Success Factor: The midst

The success factors in the literature are defined as a significant area of activities which can give a positive result for the particular organisation to reach the setting goal (Bradley, 2008). The idea of critical success factor was popularised by Rockart (1979) which described the critical success factor as a basis for determining the information that could help company success. Bullen (1981) described that the critical success factor is a primary activity which allows driving the business using an absolute positive result performance sufficiently in the respective area. Critical success factors are varied and subject to research aim and objectives which may have different element compared to the others (Ngai, Law and Wat, 2008). For instance, in the implementation of Enterprise Resource Planning (ERP), a lot of research has been done justifying the common critical success factors in ERP implementation (Bradley, 2008; Ngai, Law and Wat, 2008; Matende and Ogao, 2013). Bradley (2008) makes an effort by classifying the critical success factors for ERP implementation based on the prior research which illustrated in Figure 3-7.

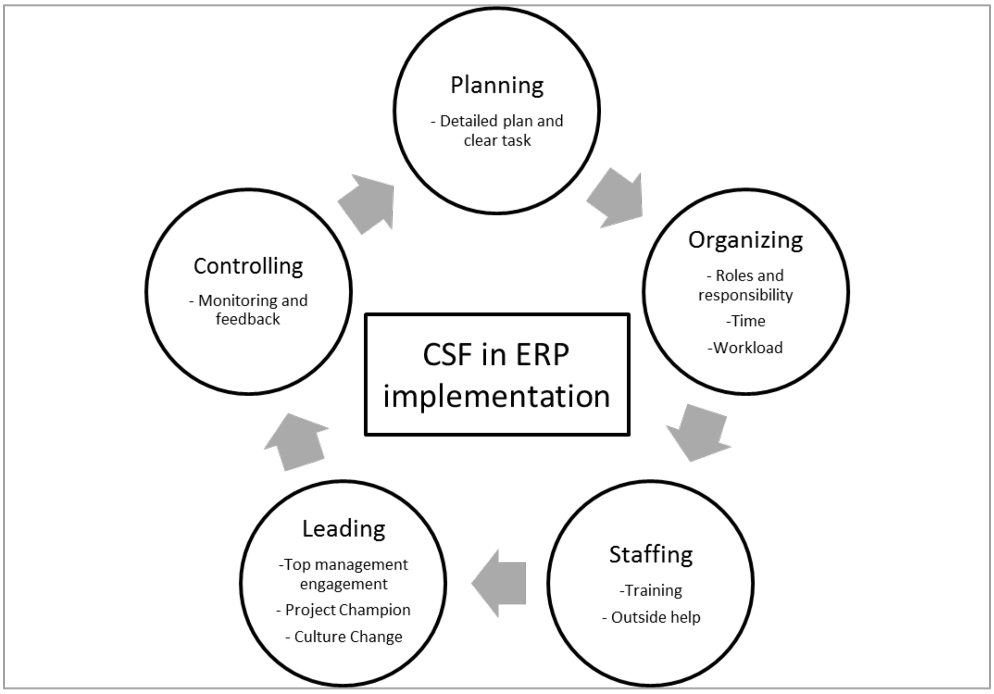


Figure 3-7 Simplified critical success factor for ERP implementation (Bradley, 2008)

In lean manufacturing, the critical success factors can be categorised into four elements which are leadership and management, organisational culture, financial capabilities, and skill as the most vital success for lean implementation (Dora *et al.*, 2013). However, in the small and medium enterprise, the vital successes are the leadership and management since good leadership can drive the skill and knowledge effectively in the small medium enterprise organisation (Achanga *et al.*, 2006). Even though the critical success factors intertwine with each other, the vital is different due to different business scenario. Figure 3-8 illustrates the critical success factor in the lean manufacturing implementation.

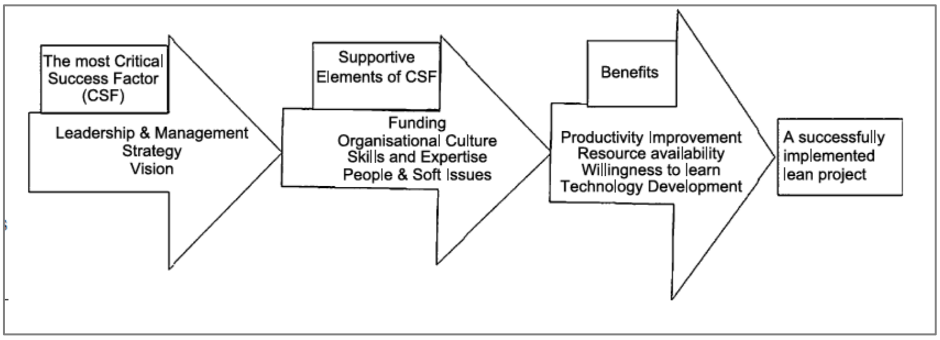


Figure 3-8 Critical success factor for a successful lean implementation (Achanga et al. 2006)

The critical success factors also can be identified in the implementation of Six Sigma. Henderson and Evans (2000) has suggested four critical success factors in the six sigma implementation; 1) Involvement of the upper management level, 2) Infrastructure readiness, 3) Training, and 4) Statistical tools. Habidin and Yusof (2013) outlines the critical success factors for Six Sigma into seven categories; 1) leadership, 2) structured improvement procedure, 3) quality information and analysis, 4) supplier relation, 5) just in time, 6) customer focus, and 7) focus in matrices. He also emphasis by identifying critical success factors in the task, it could help to ascertain the effectiveness of the implementation yet footing the promised benefit. Coronado and Antony (2002) identified the most important critical success factor for Six Sigma is from the continuous support and interest from top management.

Therefore, it is important to have a benchmark from the other project deployment to understand the critical success factor, such as in ERP, lean manufacturing, and Six Sigma which may able to help to propose the critical success factors for the introduction and the implementation of SBCE itself. However, to determine the critical success factor, the first step is to carry out an exploratory study on the topic of research (Coronado and Antony, 2002), which clarify in details in section 3.4 “State-of-the-arts of the Set-based Concurrent Engineering”.

3.4.8 An Overview of The Business Case

Even though research on the SBCE proof that the approach has got a potential for addressing the PD challenges, studies in the business case on this topic remain scarce. As companies struggle to justify the benefits of the application of SBCE, a well-structured business case is needed to overcome the matters. Therefore, literature reviews regarding business case are explained. The analysis focuses on two perspectives; which is 1) Developing a business case framework that outlines a clear guidelines on its application, and 2) Determine the necessary tangible benefits in business case to measure its effectiveness.

Press (2010) described business case as a tool for identifying and comparing multiple alternatives for pursuing an opportunity and then proposing the one course of action that will create the most value. This business case approach has described a seven steps to be followed in developing a business case which is; 1) Define the opportunity or motivation from the situation, 2) Identify the alternatives or list of option that have a potential to address the situation, 3) Gather data and estimate time frame for pursuing the opportunity, 4) Analyse the alternatives against the metrics that have been set and agreed within the team, 5) Make a choice and assess any risk that associate with it, result with low risk will generate higher chance of successful implementation, 6) Create a plan for implementing the idea by mapping the feasibility of the intended benefits, and 7) Communicate the case to get recommendations from decision makers by visual presentation. The author also emphasis that the process of building business case have a similarities to a process of problem solving by generating new ideas for how best to capture the opportunity and comparing the strength and the weakness of the alternatives.

Robinson *et al.* (2004) develops a business case framework for knowledge management. They developed the framework using a four-pronged approach which consists of 1) Questionnaire surveys, 2) Semi-structured interviews, 3) Case studies, and 4) Industrial workshops. The frameworks have three stages where the outcome explains as follow; Stage 1: Understand the challenges in the current organisation; Stage 2: Clarifies the challenges and develop a specific plan to address the challenges; and Stage 3: Evaluate the impact of the selected solution by providing a justification of the tangible and intangible benefits. They believed that the framework allows organisations to structure the business problem, smooth the process of knowledge exploration, and help to measure the impact of the initiatives.

Ward, Daniel and Peppard (2008) has described the building of the business case in information technology. The business case has been developed using six-step approach which he believed will give an impact on the development of rigorous and robust business case. The steps consist of; 1) Define business drivers and Investment objectives, 2) Identify benefits, measure, and owners, 3) Structure the benefits, 4) Identify organisational changes enabling the benefits, 5) Determine the explicit value of each benefit, and 6) Identify cost and risk. They pointed that the business case could show an evidence to support the benefits, hence enabling the success of the company.

Remenyi (1999) outlined constituent of business case methodology definition which comprise into five elements; 1) business outcome, 2) stakeholders, 3) strategic alignment, 4) technology, and 5) risk. He also believed an alignment of the business targets of an organisation could help in the development of well-structured business case.

Cresswell *et al.* (2000) described a business case in six dimensions. These are; 1) Description of the challenges faces by the organisation, 2) selection of the viable alternatives, 3) clarification of the key challenges, 4) estimation of the benefits and costs, 5) assessment of risk, and 6) project milestones. They mentioned that the business case as method to convince the stakeholders in the aspect of benefits, cultural change, cost, and risk.

Reiter *et al.* (2007) develops a business case for quality enhancing intervention in health care. They believed that in order to develop a business case, it should have a step-by-step approach which offers a guidance for the organisation. These approaches will help the organisation advancing its discipline in the business case analysis, therefore eleven steps have been developed.

Nielsen and Persson (2017) outlined developing the business case in information system by having a comprehensive method on how to do it. This method has been translated into five steps in condensed form as they believed it could ease to speed up the process of benefits realisation

Maes, De Haes and Van Grembergen (2014) developed a business case for the information technology at the company called Delphi. The aims are to investigate how the company could have a continuous business case approach to anchor its day-to-day practice. He pointed that the business case should be presented through a simplified consecutive process which could create a better understanding of the effectiveness and ease of implementation of business case practice.

Literature also defined business case as a structured document which supported by an analysis of its benefits, cost, and risk (Barnes, 1995; Cresswell, 2000; Gambles, 2009). The business case contains a specific requirement by laying the key objectives and challenges, business need and requirement, estimation of cost, justification of tangible benefit, and assessment of the risk (Barnes, 1995; Gliedman, 2004; Putten *et al.*, 2012).

Junker (2012) mentioned about establishing the business case of Quality based Design during the early stage of its introduction. He emphasises that at an early stage, the justification of the benefits was based on potential qualitative potential benefits in a few key areas such as product performance, quality improvement, and cost improvement.

Likewise, the business case could be presented in the form of spreadsheet, presentation, document or explanatory articles where all the related information is up-to-date during the project implementation (Franken, Edwards and Lambert, 2009; Putten *et al.*, 2012; Maes, De Haes and Van Grembergen, 2014). The information should be an estimated future situation relatively with the current situation which can be a qualitative, quantitative, financial or non-financial value (Ward, Daniel and Peppard, 2008; Putten *et al.*, 2012).

Furthermore, the benefits of business case could be categorised into four elements, firstly, observable benefits which could only be measured by opinion, judgement or intangible; secondly, was a measurable or quantifiable benefit where the benefits have been identified and easily put in place; Thirdly, was a financial benefit where the benefits can only be expressed in financial term (Ward, Daniel and Peppard, 2008; Putten *et al.*, 2012; Maes, De Haes and Van Grembergen, 2014). This could possibly the cost of manufacturing, material, hardware, software, implementation, maintenance, and consulting.

The reviews of the literature on the business case yield a valuable conclusion to guide the construction of a comprehensive framework for business case in introducing the SBCE. In this sub-chapter, most of the scholars recommend the development of the framework for business case in order to justify its feasibility.

3.5 Research Gaps

Even though research on the SBCE has been progressing well, there is still plenty of room for improvement. In order to identify the research gaps, an extensive literature review was conducted where the main scope of research was categorised into three areas which is the product development, SBCE, and business case. This research has identified three research gap which explain in Table 3-6.

Table 3-6 Identified research gaps

No	Identified research gaps	Section that the gap applies to	Section that the gaps has been addressed
1	There is a lack of a real industrial case study that justifies the real tangible benefits of the application of SBCE.	Chapter 3.4.2: Review of SBCE related work	Chapter 5.3: The construction of business case framework for introducing the application of SBCE Chapter 6: Industrial case study validation
2	There is no clear guide to justify the introduction of the SBCE application and their tangible benefits .	Chapter 3.4.2: Review of SBCE related work Section 3.4.5: The benefits of SBCE	Chapter 5.2: Towards the development of business case framework: An Overview Chapter 5.3: The construction of business case framework for introducing the application of SBCE Chapter 5.4 Success factor in introducing the application of SBCE
3	There is no business case that has been put forward to define the measurable benefits of the SBCE application.	Chapter 3.4.2: Review of SBCE related work Chapter 3.4.8: An Overview of The Business Case	Chapter 5.3: The construction of business case framework for introducing the application of SBCE

4 INDUSTRIAL PERSPECTIVE ON THE SET-BASED CONCURRENT ENGINEERING

4.1 Introduction

Chapter 4 explains the industrial perspective of having the Set-Based Concurrent Engineering (SBCE) in their product development process. The aim of this chapter is to provide evidence from the industry about the importance and the need of SBCE. Chapter 4 is divided into three sections consists of; 4.1) Introduction, 4.2) Semi Structured Questionnaire, and 4.3) Conclusion. Figure 4-1 illustrates the industrial field study structure.

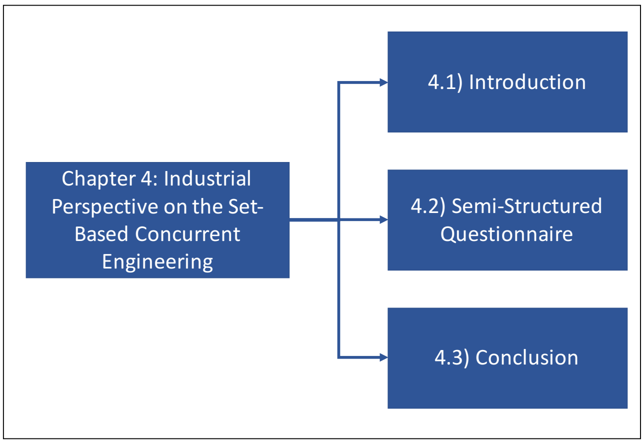


Figure 4-1 Industrial perspective structure

4.2 Semi-structured Questionnaires

This sub-chapter comprises of a semi-structured questionnaires, which aim to capture the most relevant information regarding PD process practices as well as capturing the PD challenges facing in the companies. Curwen, Park and Sarkar (2013) advocated that most of the company struggle optimising their own product development process to find a solution to address all the challenges. These challenges have been identified through an extensive literature review which explain in sub-chapter 3.3, hence lead to the formulation of the questionnaires.

The participants for the semi-structured questionnaires were selected from different business background, such as automotive, electronic, and aerospace. The selection was made due to following reasons:

1) Companies have started their own lean initiatives in the organisations.
2) Companies have its own lean initiatives plan which leads by Lean Champion.

The profiles of the participants are explained in Table 4-1.

The questionnaire comprises of three parts, namely; 1) Product Development Process, 2) Trade-off Curves, and 3) Collaboration between Commercial and Engineering teams. Only selected questionnaires in part 1 was discussed in relevance of this research topic.

Table 4-1 Profiles of the participants

No.	Company	Level of Authority	Experience (Years)	Business Background	Origin
1	Paxton	Process Improvement Manager	15	Electronic – Security and Access Control	UK
2	Visteon	Engineering Quality Senior Manager	15	Electronic – Automotive Cockpit	UK
3	Ford	Senior Program Manager	15	Automotive OEM	UK
4	GKN	Continuous Improvement Manager	23	Aerospace and Automotive	UK
5	Ricardo	Program Manager	28	Automotive – Engineering Consultancy	UK

Question 1 (Q1): *How is the current product development (PD) process followed in your organisation?*

The aim of Q1 was to understand the status of their current PD process being followed in the organisation. All participants have indicated that they have followed the current PD process in their respective organisation. Four participants mentioned that they have followed the current PD process, however at only specific stage. One of the companies shows that PD process was loosely followed in some project while others have gone beyond that by following their own PD process in each of the project. The result shows in Figure 4-2 give a significant indication as most of them employ the PD process only at a specific stage due to numbers of challenges happen during the development of the product which force them to skip some of the stage to meet the dateline.

Question 2 (Q2): *It has been observed that many organisations explore different design concepts during early design stages, but as the design progresses, it becomes too difficult to manage a set of conceptual designs and combinations of designs. This results in selection of one design (perceived as the best) which requires a lot of rework in the later design stages. (Please provide 3 reasons why do you believe this issue occurs?)*

Participants were asked to provide reasons for the issue mentioned above in Q2 as most of the company will end up with only selection of one design solutions (perceived as best design) instead of considering a set of conceptual designs in their PD process. Participants delineate three factors in response on this issue, namely process, cost, and time. In the process, participants concerned that the complexity of the gate in their current PD process enforces them to quickly select one solution (perceived as best solution). Most of participants concerned about the cost spending if considering multiple designs instead of pursuing single solution. Another concern includes time limitation and eagerness to introduce product in the market as well as limited skill peoples' readiness at the front load in PD to handle multiple designs. This result shows how importance to provide guidance on how to introduce and implement SBCE in the companies. The reason given by the participants shows a vague understanding of the SBCE and its benefits.

Question 3 (Q3): *How innovative are your products?*

The purpose of Q3 is to ascertain the process of innovating the products in current PD process practices in the companies. This question relevance as LeanPD through SBCE focuses on value creation, provision of a “knowledge environment”, continuous improvement that encourage innovation and collaboration. Participants mentioned their product innovation is mainly based on the use of previous design concepts with subject to major product design changes known as incremental innovation as illustrates in Figure 4-2. Incremental innovation is a series of small improvement usually focuses on improving an existing product design (Leonard-Barton, 1992). It is mean that innovation being pulled into product design along with customer requirement regardless lower-risk solution as long as it could maximise customer values.

Question 7 (Q7): *How are product requirements followed and finalised in your product development process?*

The aim of Q7 is to understand how participants translate product requirement in their current product development process. In response to the question, the participants define that the product requirements are provided early on by the customer, but usually undergo engineering alterations in late stages of the PD as shown in Figure 4-2. Participants' emphasis the cause is due to the imprecise decision whilst identifying product requirement at the early stage, thus creating more iteration during the process of developing a product which could give a negative impact on the end product. However, in SBCE, product requirements evolve through continuous interactions along the stages of PD as the product understanding matures and it is intentionally delaying the final specification until an optimal solution reach.

Question 8 (Q8): *How do you select the conceptual design solution that will be developed?*

In Q8, participants were asked about how they chose the conceptual design solution to be developed. It is significant to know how participants choose their conceptual design solution thus identify the opportunity for improvement of their current product development process through the SBCE. Participants outlined the selection of conceptual design solutions across the companies are based on regular PD practice which ascertain multiple solution and select the solution based on mainly subjective assessment as mentioned in Figure 4-2. Unlike SBCE approach, it initiates the design of multiple solutions in all projects, and gradually rule out the weaker solutions based on the knowledge gained from the low fidelity simulation and/or trade-off curve analysis.

Question 9 (Q9): *It has been observed that many organisations do not capture and reuse design concepts that were not selected as the optimal design in previous projects. How effectively do you incorporate the knowledge gained from previous projects into current projects?*

The purpose of Q9 is to discover the effectiveness of the participants incorporating the knowledge gained from previous projects and utilise it into the current project. Most participants in general are not aware to incorporate the previous knowledge in the current project, however, they are starting initiatives to formally capture and provide knowledge from previous projects to support the current projects as depicted in Figure 4-2. In SBCE, knowledge created in previous projects was effectively used to make a decision in all of the current projects. In addition, the newly knowledge gained are formally captured and kept for the next project.

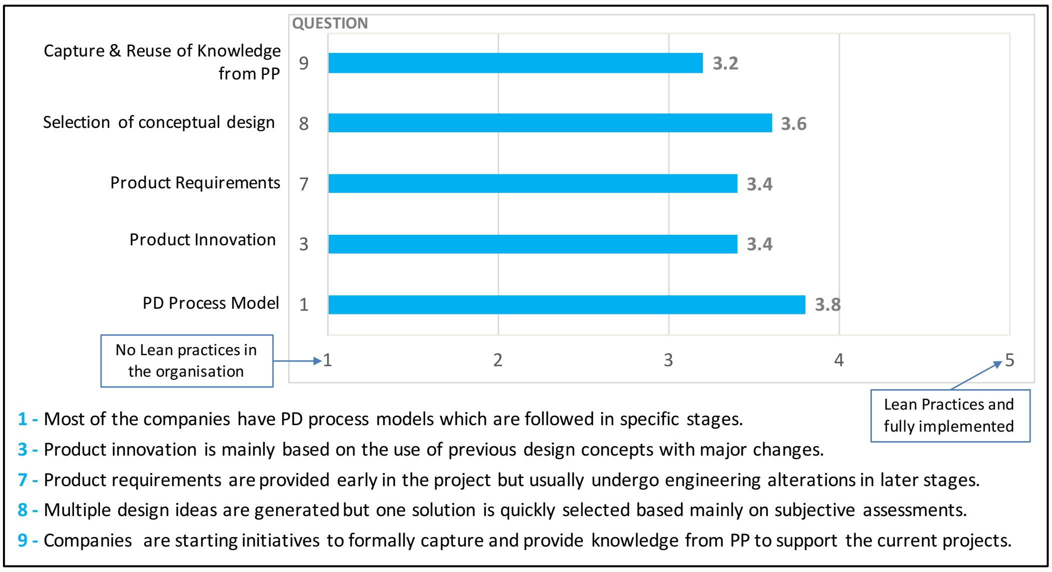


Figure 4-2 Analysis result of Question Q1, Q3, Q7, Q8, Q9

Question 11 (Q11): *What are the current product development challenges that would trigger the interest and the need of incorporating new practices into your existing PD process?*

The aim of Q11 is to identify what are the current PD challenges facing by participants in their product development process. The participant was asked to outline the challenges that would trigger the needs of incorporating new practices into their existing PD process in this case SBCE approach. Each of the PD challenges given by participants has been classified and simplified as follows:

1. Designs undergo numerous rework cycles to make it work
2. Poor communication within the project
3. Knowledge not benefitted for future projects
4. One design is selected early on (Low innovation)
5. Time to market often delayed (Higher time-to-market)
6. Low product quality
7. Loosely followed PD processes
8. Poor/none involvement of customers in early stages

4.3 Conclusion

The reason of industrial field study in this research is to acquire a better understanding of current PD practices in real industrial context. The field study has been conducted through semi-structured questionnaires in reason to obtain feedback and comment from all the participants in different business sectors. Each of the feedback and comment has been analysed where the result contributed to drive the research. The result presented support that LeanPD practises have a presence in the selected companies. However, none of them having a fully implemented of LeanPD instead of practices some portion of it informally. Other than LeanPD, such as SBCE are not found to be practices in the selected companies where participants show a vague understanding of the SBCE and its benefits. This result indicates on how importance to provide guidance to introduce and implement SBCE in the companies. The next chapter describes the development of business case framework for introducing the SBCE application.

5 THE PROCESS OF DEVELOPING BUSINESS CASE FRAMEWORK FOR INTRODUCING THE SBCE APPLICATION

5.1 Introduction

Chapter 5 presents the process of developing a business case framework for introducing the application of SBCE. The analysis of extensive literature, industrial perspective, and case studies have demonstrated that the constructive business case framework is needed in the context of introducing the SBCE in the company. Having a business case would not only help the company identify the potential solution, but also could help to sell ideas to the stakeholders with valid justification. The following chapter describes the details of the framework which entails the step-by-step process needed to be followed.

5.2 Towards the development of business case framework: An Overview

The frameworks are constructed by phases or stages, which recommended the inclusion of subjects such as “motivation or driver”, “selection of viable alternatives”, “benefits measurement”, “benefits evaluation”, and “justification of the benefits”. These recommended phases are identified through several literatures as stated in Table 5-1. In order to make a necessary rearrangement in favour of this research which is to develop the business case framework for introducing the SBCE, the phases have been classified using a singular name which is the Driver, Demonstrate, Evaluate, and Justify, which listed in Table 5-1. A supportive evidence of each of the phases is described in the following paragraph.

Table 5-1 Literature on business case structure

No.	Author(s)	1. Driver	2. Demonstrate	3. Evaluate	4. Justify
1	Nielsen and Persson, 2017	X		X	X
2	Maes, Grembergen, and Haes, 2014	X	X	X	
3	Berger, 2012	X		X	X
4	Junker, 2012			X	X
5	Press, 2010	X	X	X	X
6	Raudberget, 2010	X		X	
7	Gambles, 2009		X	X	X
8	Ward, Daniel, and Peppard, 2008	X	X	X	X
9	Morgan and Liker 2006	X	X		
10	Kennedy, 2003	X			
10	Robinson et al., 2004	X	X	X	X
11	Schmidt, 2003	X	X	X	X
12	Cresswell et al., 2000	X	X	X	X
13	Barnes, 1995	X		X	X

1. **Driver:**
    a) Nielson and Persson (2017), Ward, Elizibeth, and Peppard (2008), Schmidt (2003), Cresswell et al. (2000) outlined the importance of identifying the challenges faced by organisations that need to be addressed in the process of developing a business case.
    b) Maes et al. (2014), Press (2010), Barnes (1995) have built a business case phase, which considers project planning, roadmap, situation and project description as a driver in order to have a solid business case.
    c) Berger (2012) elaborates the current situation in the organisation at the early phase of the business case as it could help them to ease their communication hence will improve the result of the benefits.
    d) Robinson et al. (2010) and Press (2010) rule out the performance measurement to provide in-depth analysis of the current practices in the organisation at the early phase of business case.
    e) In order to ensure the success of introducing SBCE, awareness and proper training should be done to build the culture. Morgan and Liker (2006) and Kennedy (2003), developed a methodology for the

implementation of LeanPD. They structured the change process consisting of identifying team and champion as well as providing an awareness training as initial preparation to help people get on board with the new initiative.

f) Nielson and Persson (2017) has conducted a ten-hour initial workshop for awareness purposes in developing the business case for information system.

g) Raudeberget (2010) described a recommendation to have a training prior to the implementation of the SBCE in order to create a broad acceptance and identify key individuals that are willing to participate in the initiative.

2. **Demonstrate:**

a) Maes, Grembergen and Haes (2014), Press (2010), Robinson (2004) place emphasis on identifying an aim and objective as a priority to reach the most important goal in the organisation. This is in order to seize the challenges that have been identified in Phase 1 “Driver”.

b) Morgan and Liker (2006) constructed a pilot lean process in the roadmap for lean transformation. In this phase, they focus on the pilot project with the attention to show the power of LeanPD, develop a culture change by doing, and create a momentum in order to reach full implementation.

c) Cresswell et al. (2000), Schmidt (2003), Gambles (2009) synthesised a scope of feasible approach for business case in order to achieve a specific requirement within the scope of the work. This is in order to achieve a target set by the customers.

3. **Evaluate:**

a) Nielsen and Persson (2017), Press (2010) highlighted the importance to structure multiple alternatives of solutions in the business case process in order to encourage more discussion on the type of changes required towards benefit realisation.

b) Berger (2012), Maes, Gembergen, and Haes (2014), Junker (2012), Press (2010), Gambles (2009), Ward, Daniel, and Peppard (2008), Robinson et al. (2004), Schmidt (2003), and Barnes (1995) emphasise on detailed analysis and evaluation to understand the true consequence thus the clear benefits definition could be reached.

c) Press (2010) and Raudberget (2010) recommended the process of narrowing solution as part of the evaluation - that will best address the aim and objectives hence the selection of an optimal solution could be achieved. The strategies for narrowing down the solution includes; 1) Combine any alternative that could be implemented together, 2) Eliminate high risk options, and favour the less complex solution over the difficult.

4. **Justify:**

a) Nielsen and Persson (2017), Berger (2012), Junker (2012), Robinson et al. (2004), Ward, Daniel, and Peppard (2008) described the importance of identifying tangible benefits as an important criterion to demonstrate the value of business cases.

b) Junker (2012), Gambles (2009), Ward, Daniel, and Peppard (2008), Schmidt (2003), Cresswell et al. (2000), and Barnes (1995) categorised tangible benefits into three elements which is performance, cost and risk.

c) Press (2010) recommends a desired format to document the business case by using visual presentation as a communication tool to present the business case effectively.

Based on the analysis, the construction of business case framework has been developed in a manner that contributes to the success of introducing the SBCE in the company which is explained in the sub-chapter 5.3.

5.3 The construction of business case framework for introducing the application of SBCE

This sub-chapter describes the construction of the business case framework for the introduction of the SBCE. Analysis of the literature review, industrial perspective and real industrial case studies has provided a foundation in developing a SBCE business case framework and its following implementation as shown in Figure 5-1. The SBCE business case framework was developed inspiring the process of developing a business case by Press (2010) shown in Table 5-2. Then, these steps were tailored to the selected SBCE activities (see Table 5-2) in order to see its relevance. Many of the activities from the business case are intertwined with the selected SBCE activities. Thus, it reveals that having the business case in the SBCE are reasonable and fit for this research.

Table 5-2 Seven steps to develop a business case tailored to the selected SBCE activities

		Selected SBCE activities										
		Phase 1: Define Value		Phase 2: Map Design Space			Phase 3: Concept Set Development		Phase 4: Concept Convergence			Phase 5: Detailed Design
Seven Steps to develop a business case (Press, 2011)	Lean PPD Performance Measurement	1.1 Classify project type	1.2 Explore customer value	2.1 Decide on level of innovation to subsystem	2.2 Identify subsystem targets	2.3 Define feasible regions of design space	3.2 Create sets for each subsystem	3.3 Explore subsystem sets: prototype and testing	4.1 Determine set intersections	4.2 Explore system sets	4.6 Converge on final set of subsystem concept	5.1 Realease final specification
Step 1: Define the Opportunity												
• Describe the current situation	x											
• Identify aim and objectives		x										
• Prioritise objectives												
• Assigning matrics for the objectives			x									
Step 2: Identify the alternatives												
• Brainstorm for multiple alternatives							x					
• Gather input				x	x	x						
• Generate list of alternatives							x					
• Analyse the alternatives								x				
• Narrowing alternatives								x	x	x	x	
Step 3: Gather data and estimate time frame												
• Obtain information and data of each alternative based on metrics							x	x	x	x		
• Estimate time frame for implementing the initiative	x	x										
Step 4: Analyse the alternatives												
• Evaluating alternatives againts metrics							x	x	x	x		
• Identify any quantifiable and unquatifiable benefits							x	x	x	x	x	
Step 5: Make a choice and assess the risk												
• Select and justify the best solution based on data and analysis (metrics or best judgement)											x	x
• Make an assessment of the risk associated to the selection											x	
Step 6: Create a plan to implement an idea	Applies in activity 5.2 and 5.3 (see Table 3-3)											
• Developing an implementation plan for the best solution												
Step 7: Communicate the case												
• Communicate and present the business case to management by showing the benefits.												x

A number of phases defined in the framework represent the top-level process. The framework was established in four-phase approach where each of the phases consists of a series of steps or activities which are unique to the purpose of developing the business case for introducing the SBCE. These were aligned with the principles of SBCE. The framework is categorized as follows; Phase 1: Driver, Phase 2: Demonstrate, Phase 3: Evaluate, and Phase 4: Justify. Each of the phases has its own focus in order to achieve the desired aim. The aim of the framework is to provide a guideline in developing a business case for the introduction and applications of the Set-Based Concurrent Engineering (SBCE). In order to develop the SBCE business case framework five following questions were developed to represent the need of the framework.

1) What is the PD challenges? (This includes factual data analysis includes results of PD assessment or/and face-to-face interview or/and meeting with the company).
2) What should be done in addressing the PD challenges? (This includes having a clear pilot project selection as well as a clear aim and objective that are relevant to demonstrate the SBCE).
3) Which alternative solution should be considered? (This includes generating and evaluating the ideas that address the requirement).
4) What is the strategy for the manpower and their skill to undertake the application of SBCE? (This includes an appointment of the champion, formation of team members and awareness training)
5) What are the potential benefits gained from the application of SBCE? (This includes a pre-post analysis of the improvement on each of the benefits).

These key questions were then translated into the development of four-phases of the SBCE Business Case Framework. The following paragraph explains the detail of the framework.

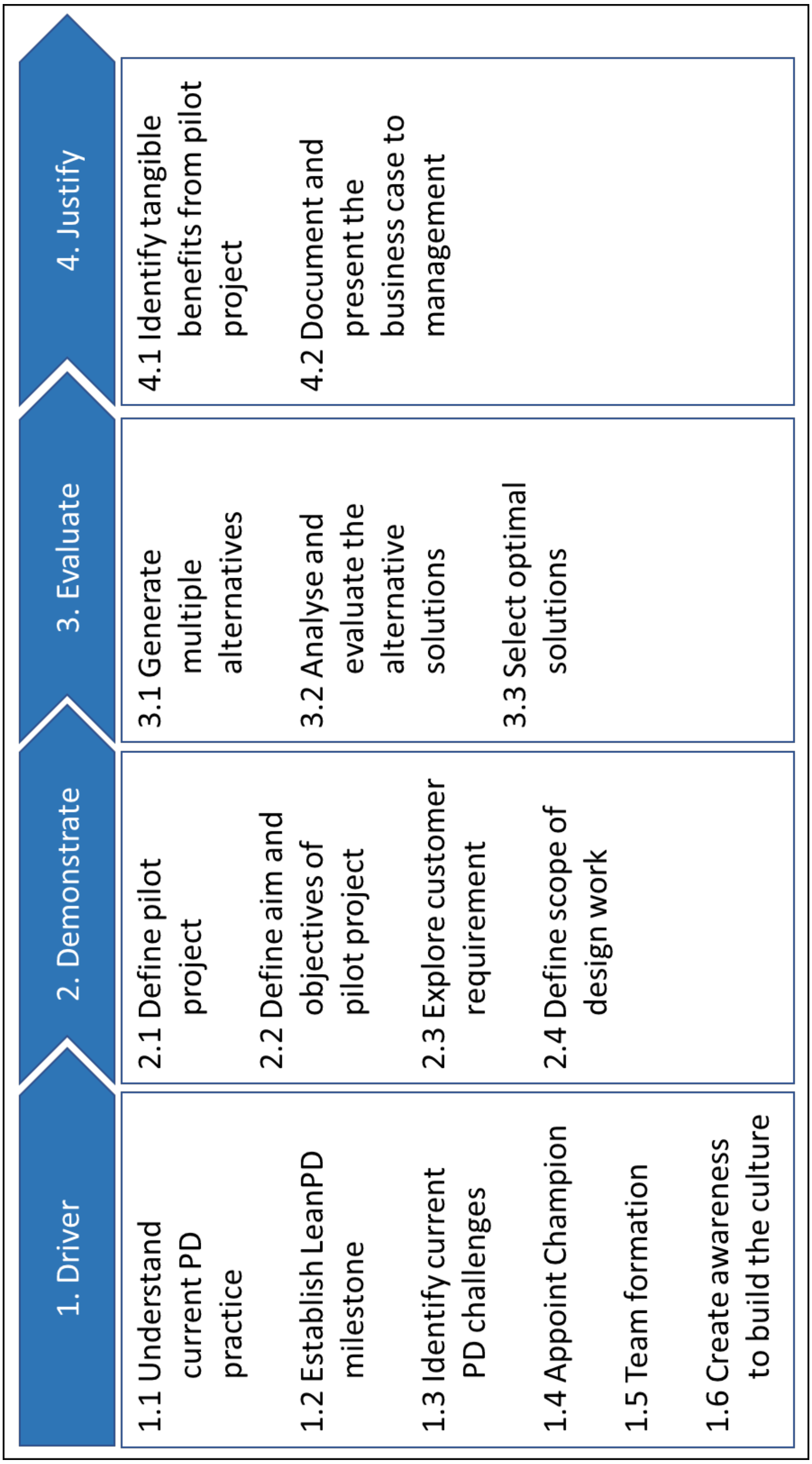


Figure 5-1 The SBCE Business Case Framework

5.3.1 Phase 1: Driver

Phase 1 provides a basic structure for formulating business case in the SBCE. The steps involved in Figure 5-1 are supported by well-established tools and methods which are the LeanPD SMART Assessment Tool (Al-Ashaab *et al.*, 2016), face-to-face interviews using a semi-structured questionnaire, meetings with industrial collaborators as well as the literatures. Phase 1 is considered as a foundation of the framework in formulating the business case. The first phase consists of several steps to follow which are 1.1) Understand the current PD situation, 1.2) Establish LeanPD milestone 1.3) Identify current PD challenges, and 1.4) Appoint Champion, 1.5) Team formation 1.6) Create awareness to build the culture. The purpose of Phase 1 "Driver" is to provide a situational understanding of the current PD practices and current PD challenges facing in the company. It is also to set up the development of the peoples by the following;

1. Construct a team to run the changes process.
2. Provide an appropriate training for the organisation.

The outcome of Phase 1 is to provide information to the company on their current product development, current PD challenges, and their journey towards LeanPD. Also, establish the team that could lead the change process as well as provide a suitable knowledge to smooth the buy-in process. The steps involved in Phase 1 is supported by the methods which are described in detail below.

<u>Step 1.1: Understand current PD practices</u>

Objective: The main objective in Step 1.1 is to understand the current PD practices against the best practice of LeanPD. It allows the finding out of where improvements could be implemented in the PD process and assess the PD challenges that may occur.

Method: Current PD practice is obtained by using LeanPD performance assessment, face-to-face interviews via semi-structured questionnaire or meetings with industrial collaborators.

Step 1.2: Establish LeanPD milestone

Objective: LeanPD milestone should be established as it will help the companies to understand simply their current PD practices and the future lean journey. This will give a clear indicator for the organisation to steer their effort towards lean transformation.

Method: LeanPD milestone is established using the results from the LeanPD performance assessment. The milestone consists of AS-IS state and TO-BE state. The data obtained is based on data from company to company.

Step 1.3: Identify current PD challenges

Objective: It is important to understand what the challenges the company faces in their current product development approaches. PD challenges are the key in developing a business case for the SBCE. It is an effective method to recognize the important PD challenges required to be focused as well as to see the difference between urgent and important PD challenges that need to be resolved.

Method: Current PD challenges are obtained by using LeanPD performance assessment, face-to-face interview via semi-structured questionnaires or meetings with industrial collaborators. Two methods could be used, either distribution of statistical data or brainstorming session.

Step 1.4: Appoint Champion

Objective: In order to ensure the initiatives are properly performed, a Champion should be appointed. Champions are the leaders in the initiatives responsible in spreading the knowledge and changing cultures in the organisation.

Method: The appointment of a Champion is based on several criteria; 1) An open-minded person; 2) A person that has knowledge and skill about lean, managing people, and business operation; 3) A person that has strong leadership capabilities and passionate about lean; and 4) Able to mentor and lead team members as well as convincing the management team and the stakeholders.

Step 1.5: Team formation

Objective: Before change can occur, team formation should be established. This is to ensure that the SBCE could be spread smoothly in the organisation. The team should be functioning as an agent for the entire organisation targeted to change.

Method: Selection of team members shall consist of people that generally aware about the initiatives and are highly effective in leading the changes.

Step 1.6: Create awareness to build the culture

Objective: The overall objectives of Step 1.6 is to embed the knowledge of LeanPD and SBCE within the organisation. This is to create a broad acceptance and awareness by having a clear definition of the principles and its application.

Method: Two days training were required in order to achieve the level of awareness. The structure of the training consists of interactive methods with real industrial case study as well as hands-on exercises. Prior to that, a short seminar was given to the senior management to gain their confidence and be supportive on the initiatives.

5.3.2 Phase 2: Demonstrate

Phase 2 demonstrates the application of the SBCE. In this phase, the SBCE are deployed and pilot project or case study are selected. The choice could be a complex or a less complex project, depending on company's preferable choice. The purpose of Phase 2 "Demonstrate" is to show the effectiveness of the SBCE application in addressing the challenges obtained in Phase 1. This will provide an opportunity for the company to get on board, experience and learn the power of

SBCE in the real industrial case study. The Phase 2 consists of four steps to follow which is 2.1) Define pilot project 2.2) Define aim and objectives of the pilot project, 2.3) Explore customer requirement, 2.4) Define scope of design work. The outcome of Phase 2 is to identify and prioritise the aim and objective of the pilot project as well as to set the design scope based on customer requirement. The step involved in Phase 2 "Demonstrate" is supported by the methods which are described in detail below.

Step 2.1: Define pilot project

Objective: Pilot project should be defined in order to forecast the time and resources effort as well as to determine which projects will give a great impact so as to ease the buy-in process among stakeholders. The selection of the pilot project aims to address some of the PD challenges discovered in Step 1.2 and 1.3

Method: Pilot project is defined through a brainstorming session between the research team and industrial collaborators.

Step 2.2: Define aim and objectives of pilot project

Objective: Aim and objectives should be defined in order to establish a sense of purpose and direction in the pilot project so that the company could set a specific target and monitor the progress towards reaching them.

Method: The aim and objectives of the pilot project are defined through a brainstorming session between the research team and industrial collaborators.

Step 2.3: Explore customer requirement

Objective: Customer requirement is crucial and must be understood to accurately define the target specifically related to the aim and objective of the pilot project. Customer requirement consists of characteristics, specifications, and feature values determined by a customer.

Method: Customer requirements are defined through a record and requirements of customer request, market survey and research, as well as meetings with a customer representative. Customer requirements later will translate into Key Value Attributes using KVA prioritisation technique.

Step 2.4: Define scope of design work

Objective: This step will provide a boundary for design work to prevent over-engineering while encouraging the necessary innovations and improvements. It is also defined as the boundaries for designers and engineers to explore and communicate with many alternative solutions. However, it is essential not to impose the activity with too many constraints as this might create a limitation on the innovation of the product.

Method: Scope of design work should be defined by designers and engineers through level of innovation, identify subsystem target, and define the feasible region. The designers and engineers should commit to their boundaries that have been agreed among the team, otherwise it could create an over-engineering situation during the development process. Scope is identified through several sources such as a brainstorming session, design rules, bill of design, and engineering specification.

5.3.3 Phase 3: Evaluate

Phase 3 provides a structure for evaluating the multiple alternative solutions using the outcome of Phase 1 “Driver” and Phase 2 “Demonstrate”. The evaluation process consists of three different methods such as engineering solution, mathematical solution, and subjective decisions subject to the level of complexity of the project. The purpose of Phase 3 is to analyse and evaluate the alternative solutions in a structured way. The result from the analysis will be used to narrow down the solutions as well as identify the potential benefits in Phase 4 “Justify”. The Phase 3 “Evaluate” consists of three steps to follow which are; 3.1) Generate multiple alternative solution, 3.2) Analyse, evaluate, and narrow down the solutions, and 3.3) Select the optimum solution. The outcome of Phase 3 is to reach an optimal solution for the pilot project. The step involved in Phase 3 "Evaluate" is supported by the method explained below.

Step 3.1: Generate multiple alternative solution

Objective: In developing a business case, it is crucial to have a full set of different alternative solutions rather than pursuing one single solution. This will drive a better result in achieving the optimal solution. This step will ensure that designers and engineers are able to brainstorm, innovate, and generating multiple alternative solution to be proposed. Each design generated corresponds to the Key Value Attributes (KVA) which is explained in Step 2.3.

Method: Generated multiple alternative solution is obtained from different types of sources such as from designers and engineer's creativity, previous projects, and benchmarking from the competitors. The idea could be hand sketched or using any CAD software using low fidelity data with the purpose to only represent the conceptual ideas. Any specifications or dimensions should be nominal without any detailed tolerances unless it is necessary to consider it.

Step 3.2: Analyse, evaluate, and narrowing the solutions.

Objective: After generating multiple alternative solutions, each of the solutions needs to be carefully analysed, evaluate and narrow down against the KVA. Step 2.3 ultimately wants to show each solution's impact on the KVA as well as the SBCE metrics.

Method: Each of the solutions should be analysed by using low-fidelity simulation techniques using a simulation software available in the market, engineering calculation, cost calculation, and etc. to determine their feasibility and potential benefits. In evaluation and narrowing down process, different options could be used such as

Functional Means Analysis (FMA), Intersection Matrix, and Trade-off Curves (ToCs) depending on the level of complexity of the project.

Step 3.3: Select the optimum solution

Objective: Based on the analysis, evaluation, and narrowing down of the solutions, designs that do not meet the target will be eliminated and the optimal design of the alternative solution will be finalised.

Method: Optimal solutions are obtained by analysing the effect of the feasible design solutions against the KVA using PUGH matrix. The PUGH matrix is based on the scale and then multiply it to the load of importance which is taken from the KVA. Highest score from the multiplication is considered as the optimal solution. The score will be given based on several brainstorming sessions within the team based on the knowledge gained during the project such as simulation results, ToCs, manufacturer and etc.

5.3.4 Phase 4: Justify

Phase 4 outlined the structure to justify the effectiveness of the SBCE by justifying the measurable benefits against the selected PD challenges. The process of identifying the benefits is established in a few key areas of improvement for instance, product innovation, performance, cost and risk. The key areas of improvement are summarised in the structured representation table which specify the category of improvement, a description of the improvement, and improvement percentage. The input data for identifying both benefits result was obtained in Phase 3. The Phase 4 “Justify” consists of two steps to follow which are: 4.1) Identify tangible benefits from pilot projects, and 4.2) Document and present the tangible benefits to stakeholder. The outcome of Phase 4 is to justify the measurable benefits and to show the ability of the SBCE to address the PD challenges which could help the buy-in process through a well-structured business case for the introduction of SBCE. The step involved in Phase 4 “Justify” is supported by the method described below.

Step 4.1: Identify tangible benefits from pilot project

Objective: Consider the aim and objective as well as the target of KVA, the tangible benefits could be anticipated from the result of the optimum solution. These will then be aligned to the SBCE matrices that has been set which is knowledge learning (innovation), product performance, cost, project success rate, and risk of failure.

Method: Expected tangible benefits are obtained by analysing them using a different method in each of the elements in SBCE matrices. Expected tangible benefits of knowledge learning (innovation) could be measured by analysing the total set of alternative design solution configurations using mathematics multiplication. Product performance could be analysed using traditional engineering calculation or by using any engineering software tools such as Computational Fluid Dynamics analysis (CFD), Solid Work, CATIA, Math Lab and etc. In terms of cost, the tangible benefits could be defined through a costing analysis subject to the complexity of the project. Finally, the project success rate and risk of failure are measured by using probability test technique.

Step 4.2: Document and present the business case to management

Objective: Once the result confirmed, document it into a desired format in order to visualise what are the benefits gained from the application of the SBCE

Method: It is an important aspect to present the business case to the stakeholders. This will help the buy-in process and sell the ideas of SBCE to the decision maker as well as to those who had the influence. It should be delivered in short, focused, and not a lengthy detailed explanation. The recommended steps to follow to map the business case are as follows: 1) The opportunity statement, 2) Pilot project overview, 3) Customer requirements, 4) Scope of design work, 5) Idea exploration and generation, 6) Summary of Analysis and Evaluation, 7) Optimal solution obtained, and 8) Justification of measurable benefits.

5.4 Success factor in the business case framework of introducing the SBCE application

The successful factor in the introduction of SBCE are based on two fundamentals which are; 1) The adoption to the flow of the SBCE process (see sub-chapter 5.2) and 2) Well-define SBCE metrics. These fundamentals are important in order to measure the effectiveness of SBCE in addressing the PD challenges through justification of potential benefits. The following paragraph explained the detail of a SBCE successful measure.

5.4.1 The adoption of the SBCE Process Model

One of the measures of success in SBCE is that it offers a well-structured and clear guideline to the practitioner. Figure 3-4 shows the activities of the SBCE which has been developed. In the event of introducing SBCE, not all of the activities in Figure 3-4 were used. The selected activities which were used in this research are the activities that lead to the development of the business case as it could demonstrate the tangible benefits of the application of SBCE. The selected activities are shown in

Figure **5-2** where the details are explained in Table 3-3 .

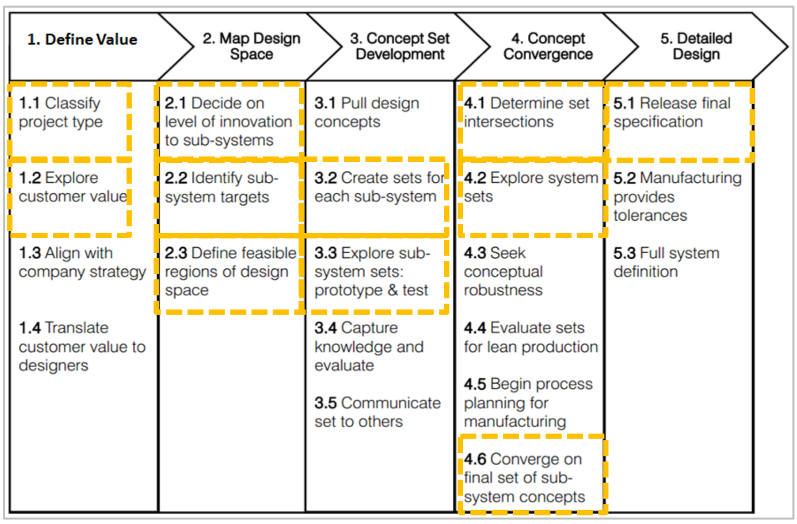


Figure 5-2 Selected activities for introducing SBCE (Khan, 2012)

5.4.2 Well-defined SBCE metrics

Another successful measure of the business case for the introduction of SBCE is assigning its own metrics. The purpose to have these metrics is to track and assess the progress of the application of SBCE. The SBCE metrics development is built on quantifiable measurements that could measure the effectiveness of SBCE applications. During the extensive literature review, field study, and performing the case study, the key SBCE metrics are identified and considered by author as "should be monitored" in introducing the SBCE which is- 1) Knowledge and learning metric, 2) Product performance metric, 3) Cost metric, and 4) Risk metric. Details are explained below:

1. **Knowledge and learning:** The innovation and knowledge creation level are important in the SBCE application due to its nature focuses on value creation, and provision of a "knowledge environment". The purpose of the knowledge and learning metric is to show the ability of SBCE in promoting the innovation which could help companies become more competitive thus survive in the fierce competitive world of business. Moreover, this also could provide an indicator to stakeholders on how well their engineers and designers improve their skills in product innovation and creativity.
2. **Product performance:** The product performance metric is important to measure the product improvement pre-post SBCE application. The criteria for product performance will be different, subject to product type and customer requirements. Data for the product performance could be obtained either from the result of a simulation or engineering calculation. However, as representation, data are mapped using a number of percentage for a generic understanding unless detail is required.
3. **Cost:** Cost is one of the key components of SBCE metrics. In the situation of introducing the SBCE, the factor of cost was seen from the aspect of direct cost for instance cost of material, manufacturing, process and so forth. These costs are persuasive and important to consider at the stage of introducing the SBCE as it is easy to justify. Even though the costs were not directly given an impact on the financial, still it could lead to the impact on the financial.

4. **Risk:** Another key metric of SBCE is the risk. Risk is crucial and has to be monitored as it could help companies identify and understand the risks level on the application of SBCE. In this research, risk was identified via probability test method. According to Ward and K. Sobek II (2014), three rules were implied in the probability test to identify the risk;
    a. The probability of failure is one minus the probability of success and vice versa
    b. The probability of a number of independent events happening at the same time is the product of the individual probabilities.
    c. The average number of occurrences of an event in a series of trials is the probability of occurrence in each trial, times the number of trials.

    Therefore, the author derives the probability rules equation as follows;

    <u>Rule 1 and Rule 2</u>

    The probability of failure;

    $$\mathrm{POF_n} = \mathrm{P_f}^{\mathrm{n}}$$ **Equation 1** Probability of Failure

    Where;

    $\mathrm{P_f}$ = Value of probability of failure

    n = Number of design solution

    The probability that all subsystems will have at least one successful design;

    $$\mathrm{POS} = (1 - \mathrm{POF_n})^{\mathrm{m}}$$ **Equation 2** Probability of at least one successful design

    Where;

POF_n= Probability of failure with n number of design solution

m = Number of subsystems

<u>Rule 3</u>

The average number of successful designs;

$$\bar{x} = n\ (P_s)$$

Equation 3 Average number of successful designs

Where;

n = Number of design solution

P_s = Value of probability of success

5.5 Summary

In this chapter, the construction of the SBCE business case framework has been described. As summarised, the research shows the purpose of the SBCE business case framework for introducing the SBCE in the manner that identifies and justifies the benefits of the SBCE application. The framework is divided into four phases where each of the phases consists of a series of steps/activities which embody the principle of SBCE and developing a business case. The framework was found to be a structured guideline as it facilitates the process of identifying and justifying the potential benefits of the SBCE. The next chapter of this thesis will be the validation of the framework by using a real industrial case study in three different business sectors.

6 INDUSTRIAL CASE STUDY VALIDATION

6.1 Introduction

In order to validate the framework, the SBCE business case framework was tested in industry. In this chapter, the constructed framework was applied on three industrial case studies in three different companies. Each of the companies has different business sector and business scale. This was important to validate the ability of the framework to undertake any type of business. Hence, it could help the buy-in process and built the confidence level of the company in adapting the LeanPD through SBCE to improve their current PD practices. The three companies are explained in brief as follows:

1. Paxton Limited is an electronic company that design and manufacture an internet protocol access control for door entry and building access. The market includes the healthcare, retail, leisure, education, commercial, and public sector.
2. Caltec Limited is an oil and gas engineering solution that design and manufacture Surface Jet Pump (SJP) which purpose to revive the production of oil and gas from the dead wells. This company currently holds 14 major design patents related to surface jet pump technology.
3. Jaguar Land Rover (JLR) is the biggest car manufacturing in the United Kingdom, where the business activities consist of design, development, manufacture, and sales of the vehicle. Currently, the company has thirteen vehicle models in the market under the JLR marque.

The detail of each of the company portfolio explained in Table 6-1.

Table 6-1 Company portfolio

Portfolio	Paxton	Caltec	JLR
Business	Electronics	Oil and Gas	Automotive
Business Size	Medium	Small	Large
Type	OEM	Engineering solution	OEM
Manufacturing Volume	Large	Small	Large
Production type	Mass produced	Customised	Mass produced
Portfolio of industrial collaborator	Development Director	Technology Director	Senior Manager Chassis Engineering
	Process Improvement Engineer	Process Engineer	Function Managers
	Senior Engineer-System Test	-	Function Engineers
Number of case study	1	1	1
Case Study purpose	Develop roduct - Imrpove design	Develop product - Improve Productivity	Develop product - Improve Design
Achievement	Optimal solution achieved	Optimal solution achieved and product on market	Optimal solution achieved

The next sub-chapter will detail the application of the SBCE business case framework by using a real industrial case study in three different company as mentioned earlier. The case studies are explained separately in sub-chapter 6.2, 6.3, and 6.4.

6.2 Paxton case study

6.2.1 Overview

The application of the SBCE process model has been demonstrated based on the real case study in collaboration with Paxton Access Limited, a leader company in the manufacturing of electronic access control systems. The company has been selected due to it continuous production of innovative products which add value to the customer and the range of services.

Figure 6-1 illustrates a basic control system with the following elements; A) Tokens (cards and key-fobs), B) Reader, C) Control unit, D) Lock, E) Door, and F) Exit button. In this type of access control system, the identification is based on credentials instead of using mechanical keys. There is a wide range of credentials; the most typical are access cards and key-fobs.

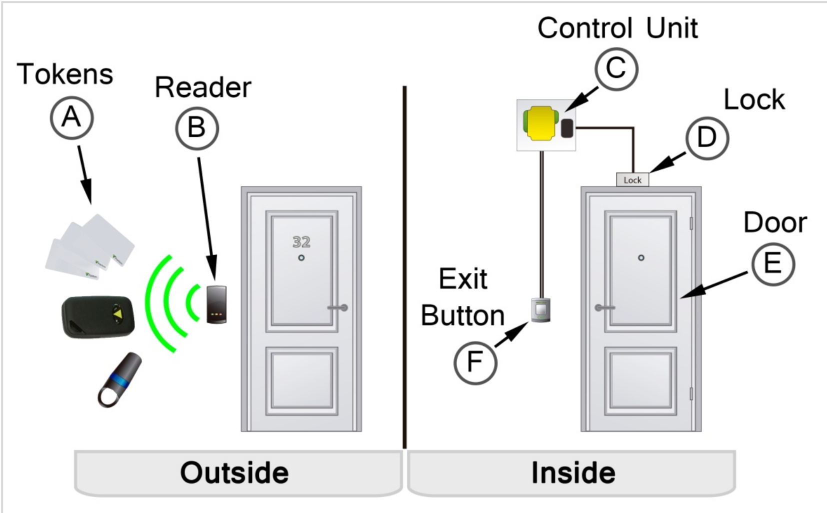


Figure 6-1 Access control system

When the token (A) is close, it can be perceived by the reader (B). The interaction between (A) and (B) relies on radio frequency: the token works as an inductor, modifying an electromagnetic field created by the reader. The signal perceived is sent to the control unit (C), where it is analysed in order to take access decisions. If the token is valid, the control unit will send an indication to the lock (D) in order to open the door (E). In case of using an exit button (F) the door is unlocked without requiring any credential.

The most important characteristic of the reader- which is the physical product that has been used to demonstrate the SBCE- is to be vandal resistant; which means, to be resistant to different types of damage; for instance, removal of the “reader” by hand, striking the “reader” with any object, burning the case with fire, and spoil with liquid, sand or stones. Other important features in this reader are the ability to capture a wide range of credentials and the ease of installation and maintenance. The following paragraphs present how the SBCE business case framework is demonstrated in the “vandal resistant reader” case study according to the SBCE process model.

6.2.2 Application of SBCE Business Case Framework in electronic access control

Phase 1: Driver

There was no formal champion was appointed as well as no team formation was established in conjunction with this case study. Even though this step is important to be followed, the company has no intention to appoint champion and form a team at this moment. This means some of activities in Phase 1 were not considered in this case which is Step 1.4 “Appoint Champion” and Step 1.5 “Team formation”.

Step 1.1: Understand current PD practice

The PD practice encountered in Paxton have been identified via a formal LeanPPD performance measurement study (Al-Ashaab et al., 2016). With the score achieved, the awareness of lean application and its benefits are acknowledged by the company. However, the practices only occurred at certain activities in their current PD yet it is not done comprehensively.

Step 1.2: Establish LeanPD milestone

The score of the performance measurement reveals that the AS-IS score is ‘2.63’ and desired aim TO-BE score ‘4.3’ as shows in Figure 6-2. Both scores were analysed and calculated individually using a mathematic average formula. In order to calculate the average score, scores of each perspective are summarised and the sum is then divided by the number of questions which describe in detail in formal LeanPPD performance measurement study (Al-Ashaab et al., 2016). However, to have the overall result, average score from each perspective are then multiplied by corresponding weightage. The TO-BE target score of ‘4.3’ shows the company’s willingness to improve themselves to formally implement the LeanPD in their product development process. It means that, the company shows an interest in the LeanPD initiative to be introduced to the company.

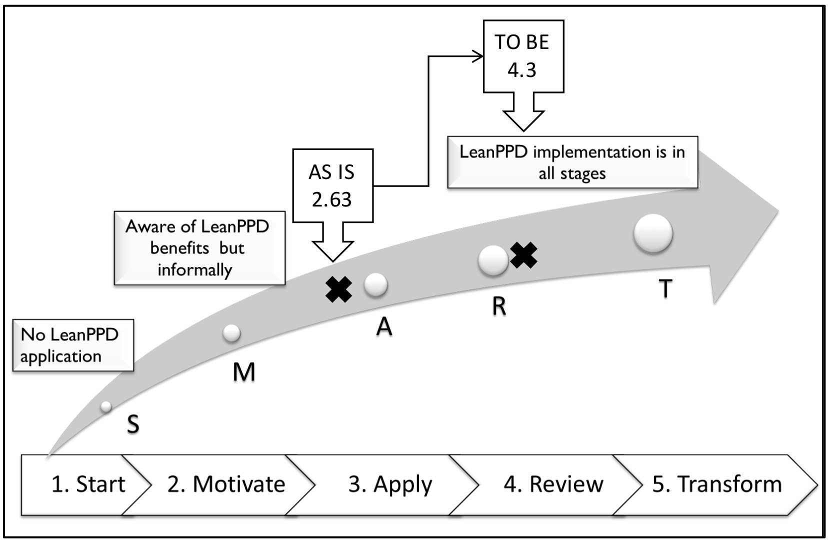


Figure 6-2 Overall Lean-PPD performance assessment result in Paxton

<u>Step 1.3: Identify current PD challenges</u>

The current PD challenges have been identified through a several meetings with the key person in the company. The PD challenges have been listed as follows:

1. There is a need to have a clear plan to improve the current PD process with emphasis on eliminating wasteful activities.
2. Providing bigger space for exploring design alternatives and innovation.
3. Improving the practices of different formal design tools and methods.
4. Providing the designers and engineers with the suitable knowledge environment to support decision making throughout the PD process.
5. Reuse of knowledge gained from previous projects

<u>Step 1.6: Create awareness to build the culture</u>

A short seminar was given to the senior management of Paxton prior the introduction of SBCE application to the organisation. This is in order smooth the buy-in process, gain their confidence and be supportive on the initiatives. Awareness training was performed correspond to the needs of understanding of how SBCE should be performed. Two days short course were held comprises LeanPD and SBCE subject. Two types of method were used for training delivery which is theoretical and hands-on using interactive method with real industrial case study. Participants in the awareness training includes management and technical level (e.g. Managers and Engineers) in the organisation.

Phase 2: Demonstrate

Step 2.1: Define pilot project

A pilot project has been selected to demonstrate the SBCE process to overcome the challenges mentioned in Step 1.2. Access Control is the selective restriction of access to a place or other resource. The product studied is commonly known as "Reader" and it is an important part of an electronic access control system. The task of the reader is to identify the different users trying to access the system and to send this information to another device which verifies if the users are allowed to have access. Since the pilot project is using real engineering data, all the sensitive information has been modified or eliminated.

Step 2.2: Define aim and objective of pilot project

In Step 2.2, there was a formal template to tabulate the aim and objective of the pilot project. The establishment of the template is crucial as it reflect to the nitty-gritty of the project. A table was created to include all the information such as project name, project aim, duration, and expected end date as shows in Table 6-2.

Table 6-2 Project definition matrix

No	Pilot Project Name	Aim	Objectives	Duration
1	Access Control "Reader"	The aim is to demonstrate the application and validation of the SBCE process	1. Develop optimal Reader design that could stand vandal resistant. 2. Identify the potential benefits from the application of SBCE in the pilot project	• 3 month (This include LeanPPD performance asessment, face-to-face interview, LeanPD short course, and pilot project)

Step 2.3: Explore customer requirement

Figure 6-3 illustrates the range of sub-activities that have been performed in order to obtain the Key Value Attributes (KVA). In order to understand Paxton's customer needs, the values of the customer are explored thoroughly in order to define system targets specifically related to the vandal resistance, which is the key value of the “Reader” case study. The values were extracted through face to face interviews and brainstorming sessions with designers and engineers as illustrated in Figure 6-3-A. Figure 6-3-B shows a list of the identified 26 values that have also been given a number. These values will be used to determine design criteria to support the evaluation of the alternative designs of the “Reader”. In order to ensure customer needs are addressed properly, values with similar objectives were classified into a singular value. For example, value numbers 4, 5, 25 and 26 in Figure 6-3-B are respectively; value number 4 “The product must be saved, and should not give access to people that do not have valid card”, value number 5 “the system should not be easily hacked to ensure safety”, “The product should be resistant to vandalism without affecting normal working” and “The product has to be vandal resistant without paying attention to the appearance”. These four (4, 5, 25 and 26) values have been classified as “Security and Protection” as shown in Figure 6-3-C. Similarly, the rest of the values have been also classified as shown in Figure 6-3-C namely; safety, security and protection, reliability, cost, connection, user friendly and product size. These are the high importance values as they address the aim of the “reader” project, which is vandal resistance, ability to capture a wide range of credentials, and ease of installation and maintenance. Other values were considered to have low importance due to several reasons, for instance, there was no need of improvement; they already had to follow specific regulations, or their aim could be achieved as a consequence of improving any of the most important values.

The values that have been classified as high importance were analysed through the Analytical Hierarchy Process (AHP) (Bhushan and Rai, 2007; Schuh and Drescher, 2014), where the result is illustrated in Figure 6-3-D. The AHP matrix helps to calculate the loads of importance of each of the categories compared (Henry and Kato, 2011). Based on the loads of importance rank in AHP and company prioritisation, the customer value attribute has been listed accordingly as follows; 1) Security and protection, 2) Reliability, 3) Cost, 4) Connection, 5) User friendly, and 6) Product size; as depicted in Figure 6-3-D. Since safety is compulsory for the product, the safety value was evicted from the analysis and became a denominator factor. The results of the AHP helped to identify the key value attributes as illustrated in Figure 6-3-E these are; 1) Security and protection, 2) Cost, 3) Reliability. The loads for the key value attributes in Figure 6-3-E are calculated respectively by AHP value in Figure 6-3-D. The calculations are as follows:

- Security and protection: (0.38 / 0.77) x 100 % = 49 % (approx.)
- Reliability: (0.27 / 0.77) x 100% = 35% (approx.)
- Cost: (0.12 / 0.77) x 100% = 16% (approx.)

The down-selection of the values was done with the aim of having a feasible number of values to improve; thus, preventing non-fulfilment of the expectations as a consequence of paying attention to a large number of criteria. Nevertheless, the values remaining (connection, user friendly and product size) were designated as values of consideration and despite the fact that the values are not the key values, it still could satisfy the aim of the “Reader” project.

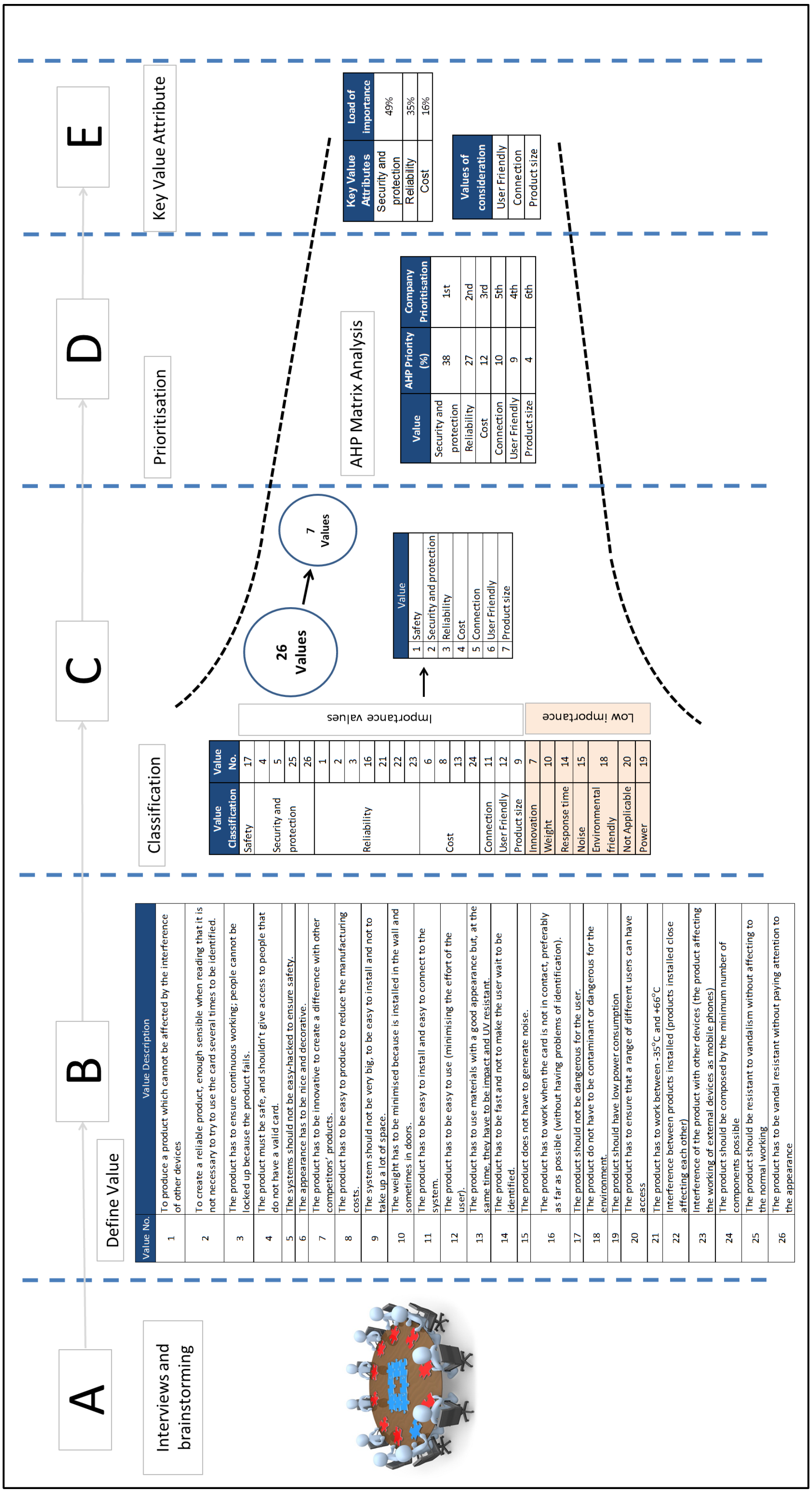


Figure 6-3 The process of identifying Key Value Attributes (KVA)

Next, the system targets should be defined in order to clarify how the value attributes will be achieved. These targets should be reviewed at the subsystem level in order to ensure the correct flow down on system targets. System targets are measurable/numeric values of key value attributes; however, several targets may occur that cannot be represented by a numerical value. For instance, the value for security and protection, the system target for the reader are defined as follows: 1) The reader must be damage resistant which can withstand a hit-force of up to 4500 Newton; 2) The reader shall comply the V-0 fire resistant standard rating, which can withstand the flaming combustion for more than 10 second or the total flaming combustion time shall not exceed 50 second for 10 time repetitive flame application; 3) The reader must be well protected in term of accessibility; 4)The reader must survive the IK9 resistance index for impact which equal to 5 kilogram mass impact; 5) The reader must survive the IPX6 rating index protection against intrusion of dust or liquid which is equal to 100 litres per minutes spray of water at any direction for at least 3 minutes. The same approach has been used for the other value in defining the system target as depicted in Table 6-3.

Table 6-3 System target of the KVA of the “reader” case study

No	KVA	System targets
1	Security and protection	1. The reader must be damage resistant (approx. 4500N). 2. The reader must ensure V-0 (flammability standard). 3. The reader internal system must be well protected (in terms of accessibility). 4. The reader must ensure IK9 rating (impact protection). 5. The reader must ensure IPX6 rating (ingress protection).
2	Reliability	1. 250,000 activations during the product life (5 years). 2. No more than 5 fail per hour. 3. Minimise the interferences. 4. The reader must work between -40ºCelcius and +80ºCelcius 5. Minimum operational distance of 1 cm 6. Maximum operational distance of 5 cm
3	Cost	1. The reader price must not exceed £x (value not given). 2. To re-use 80% from the existing reader.

Step 2.4: Define scope of design work

The scope of the design work as well as feasible regions for the "Reader" design was defined in this step. In order to perform Step 2.4, the "Reader" structure is needed and is as follow as shown in Figure 6-4; Front cover (1), the "Reader" module (2) - which separate into two sub-component; Housing front cover (2.a), Housing back plate (2.b), Coil (3), Main PCB (4), Exciter (5), Power connection (6), and Back plate (7).

The level of innovation is a colour-coded tool that is used to communicate simply the level of innovation required for different subsystems/components of a product as illustrated in Figure 6-4. The colour has been coded in "Grey" (Level 1) which represents no change will be made to the product; "Green" (Level 2) which represents a low innovation; "Yellow" (Level 3) which represents medium innovation; "Red" (Level 4) which represents high innovation; and "Black" (Level 5) represents a need for research and development. For instance, the "Red" colour code shows a high innovation where it requires a new technology or new design concept to be implemented in the product. The level of innovation for the front cover (1) has been classified with a red colour code (Level 4). The front cover (1) will be the first component to receive any force that might damage the "Reader"; therefore, it needs a new design concept that can be resistant to any type of damage. The back plate (7) has been classified as a medium innovation, coded by the colour yellow (Level 3). Since the back plate is attached to the wall and front cover (1), it might also be affected by the vandalism act, thus, the back plate needs a medium level of design changes to enhance its physical performance to withstand forces that may possibly damage the "Reader". Other components such as the Reader module (2), Housing front cover (2.a), Housing back plate (2.b), Coil (3), Main PCB (4), Exciter (5), and Power connection (6) are coded with a "Grey" colour which is to say no change has to be made; the designs remain as they do not impact in the level of protection for the "Reader" against vandalism.

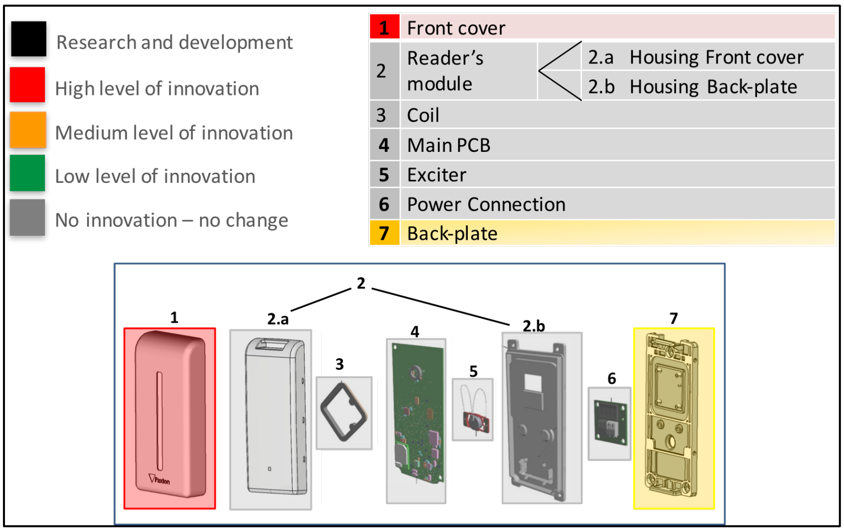


Figure 6-4 Level of innovation of the Reader

The feasible target for each component also been defined to prevent over-engineering while encouraging the necessary innovation and improvement. Some of the targets were adapted from the system target as shows in Table 6-3, others were defined as a new target in order to ensure it meets the key value attributes; security and protection, reliability, and cost. The component targets for the front cover (1) are listed as follows;

- No sharp edges, must be damage resistant, which can withstand the hit force up to 4500 Newton,
- Must withstand the V-0 fire-resistance rating,
- Must be UV resistant, must be survive in the IK9 resistance index for impact which equal to 5-kilogram mass impact,
- Must be survive in the IPX6 rating index protection against intrusion of dust or liquid,
- Must let the Radio Frequency signal and the Infra-red to go through and must be able to cover and protect the same electronic subsystem as used in the standard "Reader".

Similarly, the rest of the component targets are listed accordingly as illustrated in Table 6-4.

Table 6-4 Component target for the Reader

Component	Target
1 Front cover	1.1 No sharp edges. 1.2 Front cover must be damage resistant (approx. 4500N). 1.3 Front cover must ensure V-0 (flammability standard). 1.4 Front cover must be UV resistant. 1.5 Front cover must ensure IK9 rating (impact protection). 1.6 Front cover must ensure IPX6 rating (ingress protection). 1.7 Front cover must let the RF signal and the IR go through. 1.8 Front cover has to cover and protect the same electronic components as used in the standard reader.
2 Reader's module	2.1 No sharp edges. 2.2 Reader's module must ensure IK9 rating (impact protection). 2.3 Reader's module must ensure IPX6 rating (ingress protection). 2.4 Reader's housing must let the RF signal go through. 2.5 Reader must work between -40^{o}C and +80^{o}C. 2.6 Reader's housing has to contain the same electronic components as used in the standard reader.
3 Coil	3.1 Eliminate the possibilities of electrical discharge. 3.2 Minimise the interferences.
7 Back-plate	7.1 No sharp edges 7.2 Back-plate must be damage resistant (4500N). 7.3 Back-plate must ensure V-0 (flammability standard).

Moreover, the design space is a boundary for designers and engineers to explore and communicate with many alternative conceptual design solutions which are done as well in the Step 2.4. Figure 6-5 illustrates the overall design space for the "Reader" case study as well as its components that have a level of innovation; namely front cover (1) and back plate (7). The following are the "Reader" boundaries: -

General boundaries:

1. Size; maximum height is 160mm and maximum width is 90mm,
2. Use of rounded edges,

3. Allows Radio Frequency (RF) and Infra-red (IR) transmittance, therefore the new design must allow RF and IR signal receiving. This is particularly related to the “front cover” design as excessive thickness or the use of certain materials may significantly affect RF and IR signal receiving.

Subsystem boundaries for front cover (1):

1. Minimum height is 100mm and the minimum width is 50mm.These have been identified in order to create an appropriate space for the other subsystems with no modification to fit together with the “front cover” designs.

It is important not to impose too many constraints on the design space, as this may limit innovation of the product.

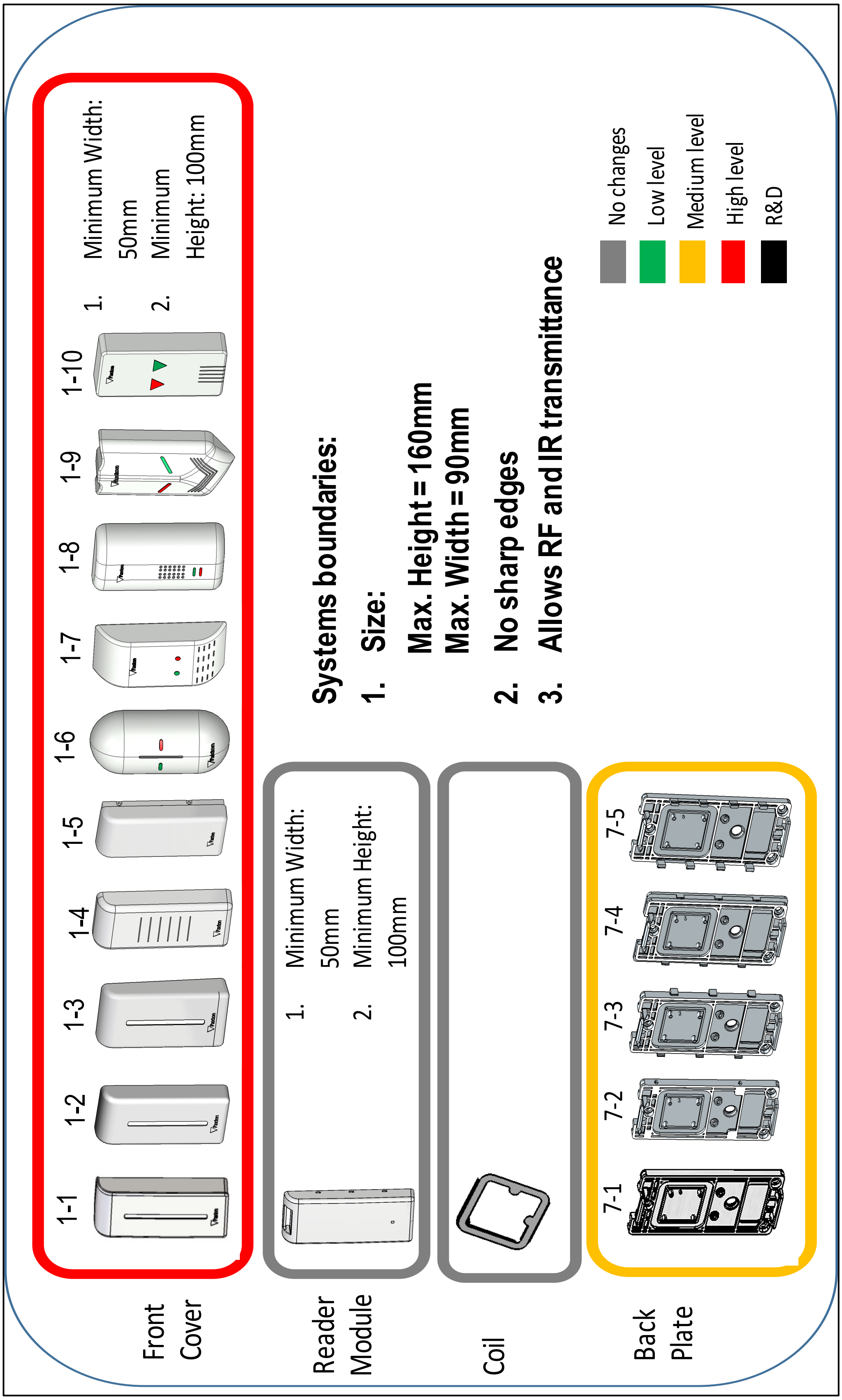


Figure 6-5 System and component boundaries for the Reader

Phase 3: Evaluate

Step 3.1: Generate multiple alternative solution

In this phase, the set of possible conceptual design solutions was developed for each component of the “Reader”. The aim in Step 3.1 is to propose alternative design solutions. The possible design solutions are developed specifically for the front cover (1) and back plate (7). The following paragraph explains how the front cover (1) is designed and proposes as a possible conceptual design solution as illustrated in Figure 6-6. At first, the component target is taken into consideration while generating the new alternative designs as illustrated in Figure 6-6-A. Furthermore, the defined boundary in activity 2.3 “Define feasible region of design space” should also be considered in order to guide the “Reader” design process as illustrated in Figure 6-6-B. The new alternative designs of the front cover are going to have features that address the identified key value attributes and the target shown in Figure 6-6-A. These features are: 1) Rounded edges, 2) Simple case, 3) Retain element, 4) Standard fitting, 5) Impact resistant materials, 6) Flame retardant material, and 7) Not vertical surface as illustrated in Figure 6-6-C. A set of ten front design concepts has been generated and shown in Figure 6-6-D.

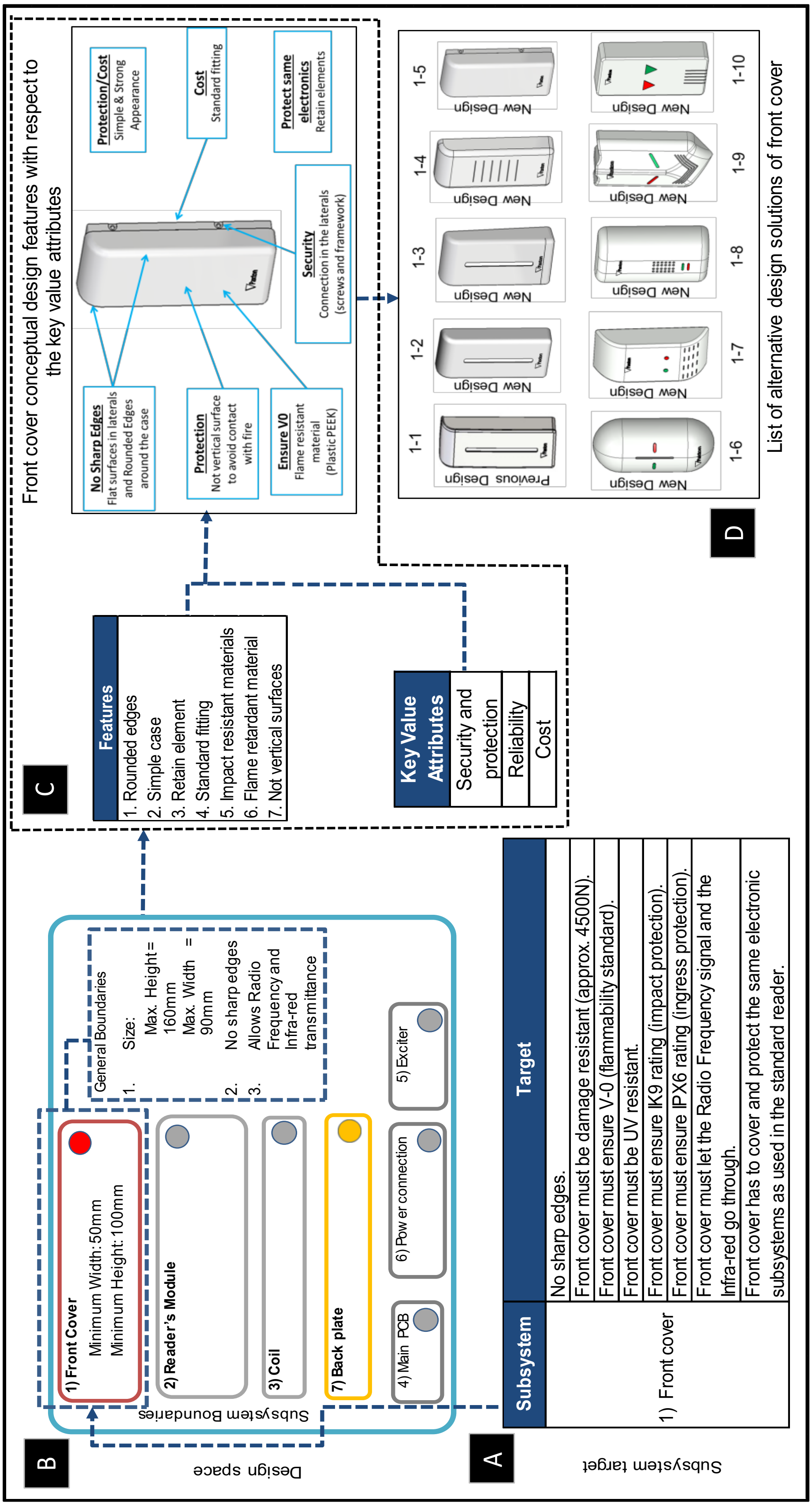


Figure 6-6 The conceptual design features for the Reader

For the back plate (7), 5 different concepts were created, including one from a previous design using the same approach for the front cover (1). Figure 6-7 illustrates the sets of conceptual design solutions for the back plate. The rest of the reader's components shown in Figure 6-5 keep the same previous design without any change. Therefore, the design space of the reader could generate 50 potential solutions (refer to Figure 6-8). This is calculated as follows;

10 (front cover) x 1 (reader's module) x 1 (coil) x 1 (main PCB) x 1 (exciter) x 1 (power connection) x 5 (back plate) = 50.

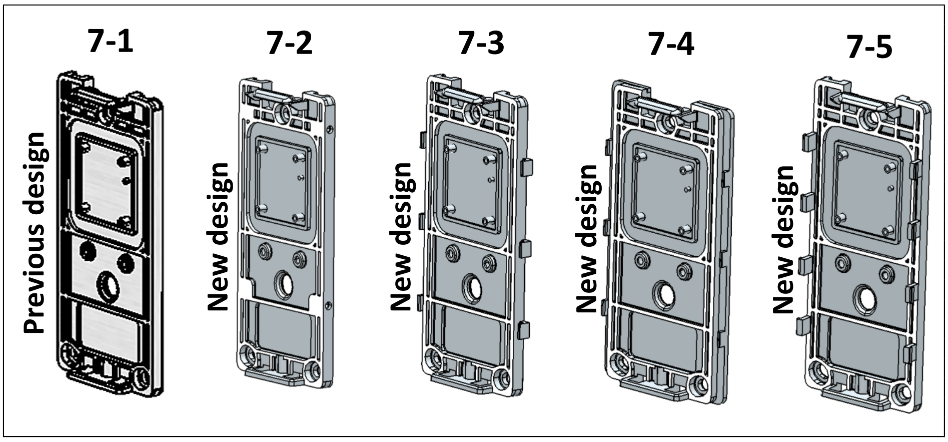


Figure 6-7 Sets of conceptual design solutions of the back plate component

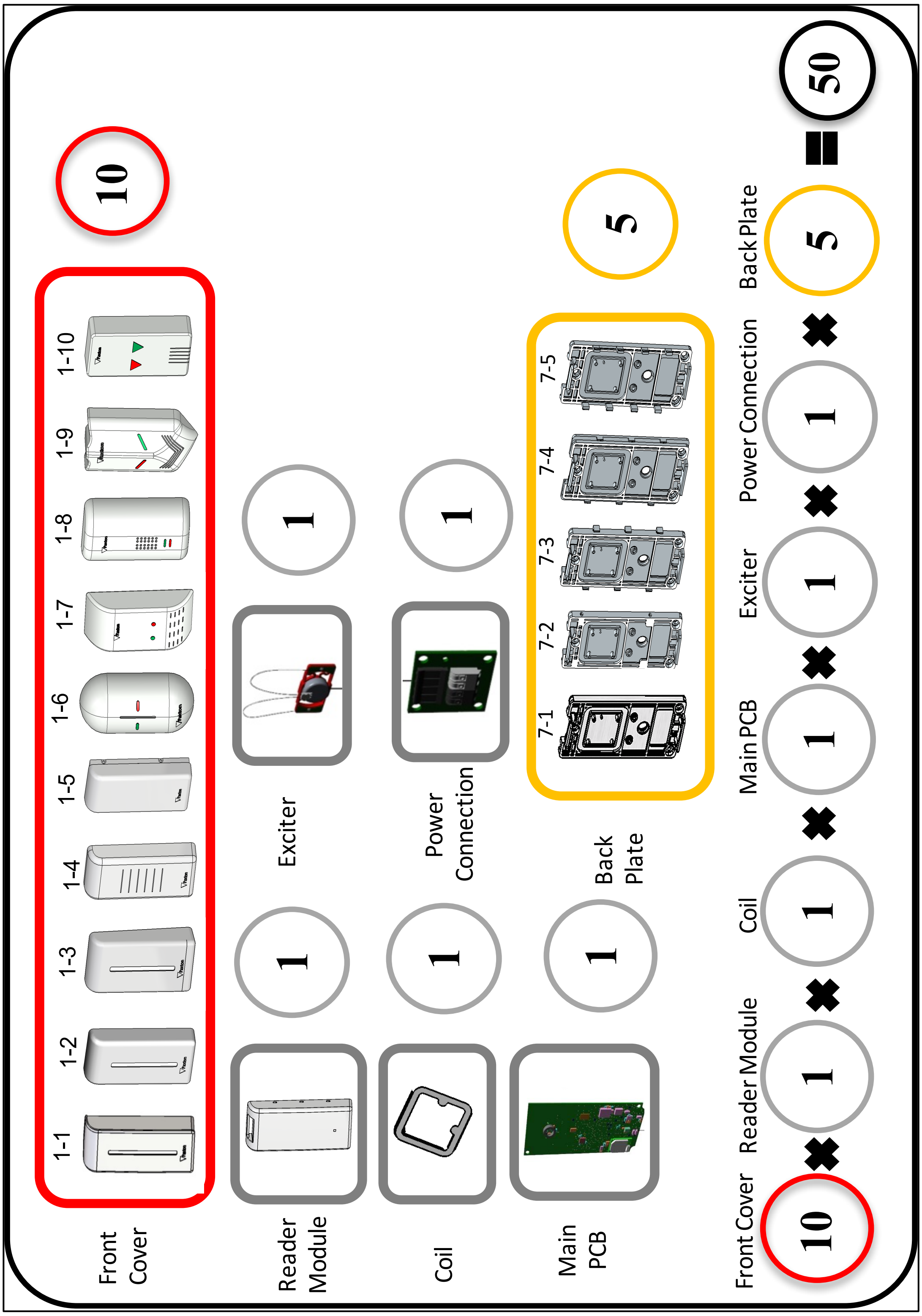


Figure 6-8 Possible design solutions for the Reader

Step 3.2: Analyse, evaluate, and narrowing the solutions

At first, Step 3.2 will analyse the conceptual solutions in order to evaluate their reliability. This analysis has been focused on the structural and thermal properties which fit the aim of the "Reader" case study. This is done for the front cover and back plate components as they are the only parts that have a level of innovation (see Figure 6-5). Figure 6-9 illustrates an example of structural analysis and thermal analysis for the front cover for design option 1-9 as shown in Figure 6-6-D, which shows a weak area to the right of the centre. Therefore, modifications are needed in this design option, as otherwise it is considered a weak solution.

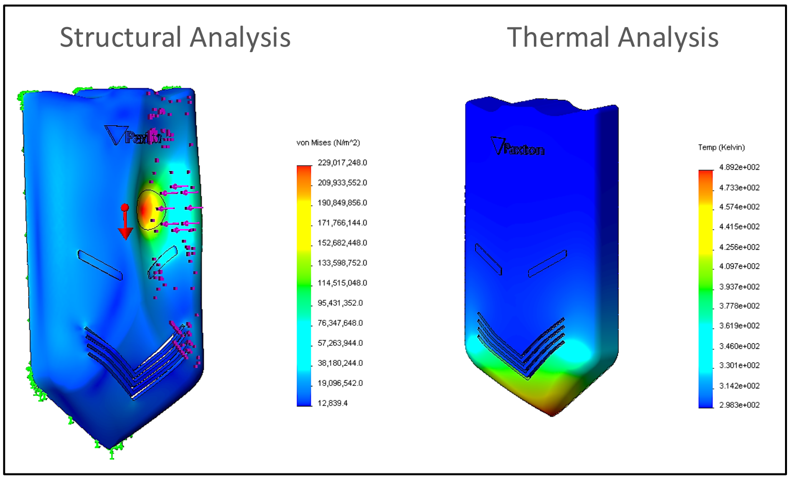
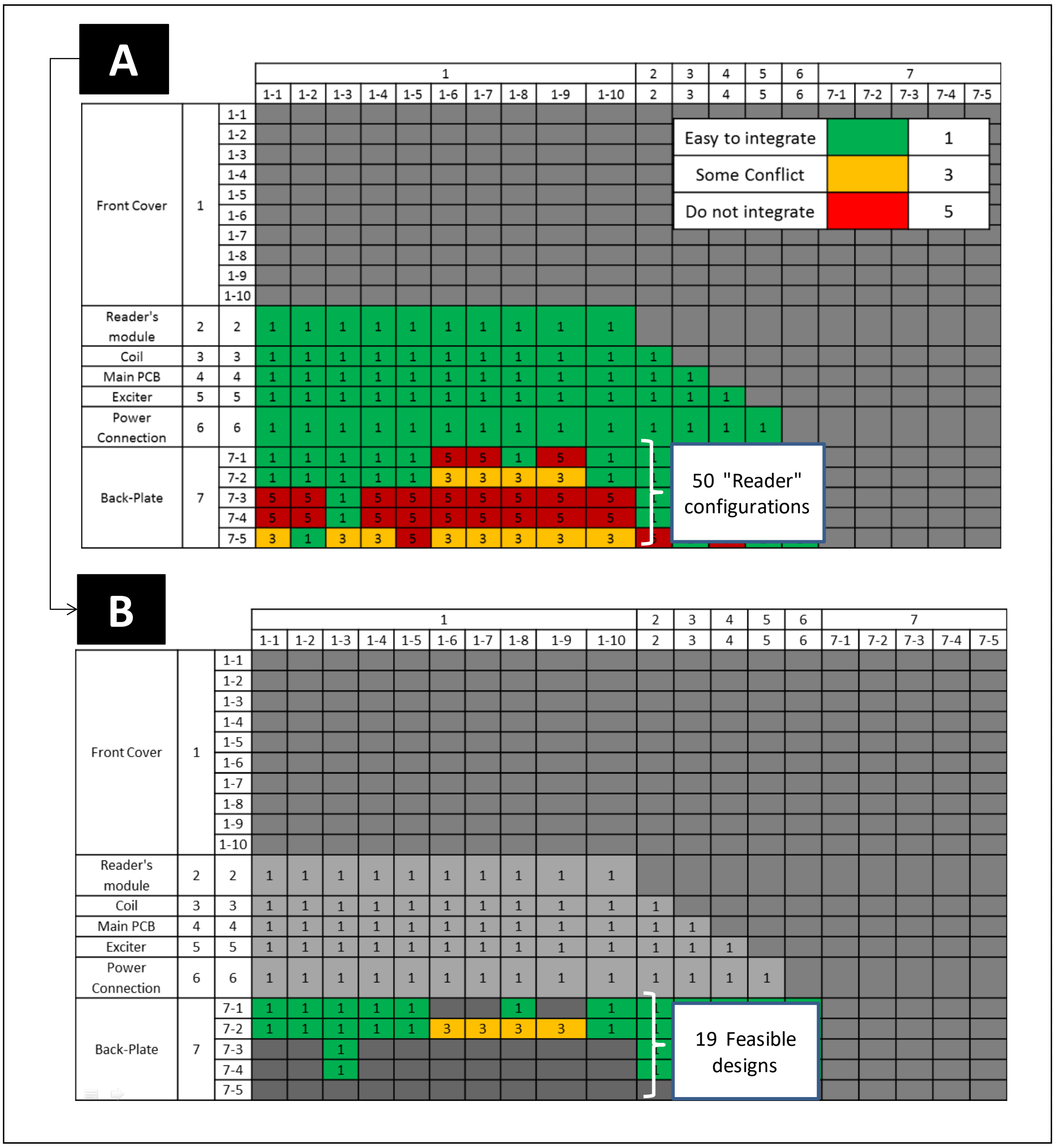


Figure 6-9 Examples of structural and thermal analysis for front cover (1-9)

Secondly, an integration of the subsystems was explored based on the knowledge produced. Any weaker alternatives were discarded so that the final optimal "Reader" design could be allowed to progress until the design stage could be completed. From the 50 potential solutions, not all are compatible to become a "Reader". Therefore, an intersection matrix was used to analyse the feasibility of the "Reader" configurations (illustrated in Table 6-5). The intersection matrix has as many columns as rows; each of them represents a subsystem of the "Reader": 1) Front cover which has 10 alternative solutions, 2) Reader's module 3) Coil, 4) Main PCB, 5) Exciter, 6) Power connection, and 7) Back plate which has 5 alternative solutions (see Figure 6-8). The intersection matrix evaluates the combination between the elements in the columns and the elements in the rows according to the scores which are as follows; 1: Options that can be integrated without any modification, 3: Options that need modification to be integrated but provide potential benefits, and 5: Options that cannot be integrated because they need a high level of modification. Combinations that require a high level of modification or components that create conflicts with other subsystems that could not be changed, will be discarded from the alternative list. This is done via brainstorming sessions between designers and engineers. For instance, the back plate (7-5) had conflicts of assembly and integration with the reader's module (2) and the Main PCB (4). The same evaluations have been made for the other sets which have scored a 5 as illustrated in Table 6-5-A. Since there is no modification required for the Reader module, Coil, Main PCB, Exciter, and Power connection, the sets are kept progressing into detailed designs as shown in Table 6-5-B. In addition, during brainstorming sessions, decisions have been made to further progress the detail for design solutions 7-2 (of the back plate) as it requires small modifications. From the intersection matrix, the reader's configurations were reduced from 50 to 19 feasible configurations as shown in Table 6-5-B.

Table 6-5 The intersection matrix of the alternative design solutions of the Reader components



A

			1										2	3	4	5	6	7				
			1-1	1-2	1-3	1-4	1-5	1-6	1-7	1-8	1-9	1-10	2	3	4	5	6	7-1	7-2	7-3	7-4	7-5
Front Cover	1	1-1																				
		1-2																				
		1-3																				
		1-4																				
		1-5																				
		1-6																				
		1-7																				
		1-8																				
		1-9																				
		1-10																				
Reader's module	2	2	1	1	1	1	1	1	1	1	1	1										
Coil	3	3	1	1	1	1	1	1	1	1	1	1	1									
Main PCB	4	4	1	1	1	1	1	1	1	1	1	1	1	1								
Exciter	5	5	1	1	1	1	1	1	1	1	1	1	1	1	1							
Power Connection	6	6	1	1	1	1	1	1	1	1	1	1	1	1	1	1						
Back-Plate	7	7-1	1	1	1	1	1	5	5	1	5	1	1									
		7-2	1	1	1	1	1	3	3	3	3	1	1									
		7-3	5	5	1	5	5	5	5	5	5	5	1									
		7-4	5	5	1	5	5	5	5	5	5	5	1									
		7-5	3	1	3	3	5	3	3	3	3	3	5									

B

			1										2	3	4	5	6	7				
			1-1	1-2	1-3	1-4	1-5	1-6	1-7	1-8	1-9	1-10	2	3	4	5	6	7-1	7-2	7-3	7-4	7-5
Front Cover	1	1-1																				
		1-2																				
		1-3																				
		1-4																				
		1-5																				
		1-6																				
		1-7																				
		1-8																				
		1-9																				
		1-10																				
Reader's module	2	2	1	1	1	1	1	1	1	1	1	1										
Coil	3	3	1	1	1	1	1	1	1	1	1	1	1									
Main PCB	4	4	1	1	1	1	1	1	1	1	1	1	1	1								
Exciter	5	5	1	1	1	1	1	1	1	1	1	1	1	1	1							
Power Connection	6	6	1	1	1	1	1	1	1	1	1	1	1	1	1	1						
Back-Plate	7	7-1	1	1	1	1	1			1		1	1									
		7-2	1	1	1	1	1	3	3	3	3	1	1									
		7-3			1								1									
		7-4			1								1									
		7-5																				

Step 3.3: Select the optimum solution

In Step 3.3, an aggressive narrowing process has been carried out to reduce the feasible “Reader” configurations from 19 to 6 solutions. Based on brainstorming sessions within the design team, several criteria which associated to the key value attributes of the “Reader” have been selected and evaluated as shown in Table 6-6. For example, the combination of front cover (1-1) and back plate (7-1) could give significant cost effective since it comes from previous design. There is no issue with the manufacturability since it used an existing mould where no modification is required. The complexity of the assembly is also minimal due to its simple snap-fit assembly technique. However, the design is not capable to withstand the fire burn due to its material. It is also could not be able to survive any high impact forces due to its snap-fit assembly technique. Even though cost and complexity criteria are meeting the target, the security and protection, and reliability are failing to meet the aim of the vandal resistant “Reader”. Hence, the combination was discarded from the list of alternatives. Similarly, the rest of the combinations have been evaluated which then helped to narrow down the solution as shown in Table 6-6 and Figure 6-10-A.

Table 6-6 A portion of the evaluation of the 19 alternatives potential “Reader” system solutions. Narrowing down from 19 system solutions to 6

Combination		Evaluation Criteria				
Front Cover	Back Plate	Cost	Complexity		Security	Decision
			Manufacturability	Assembly		
1-1	7-1	No modification in moulds	Plastic, no modification required and existing moulds	Simple assembly (Snap-fit)	1. Not fire resistant because of the material. 2. Possible weaknesses by pulling from the laterals due to fitting. 3. Design is easy to hold thus it is subject to pulling.	<u>Discarded</u> Cost effective but there is no improvement in fire resistance
1-1	7-2	Modification in moulds to add screws (addition of slider)	Plastic, modifications in mould required (using the same mould but adding slides)	Simple assembly (Screws)	1. Not fire resistant because of the material. 2. Improved fitting in laterals (screws difficult to hide) 3. Design is easy to hold thus it is susceptible to pulling.	<u>Discarded</u> Modifications required are expensive for the benefits obtained
1-2	7-1	Simple case Mould easy to manufacture but should be created from scratch	Plastic, mould required. Uniform thickness	Simple assembly (Snap-fit)	1. Possible weaknesses by pulling from the laterals due to fitting. 2. Structural analysis simulated large displacements (specifically in the central hole)	<u>Discarded</u> Required a new mould, but security is not ensured due to reuse of the back plate 7-1. Additionally, the concept is weak against impacts.
1-5	7-2	Difficult medium mould; should use a slider and should be created from scratch	Plastic, mould required. Uniform thickness.	Simple assembly (Screws)	1. Structural analysis simulated only small displacements occurred (thinner area in centre) 2. Need of framework to make the part easy to manufacture	<u>Kept</u> Option to consider

In order to define the optimal solution of the “Reader”, the PUGH matrix (Pugh, 1991) was used to evaluate the six selected alternative system solutions in order to reach the final optimal solution of the “Reader” system as shown in Figure 6-10-A. The performance scale from 7 to -7 was used to indicate the score. The score is arranged in the odd number order where a value of 7 as the highest score represents that the target is met, zero represents no changes being made, -7 represents completely negative impact, and other scores are arranged in between as illustrated in Figure 6-10-B. The different criteria can be weighed according to their importance as shown in Figure 6-3-E and Figure 6-10-C. Thereafter, each of the potential options are scored and also multiplied by their weighting in order to produce a result. For instance, the “Reader” system concept 3 which is based on the configuration of front cover (1-5) and back plate (7-2) has been evaluated as follows:

- “Safety and protection” is scored as 5, which means big design improvements were made for the front cover.
- “Reliability” is scored 0, no change is required in terms of the ability of the “reader” to transmit the radio frequency and infra-red signal.
- “Cost” is scored as 3, which provides a moderate improvement in the cost reduction.

Therefore, the PUGH matrix result in this system configuration is calculated as follows:

- (49% x 5) + (35% x 0) + (16% x 3) = 2.93.

Similarly, the rest was analysed and calculated accordingly as depicted in Figure 6-10-C. The solution with the highest score was recommended to become a preferred solution. As a result, the optimal solution of the “Reader” system is concept 3 (see Figure 6-10-D) which is going to be released to the final specification in the detailed design on phase 5 in the SBCE process model.

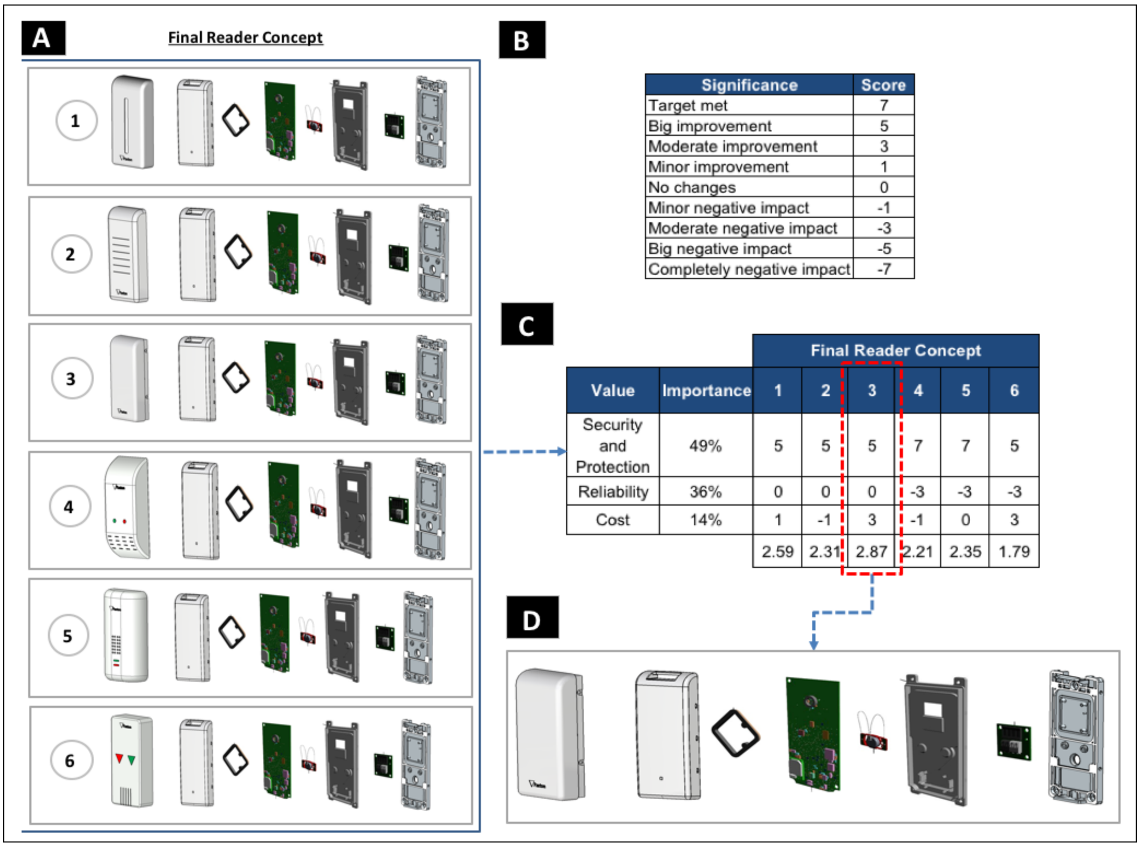


Figure 6-10 Selection of optimal solution for the “Reader”

Phase 4: Justify

<u>Step 4.1: Identify tangible benefits from pilot project</u>

The SBCE approach provided a suitable knowledge environment to support decision making throughout the development process. The innovation and knowledge creation level has increased where 50 system design configurations were identified via the application of the SBCE process model in the case study.

Secondly, product performance has improved through an implementation of the SBCE. The analysis of the safety and protection are focused on impact and fire resistance. These could be analysed quickly through a simulation of von Mises stress (structural analysis) and thermal analysis in Solidwork software. The result of the analysis is depicted in Figure 6-11.

Design-Set	Front Cover Thickness [mm]	Depth [mm]	von Mises Stress Level [Nm^{-2}] x 10^8	Highest Temp. Level [°C]	Deformation Scale
1-2	2	20	4.6	502	0.72
1-3	2	25	7.06	352.05	12.95
1-4	2	20	5.34	563.05	1
1-5	4	25	2.72	604.05	2.29
1-6	2	30	11.10	29.65	42.97
1-7	2	25	6.10	-9.95	31.13
1-8	2	30	4.72	128.95	49.71
1-9	3	30	3.62	216.05	4.9
1-10	2	25	5.37	114.25	25.92

Figure 6-11 Simulation result for front cover designs

In order to show the tangible benefits in product performance, improvement percentage calculation was used. This calculation could be explained as a positive change of number ratio expressed by a percentage.

Improvements were achieved in safety and protection (Stress) for the “Reader” by 39.5% from the previous “Reader” where the calculation of improvement percentage are as follows:

$$\frac{4.5 \times 10^8\,Nm^{-2}\text{ (Front Cover 1-1)} - 2.72 \times 10^8\,Nm^{-2}\text{ (Front Cover 1-5)}}{4.5 \times 10^8\,Nm^{-2}}$$

$$= 0.395 \times 100\%$$

$$= 39.5\%$$

The analysis of the stress was originated from the equation of von Mises Stress which connected using distortion energy failure theory (Segalman *et al.*, 2000). Fire resistance also has been improved by 163% compared to the previous design (Front Cover 1-1); the calculation as follows:

$$\frac{604.05^{\circ}C\text{ (Front Cover 1-5)} - 230^{\circ}C\text{ (Front Cover 1-1)}}{230^{\circ}C}$$

$$= 1.63 \times 100$$

$$= 163\%$$

These improvements have been gained through an analysis using Solidwork software for the front cover of the “Reader”. The comparison of the result is between the component target and final solution. The input parameters prior to the analysis are shown in Table 6-7.

Table 6-7 Data input for structural and thermal simulations

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

The cost is expected to be reduced up to 43% for the "Reader" product with configuration of front cover 1-5 and back plate 7-2 shown in Figure 6-10-D. Due to confidentiality the data for cost are shown in percentage values.

The probability of having a successful project also was increased by implementing the SBCE in the product development. The test is to show how SBCE was able to eliminate the rework activities in product development by having the highest rate of successful designs and least percentage of failure risk. As explained in sub-chapter 5.4.2, Ward and K. Sobek II (2014) described three rules employed in the probability test to identify the risk. In the probability test, the comparison was made between 6 final possible solutions obtained from using the SBCE approach and one solution in traditional point-based design approach. The possible solutions were taken from the step 3.3 "Select the optimum solution" as each of the subsystems at this stage has a potential to integrate with each other. Meanwhile, the one solution is taken from the current practice of product development in the company.

Due to confidentiality, the probability value of the component will be expected to cause a major problem is taken from average fraction values of the number of components represents in the "Reader". It means that 14.3% of each of the components might have a potential of having a problem while another 85.7% have the probability of success as depicted in Table 6-8.

Table 6-8 Probability of failure and success for subsystem

Component	Probability of Failure (P_f)	Probability of Success (P_s)
Front cover	0.143	0.857
Reader Module	0.143	0.857
Coil	0.143	0.857
Main PCB	0.143	0.857
Exciter	0.143	0.857
Power connection	0.143	0.857
Back plate	0.143	0.857

Therefore, the author applied the probability rules equation (see sub-chapter 5.4.2) as follows;

Firstly, from Table 6-8, the probability of considering 3 design concepts calculated as follows;

<u>Rule 1 and Rule 2</u>

The probability of failure from 3 design concepts is;

$$\mathrm{POF_n} = \mathrm{P_f}^{\mathrm{n}}$$

$$= 0.143^6$$

$$= 0.0000086$$

$$\approx 0\%$$

The probability that all subsystems will have at least one successful design;

$$\mathrm{POS} = (1 - \mathrm{POF_n})^{\mathrm{m}}$$

$$= (1 - 0)^7 \approx 1$$

$$\approx 100\% \text{ succesful rate}$$

Rule 3

The average number of successful designs;

$$\bar{x} = n\ (P_s)$$

$$= 6\ (0.857)$$

$$\approx 5.14 \text{ sucessful design}$$

Secondly, from Table 6-8, the probability of considering only 1 design concept calculated as follows;

Rule 1 and Rule 2

The probability of failure for 1 design concept is;

$$POF_n = P_f^{\ n}$$

$$= 0.143^1$$

$$= 0.25$$

$$= 14.3\%$$

The probability that all subsystems will have at least one successful design;

$$POS = (1 - POF_n)^m$$

$$= (1 - 0.143)^7$$

$$= 0.34$$

$$= 34\% \text{ succesful rate}$$

Rule 3

The average number of successful designs;

$$\bar{x} = n\,(P_s)$$

$$= 1\,(0.857)$$

$$= 0.857 \text{ sucessful design}$$

From the probability tests, the success rate has increased from 31.6% to approximately 100%. This result shows how SBCE approach is much more reliable compared to point-based approach. In addition, the risk of having a design failure also have been reduced from only average 0.857 successful designs (not even 1) to average 5.14 successful designs after SBCE application. As summarised, the research proves that the SBCE has the potential to produce high quality products on time, low risk and in a cost-effective manner.

Step 4.2: Document and present the business case to management

The map of the business case is presented in step 4.2. This step will explain the summary of the business case activity by providing the outcome in short presentable information. The information should contain the tangible benefits gain from the application of the SBCE. This information should not include any formula or calculation. Instead, keep the backup files containing the details in case of someone from the stakeholder need that information for clarification. In this research, a PowerPoint slide has been created to show the value of SBCE application, however the details of the slides are not presented in this thesis except the summary of the benefits as shows in Figure 6-12. In addition, the steps of the slides are the same as explained in the previous chapter.

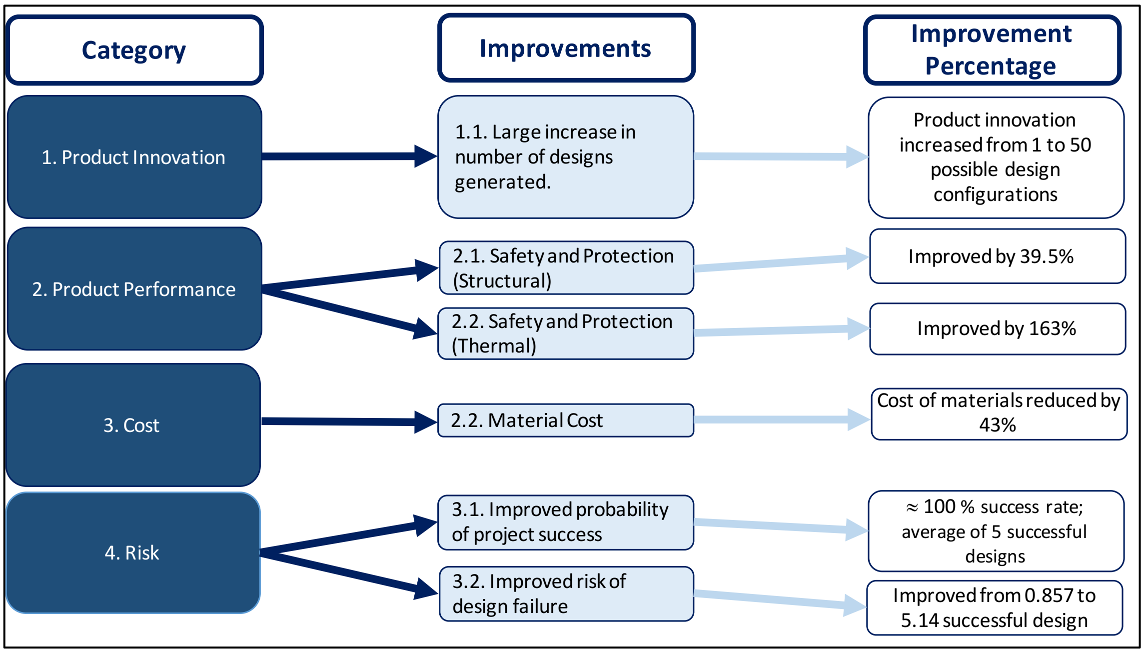


Figure 6-12 Example of the slides; mapping the tangible benefits of SBCE

6.3 Caltec case study

6.3.1 Overview

The SBCE process model was implemented during the case study of SJP in collaboration with Caltec Limited. The aim of the case study is to present a novel application of the SBCE in order to generate a new design to enhance the efficiency of the Surface Jet Pump (SJP) in term of its productivity and performance of producing the oil and gas in oil and gas well. The main feature of SJP is to enhance performance of gas extraction what could be understood as an increase of pressure at the output or High Pressure (HP) source, the reduction in pressure on Low Pressure (LP) source by maintaining output parameters. In literature, SJP is also known as Ejectors, Educators, Venturi Pumps and Jet Compressors. Figure 6-13 shows standard SJP with the following elements:

A. HP inlet

B. LP inlet

C. Nozzle

D. Mixing tube

E. Diffuser

F. Discharge - outlet

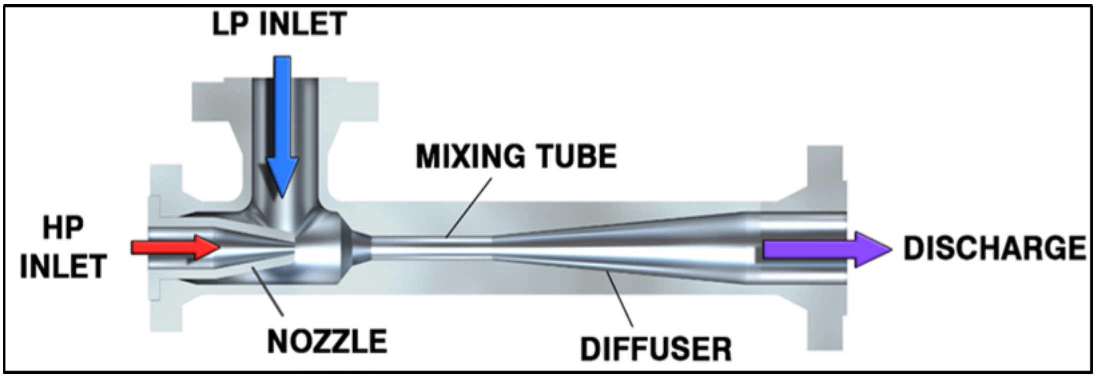


Figure 6-13 Caltec Surface Jet Pump (Beg and Sarshar, 2009)

The velocity of the flow is boosted significantly when HP pressure fluid (A) passes through the nozzle (C). The high momentum and energy of the motive flow (A) carries the LP flow (B) through a mixing tube (D) where the HP and LP fluid streams are mixed with each other. As the flow passes through the nozzle (C), conversion of potential energy (pressure) to kinetic energy (velocity) is occurring. Later, the mixture passes through the diffuser (E) where the velocity is progressively decreased, and further pressure recovery occurs. The pressure of the mixture at the outlet (F) of the SJP is at an intermediate level between the HP and LP pressures as well as the velocity to meet the downstream process conditions (Beg and Sarshar, 2009). The next paragraphs explain the application of the SBCE business case framework in the Caltec case study.

6.3.2 Application of SBCE Business Case Framework in surface jet pump

Phase 1: Driver

There was no formal LeanPD assessment has been performed in conjunction with this case study. Even though this step is important to be followed, the company's intention is focusing only on the application of the SBCE. The decision was made after a series of meeting with the Director of the company. This meant some of activities in Phase 1 were not considered in this case. However, awareness training on the SBCE application were provided in order to embrace and build the culture, hence only Step 1.6 were implemented in Phase 1.

<u>Step 1.6: Create awareness to build culture</u>

A short seminar was given to the senior management of Caltec prior the introduction of SBCE application to the organisation. This is in order smooth the buy-in process, gain their confidence and be supportive on the initiatives. Furthermore, awareness training has been conducted in order to provide the knowledge of SBCE and its application before case study commencement. Awareness training is purposely to provide an essence of the SBCE into the organisation. A short course training was delivered involving top management and engineers of the company. The subject covered the LeanPD and SBCE with theoretical and hands on exercise using real case study.

Phase 2: Demonstrate

<u>Step 2.1: Define pilot project</u>

A pilot project has been selected to demonstrate the application of SBCE. The product studied is commonly known as Surface Jet Pump (SJP) as explain in detail earlier in 6.3.1. The SJP as shown in Figure 6-14, is a device used to enhance productivity of oil or gas extracted in oil and gas well by using the energy from a high-pressure fluid/gas to boost the pressure of a low-pressure fluid/gas to obtain an intermediate pressure level. Since the pilot project is using real engineering data, all the sensitive information has been modified or eliminated.

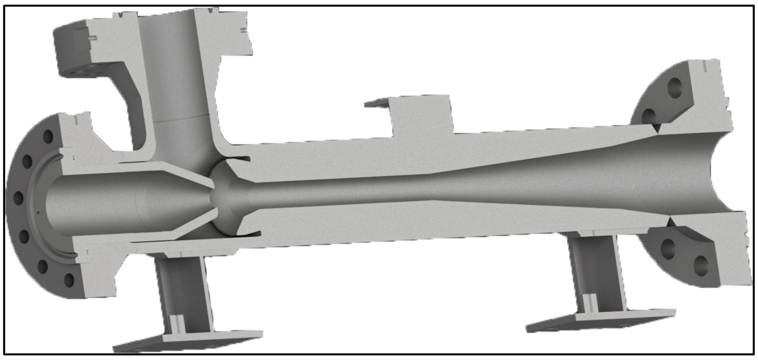


Figure 6-14 Cross-section view of Surface Jet Pump

Step 2.2: Define aim and objective of pilot project

In Step 2.2, there was a formal template to tabulate the aim and objective of the pilot project. The establishment of the template is crucial as it reflect to the nitty-gritty of the project. A table was created to include all the information such as project name, project aim, duration, and expected end date as shows in Table 6-9.

Table 6-9 Project definition matrix

No	Pilot Project Name	Aim	Objectives	Duration
1	Surface Jet Pump (SJP)	The aim is to presents a novel application of the SBCE in order to generate a new SJP design	1. Develop optimal SJP design to reduced manufacturing cost and improved design performance 2. Identify the potential benefits from the application of SBCE in the pilot project	• 3 month (This include meetings, face-to-face interview, LeanPD training, and pilot project)

Step 2.3: Explore customer requirement

Customer needs must be understood to accurately define system targets specifically related to the increment of the design performance, which is the most important value in this case. Identified 38 values are listed (see Figure 6-15-B) and then the values are classified into a singular value to confirm that customer needs are formed properly as shows in Figure 6-15-C.

Through the Analytical Hierarchy Process (AHP) values that have been classified as high importance were analysed (Bhushan et al., 2004), where the result is illustrated in Figure 6-15-D. Based on company prioritisation and the loads of importance rank from the AHP, the customer value attribute has been listed respectively (see Figure 6-15-D). This led to define the key value attributes (KVA) as shown in Figure 6-15-E where the 3 highest percentage were selected, these are; 1) Design Performance, 2) Manufacturability, 3) Cost and 4) Durability. Cost was classified as KVA due to company's preference choice which has the major impact in the creation of this order. The values which remain (reliability and installation) were assigned as values of consideration. The loads for the key value attributes in Figure 6-15-E are calculated respectively by AHP value in Figure 6-15-D. The values calculated are an approximate value. The author constructs the loads for KVA equation as follows:

$$\text{Loads for KVA} = \frac{\text{AHP}_\text{P}}{\sum_{\text{i}=1}^{3} \text{AHP}_\text{P}} \text{ x } 100\%$$

Equation 4 Loads for KVA

Where;

AHP_P = AHP Priority percentage (e.g.: Design performance; 22.3%)

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

The calculation are as follows:

Design performance: (23%/58%) x 100% = 38.5% (approx.)

Manufacturability: (22%/58%) x 100% = 37.5% (approx.)

Cost: (14%/58%) x 100% = 24.0% (approx.)

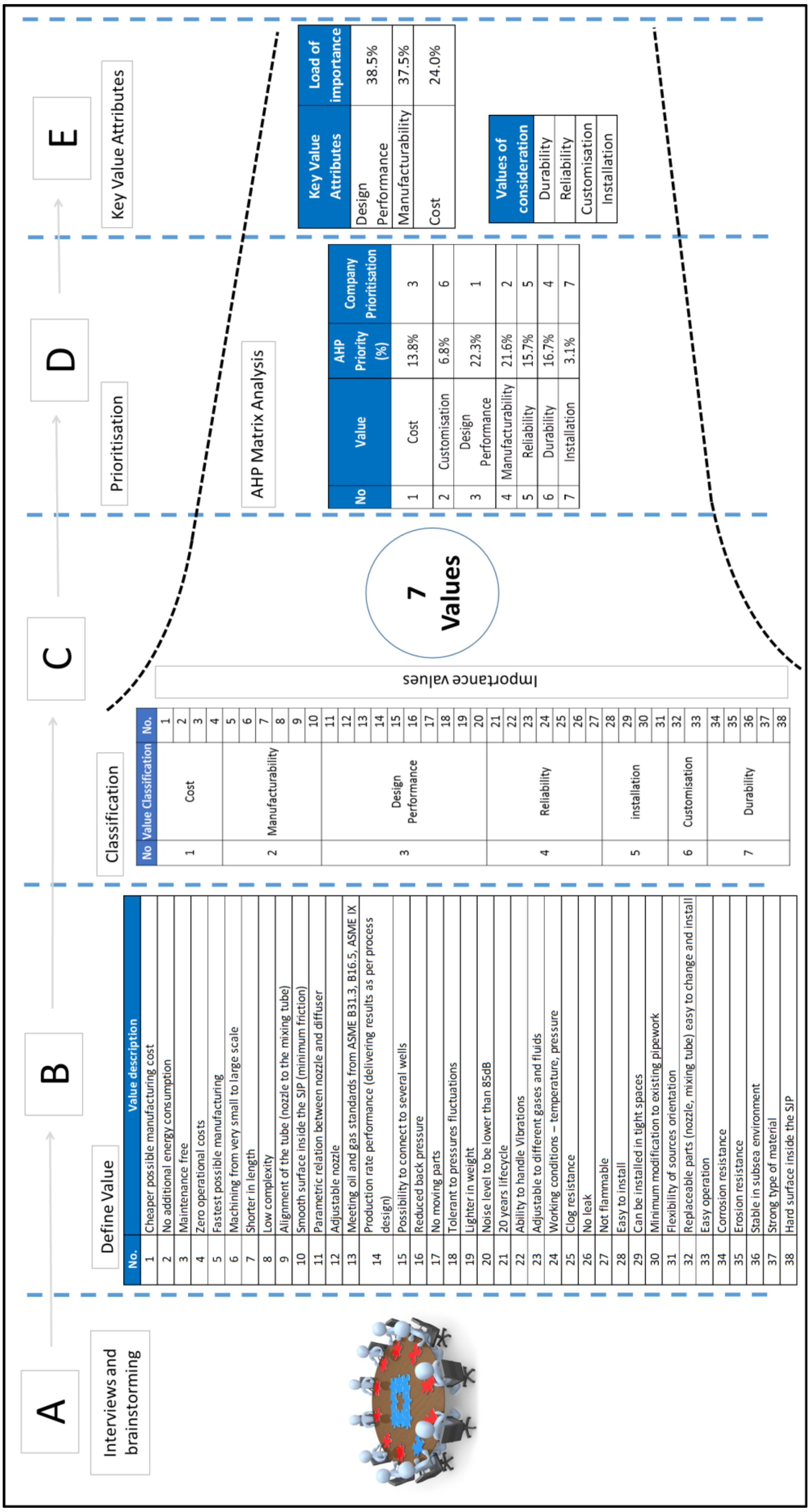


Figure 6-15 The process of identifying Key Value Attributes (KVA)

The next step, 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. The system targets as depicted in Table 6-10 are measurable values which represent key value attributes. Nevertheless, rarely several targets cannot be depicted by a numerical value.

Table 6-10 System target for KVA in the Surface Jet Pump

KVA	System Target
Design performance	1) HP Pressure ≥ 400 psig 2) LP Pressure ≤ 205 psig 3) Discharge Pressure ≥ 320psig 4) Nozzle are replaceable 5) No moving parts 6) Smooth surface inside the mixing tube 7) Easy to change and install 8) Great production rate performance
Manufacturability	1) Low complexity 2) Fastest possible way to manufacture
Cost	1) Low manufacturing cost 2) Maintenance free
Durability	1) Strong material type 2) Ability to handle vibration

<u>Step 2.4: Define scope of design work</u>

In Step 2.4 the scope of the design work as well as feasible regions of the SJP design was defined. The SJP system structure was divided into subsystems as listed below and shown in these are; Flanges (1), Nozzle (2), Body (3), Mixing Tube (4), and Mounts (5). The level of innovation is a colour-coded tool that is used to visualise the level of innovation needed for subsystems of a product as illustrated in Figure 6-16. High level of innovation is required for the nozzle (2) and body (3). The nozzle (2) determines the performance of the system. The function of the body (3) 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 (4) has been classified as a medium innovation. Inside the mixing tube (4), 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 (4) needs a medium level of design changes to enhance system performance. Mounts (5) are defined as "Low innovation" to ensure proper absorption of the vibration. Flanges (1) are coded as "no change in the design".

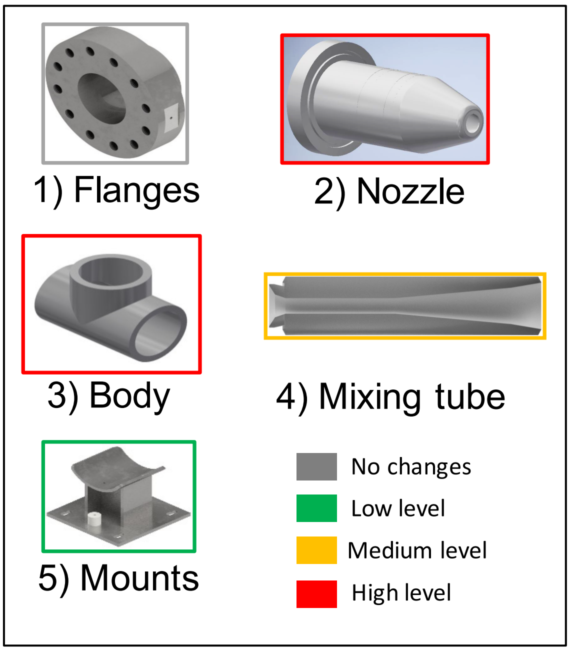


Figure 6-16 Level of innovation of SJP subsystem

Moreover, feasible target for each subsystem is defined to prevent over engineering and supporting the development of innovation. Some of the system targets were adapted onto subsystem targets. The rest were defined as a new target to ensure that it meets KVA: design performance, manufacturability, cost and durability. The subsystem targets for the nozzle (2) are listed as follows:

- The nozzle is replaceable,
- Low complexity of the geometry,
- No moving parts,
- Maintenance free,
- Faster manufacture method,
- Low manufacturing cost.

Others subsystem targets are listed correspondingly as presented in Figure 6-17.

No	Subsystem	Subsystem Target
1	Nozzle	1) Nozzle are replaceable 2) Low complexity 3) Fastest possible to manufacture 4) No moving part 5) Maintenance free 6) Low manufacturing cost
2	Mixing tube	1) Easy to change and install 2) Ability to handle vibration 3) Smooth surface inside the mixing tube 4) Fastest possible to manufacture 5) Low complexity 6) Low manufacturing cost
3	Mount	1) Ability to absorb vibration
4	Body	1) Strong material type 2) Great production rate performance 3) Fastest possible to manufacture 4) Low complexity 5) Low manufacturing cost

Figure 6-17 Subsystem target for SJP

Furthermore, the design space is defined as the boundaries for designers and engineers to explore and communicate with many alternative conceptual design solutions. The design space for the SJP and for the nozzle is presented in Figure 6-18 which are;

- HP pressure must be higher or remain on the level of 400 psig,
- LP pressure must be lower or remain on the level of 205 psig,
- Discharge pressure must be higher or remain on the level of 320 psig
- HP inlet diameter is 131 mm
- Discharge outlet and LP inlet diameters are 173 mm

The subsystem boundaries for the nozzle have been identified in order 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 (3) and flanges (5).

Subsystem boundaries for the nozzle (2) are listed below;

- Nozzle angle =17. 5°
- Inside diameter = 131 mm
- Nozzle length = 445 mm
- Nozzle tip diameter = 41.28 mm

It is essential to not impose the activity with too many constraints which might create a limitation on the innovation of the product.

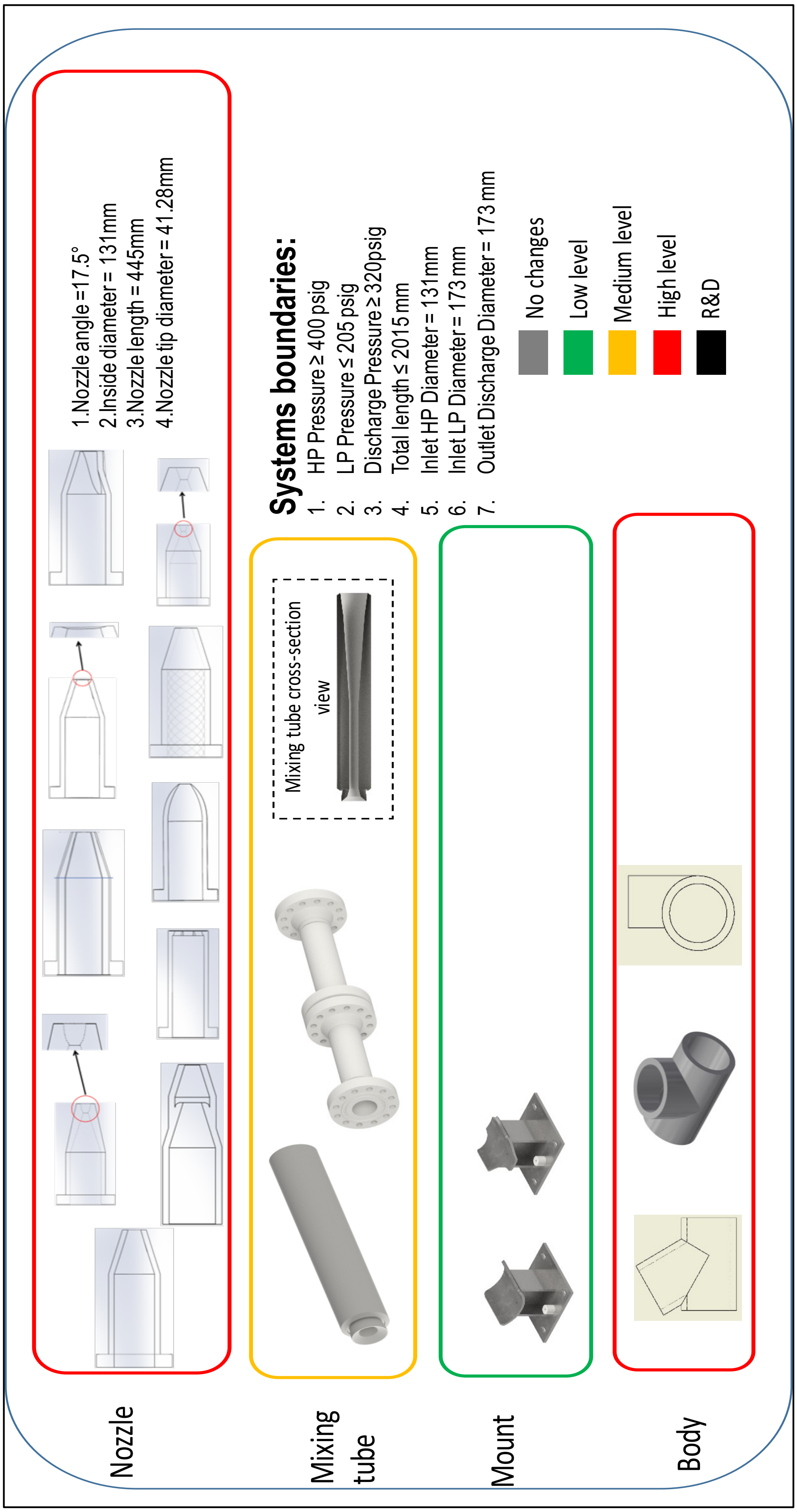


Figure 6-18 System and Subsystem boundaries

Phase 3: Evaluate

<u>Step 3.1: Generate multiple alternative solution</u>

In Step 3.1, the sets of possible conceptual design solutions were developed and generated for each of SJP subsystems. The following paragraph clarifies how the nozzle is designed and suggests possible conceptual design solutions as illustrated in Figure 6-19.

The subsystem targets are taken into account during generation of the alternative designs as illustrated Figure 6-17. In addition, the defined boundaries also have been considered in the SJP design process as depicted in Figure 6-18. As a result, set of 10 nozzles, 2 mixing tube, 3 body design concepts have been generated based on the creativity which corresponds to the key value attributes.

In the body, 2 different concepts were created together with the one from the original design (previously used by Caltec) using the same approach as for the nozzle in Figure 6-19. In addition, mounts and flanges keep the same original design without any changes. The design space of the SJP could generate 60 potential systems as illustrated in Figure 6-19 and it is calculated as follows:

- 10 (nozzle) x 2 (mixing tube) x 1 (mount) x 1 (flange) x 3 (body) = 60.

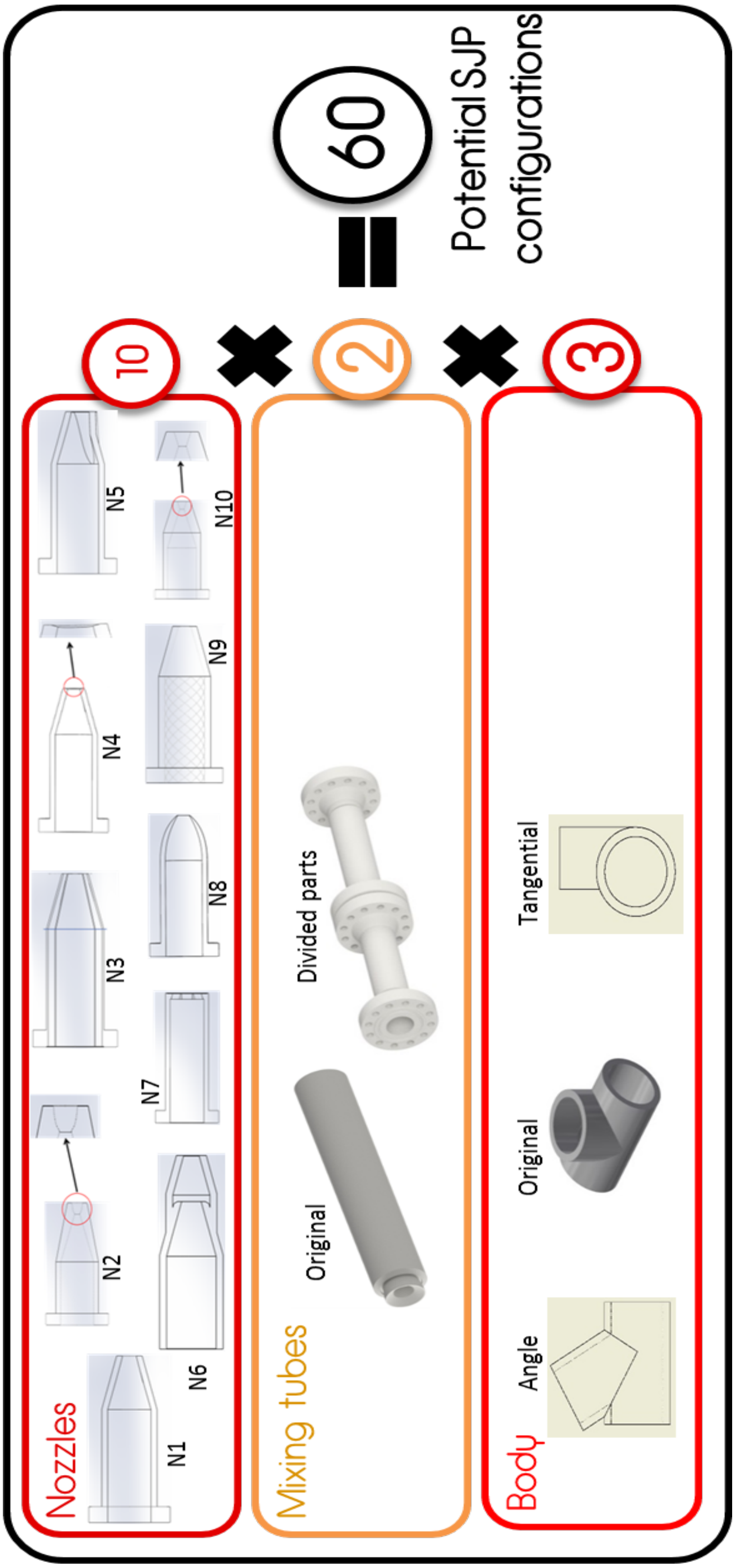


Figure 6-19 Possible conceptual design solutions for each subsystem

Step 3.2: Analyse, evaluate, and narrowing the solutions

In Step 3.2, the conceptual solutions were evaluated. The analysis has been focused on the flow motion to determine the HP and LP values which give an impact to the performance of the SJP. The analyses were carried out for the nozzles by using the ANSYS software as shows in Figure 6-20 while Table 6-11 shows the parameter of the analysis. However, the analysis at this stage is done only for the nozzles as it is the only subsystem 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.

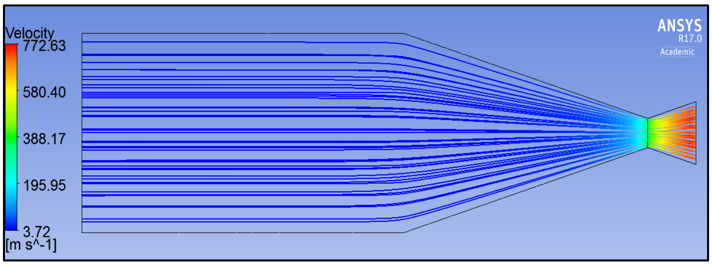


Figure 6-20 Example of CFD result for nozzle N10

Table 6-11 CFD simulation parameters for the nozzle

No.	Parameter
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: 2340 J/kg*K
6.	Dynamic viscosity: 1.03971 e-10 kg/m*s

From the 60 potential SJP configurations, not all are suitable to become the final solution of the SJP. Therefore, trade-off curves were used to narrow down the subsystem solutions based on the CFD simulation results, manufacturing complexity and manufacturing cost of the solutions. The Trade-off Curves (ToCs) illustrated in Figure 18 shows the reduction of solutions from 10 to 3 following designs which is the N2, N4, and N10. These ToCs were generated based on simulation result and consultancies from Caltec.

In order to narrow down the 60 system configurations, ToCs were generated for the nozzle designs considering the KVA mentioned above. As it could be seen in Figure 6-21, 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. As a result of the analysis of the generated ToCs in Figure 6-21, the number of the nozzle designs was reduced from 10 to 4. Since the nozzle design N1 is the original design, it is excluded from the design set. As a result, from the nozzle ToCs analysis the configuration has been reduced from 60 to 18 (see Figure 6-22), the calculation as follows;

3 (nozzle) x 2 (mixing tube) x 1 (flange) x 3 (body) = 18.

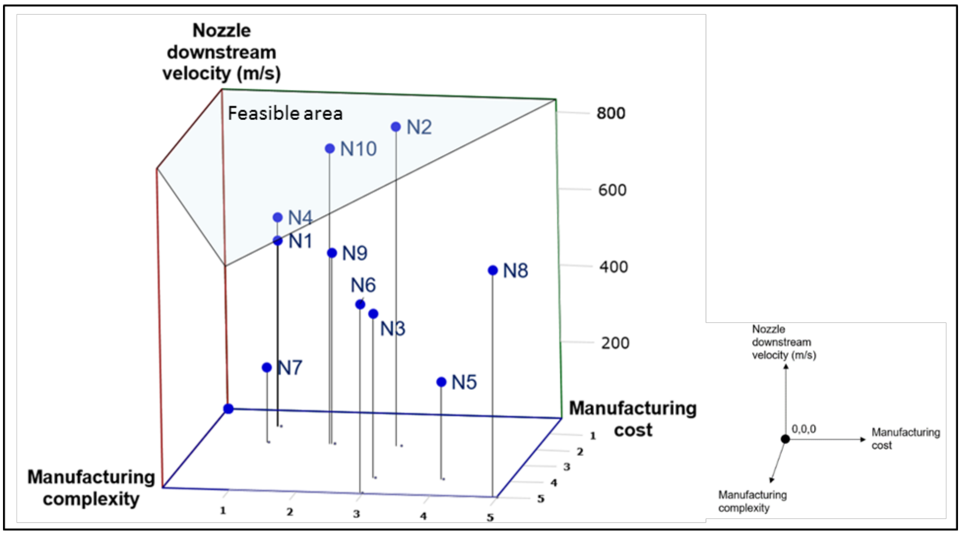


Figure 6-21 3D ToCs comparing manufacturing complexity and manufacturing cost to nozzle downstream velocity

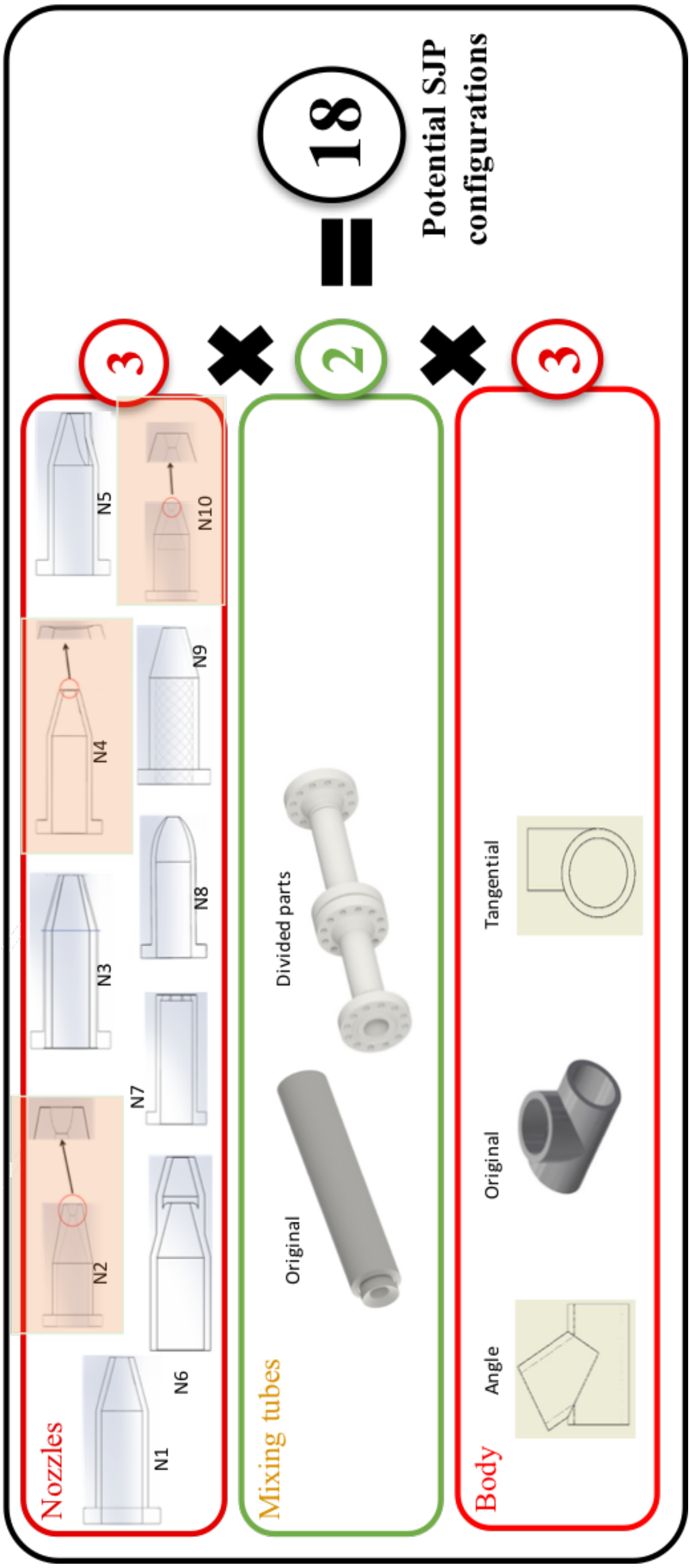


Figure 6-22 Narrowing process for possible conceptual design solutions for Nozzles

Step 3.3: Select the optimum solution

To obtain the final optimum SJP design, alternatives which not increase the design performance were discarded and the rest of the possibilities have been developed until the optimum design solution reached. In Step 3.3 “Select the optimum solution”, the final designs of SJP systems were generated using feasible subsystem set of solutions. From 18 possible solutions, not all of them should be considered in the final analysis. Two techniques were used in order to narrow down the set of solutions which is the CFD simulation of the SJP system as illustrated in Figure 6-23 and the ToCs as shows in Figure 6-24. From both analyses, it gives two conclusions which are listed as follows;

- There is not necessary to divide the mixing tube (4) in Figure 6-24 into parts as the length of mixing tube is only 1.3 m in the case study. However, if the length of mixing tube (4) is more than 5 m, the divided mixing tube is more economical to use as shows in Figure 6-24.

- The Body (3) designs with tangential and angle low pressure (LP) inlet were discarded due to their complexity and higher cost as well as it does not give a huge impact on the performance on the simulation. Figure 6-23 shows an example of the result of the SJP system using the CFD simulation.

As a result of the activity possible solutions were narrowed down from 18 to 3 which calculated as follows: 3 (nozzle) x 1 (mixing tube) x 1 (mount) x 1 (flange) x 1 (body) = 3.

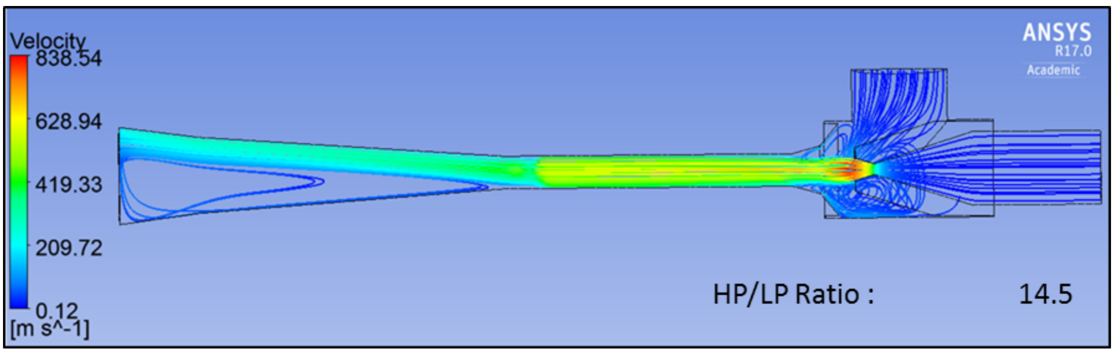


Figure 6-23 Example of system analysis using CFD for nozzle N10

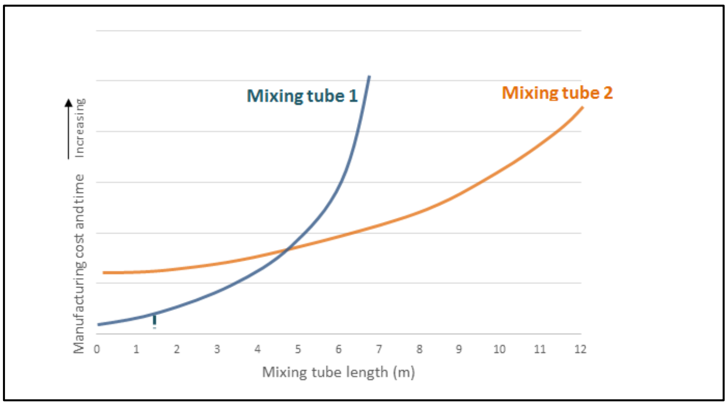


Figure 6-24 ToCs for Mixing tube; Manufacturing cost and time vs. Length of mixing tube

Furthermore, an aggressive narrowing process has been implemented based on the loads of importance from the KVA and 3 ToCs, which is design performance, manufacturability, and cost. Figure 6-25 shows the ToCs for the system design performance where systems are compared using HP pressure, LP pressure and HP/LP pressure ratio which obtained from the CFD simulation. The higher HP/LP pressure ratio results a better performance of the SJP hence improve the productivity of the SJP. Figure 6-26-A and Figure 6-26-B show the relation between manufacturing complexity, manufacturing cost and nozzle velocity. From the figures, the N10 system looks to be the optimum result in term of the manufacturability and cost. Even though N4 system gives the best result in manufacturability and cost, the velocity does not give a good impact to the performance of the SJP. Likewise, the N2 system give the best result in term of the performance (velocity) compared to others, however, it is not easy to manufacture due to its complexity. Nevertheless, the cost is the same between N2 system and N10 system.

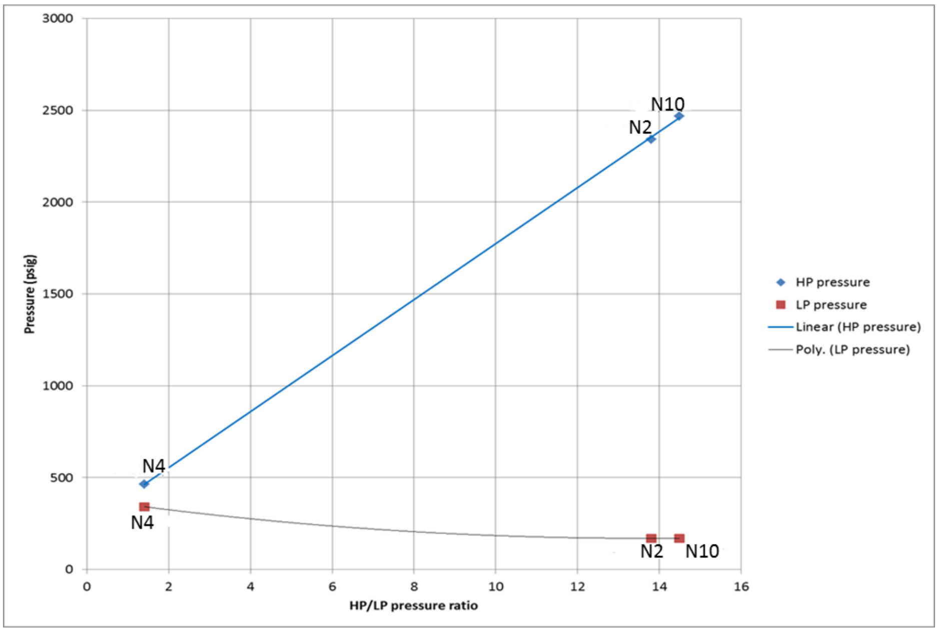


Figure 6-25 ToCs for HP/LP pressure ratio to HP and LP inlet pressure

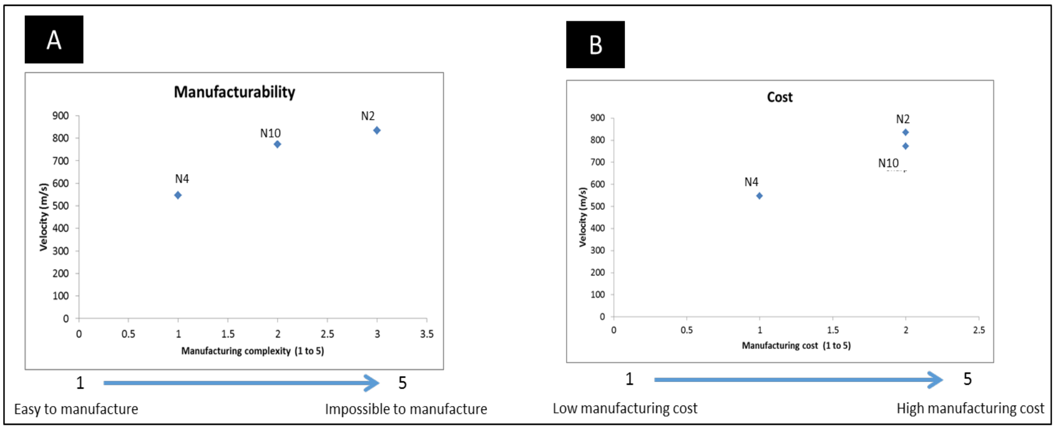


Figure 6-26 ToCs for Manufacturability and Cost

To manage the conflict, the Pugh Matrix (Ward and K. Sobek II, 2014) was used to evaluate the final optimum solution. At first, scale from 1 to 4 were used to identify the score of the systems as depicted in Figure 6-27-A. The scale later on will be multiplied with the loads of importance from Figure 6-15-E where the highest total weightage will be selected as the optimal solution. These were made through a several brainstorming sessions within research team based on the input from the manufacturer, CFD simulation and ToCs. As a result, the optimal solution of the SJP is N10 system which gives the highest score of 2.53 as depicted in Figure 6-27-B. The final optimum solution N10 nozzle, original body and original mixing tube is presented in technical drawing as shown in Figure 6-28 where all the components are integrated as a system. Due to confidentiality of data, the engineering drawing for the final optimum solution are given without the dimensions.

A

Scale	
4	The best
3	Good
2	Moderate
1	The worst

B

KVA	Loads of importance	Angle Tip (N4)	Sharp Tip (N10)	De Laval (N2)
Design performance	38.5%	1	4	3
Manufacturability	37.5%	3	2	1
Cost	24.0%	3	1	1
Total Weightage		2.23	2.53	1.77

Figure 6-27 The Pugh matrix based on the key value attributes (KVA)

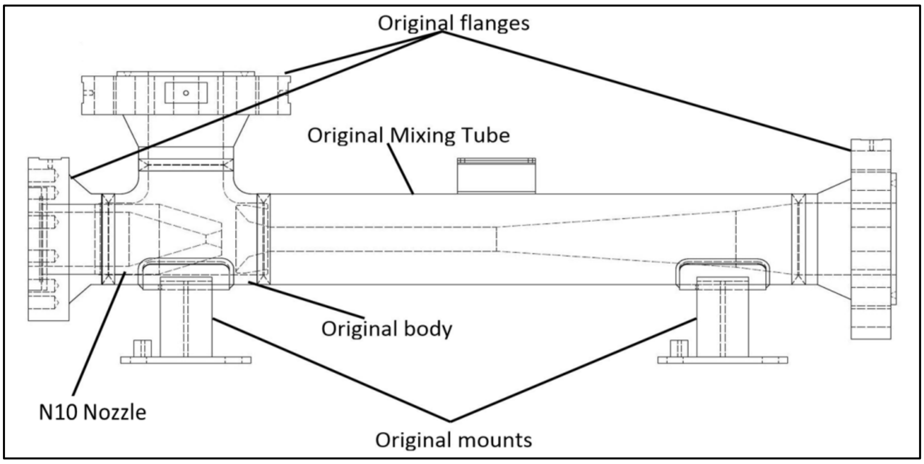


Figure 6-28 Engineering drawing of the final optimum solution for system (N10)

Phase 4: Justify

<u>Step 4.1: Identify tangible benefits from pilot project</u>

The SJP case study shows the detailed application of the Set-based Concurrent Engineering (SBCE) process model in the real scenario. This case study has benefited the company, by enhancing its current product development process by providing a space to explore alternative designs from different angles i.e. product performance, manufacturability, and cost. The SBCE approach guided the development of a SJP with the right design and engineering activities as well as the associated tools and method to enable the application of the different activities. In addition, the SBCE approach provided a suitable knowledge environment to support decision making throughout the development process.

There are several tangible benefits which could be as an evidence of having a business case in the SBCE. Typically, business case built on the return on investment, however, during the early stage of SBCE introduction, the business case is based on the potential tangible benefits in a few key areas which is;

1. Improved product innovation
2. Improved product performance
3. Minimized impact of manufacturing cost
4. Maximized probability of project success

The innovation and knowledge creation level has increased where 60 system design configurations were identified through the application of the SBCE process model in the case study as shows in Figure 6-19. This could give an opportunity for the designers and engineers in Caltec to explore the possible design within the design space without any difficulties from the current product development practices. The 60 system designs have been generated based on the creativity which corresponds to the key value attributes; Design performance, manufacturability, and cost.

Product performance has improved through an implementation of the SBCE. The improvement achieved in 3 areas which is velocity, pressure, and HP/LP ratio. These improvements have been gained through an analysis using Ansys simulation software for the subsystem (only for nozzle) and system. The result was based on the comparison between the N1 (original) design and the optimum solution, the N10. This analysis originated from the principle of Bernoulli in the fluid dynamics (Munson, Young and Okiishi, 2005). The Bernoulli principles state increase the velocity of the fluid or gas simultaneously will decrease the pressure of the fluid or vice versa. This is to determine the velocity and pressure at points in the flow connected by a streamline, in this case within the contracting and expanding pipe as depicted in Figure 6-29.

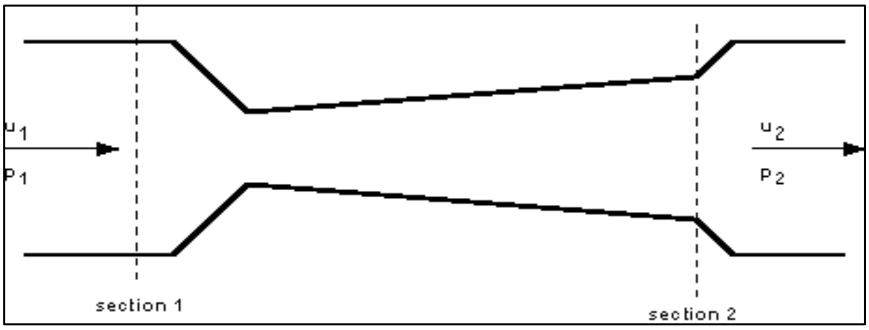


Figure 6-29 A contracting expanding pipe

The theory of Bernoulli principle equation is described as follows;

$$\frac{p_1}{\rho g} + \frac{u_1{}^2}{2g} + z_1 = \frac{p_2}{\rho g} + \frac{u_2{}^2}{2g} + z_2$$

Equation 5 Bernoulli principle

Where;

p_1 = Pressure at the inlet (kN/m^2)

p_2 = Pressure at the outlet (kN/m^2)

u_1 = Velocity at the inlet (m/s)

u_2 = Velocity at the outlet (m/s)

ρ = Density of fluid or gas

g = Gravity (m/s)

z_1 = level at the inlet (m)

z_2 = level at the outlet (m)

In order to run the ANSYS simulations, two operating conditions are set which is;

- Operating condition for the nozzle
- Operating condition for the system

The operating condition is given by Caltec Limited which refer to the Basis of Design (BOD). The data are given as follows:

Operating condition for the nozzles

HP Flow rate: 10.33 kg/s

Nozzle Outlet Pressure: 196 psig (1350611.3 Pa)

Nozzle inlet Temperature: 88 °C

Properties: Natural Gas

HP Molar Weight: 24.89 kg/kmol

Specific Heat: 2340 J/kg*K

Dynamic viscosity: 1.03971 e-10 kg/m*s

Operating condition for the system

HP Flow rate: 10.33 kg/s

LP Flow rate: 2.845 kg/s

Reference Discharge Pressure: 320 psig (2206000 Pa)

Inlet Temperature: 87.7 °C (361.15 K)

Properties: Natural Gas

HP Molar Weight: 24.89 kg/kmol

Specific Heat: 2340 J/kg*K

Dynamic viscosity: 1.03971 e-10 kg/m*s

At first, a simulation is run for the nozzle to obtain the velocity of each nozzle. Then, the simulation is run for the complete system of the Surface Jet Pump (SJP) to obtain the pressure. The image of the simulations for the nozzle and the system are shown in Figure 6-30 and Figure 6-31.

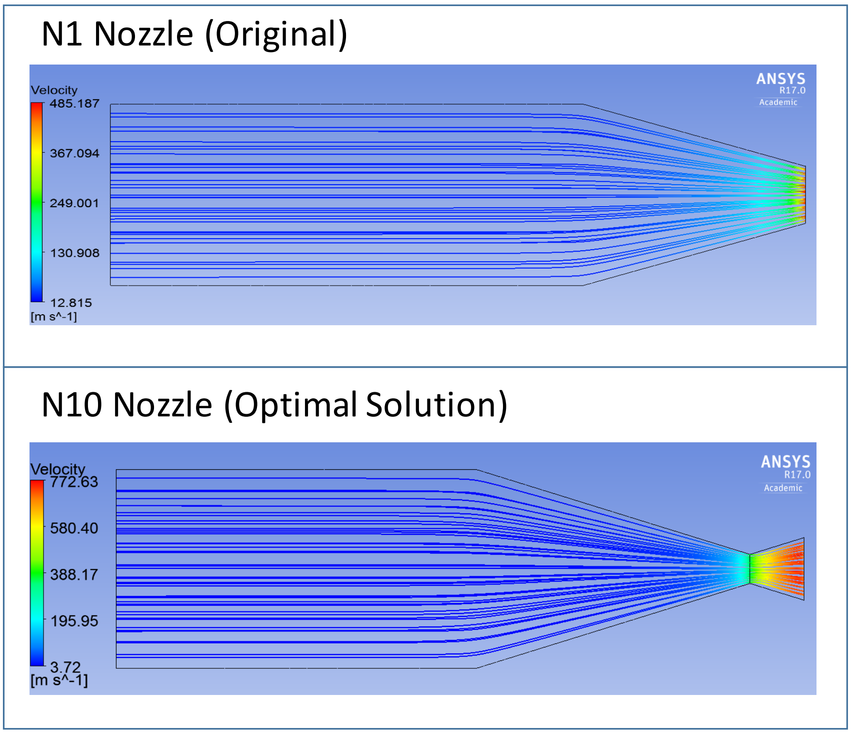


Figure 6-30 Ansys simulations for Nozzles N1 and N10

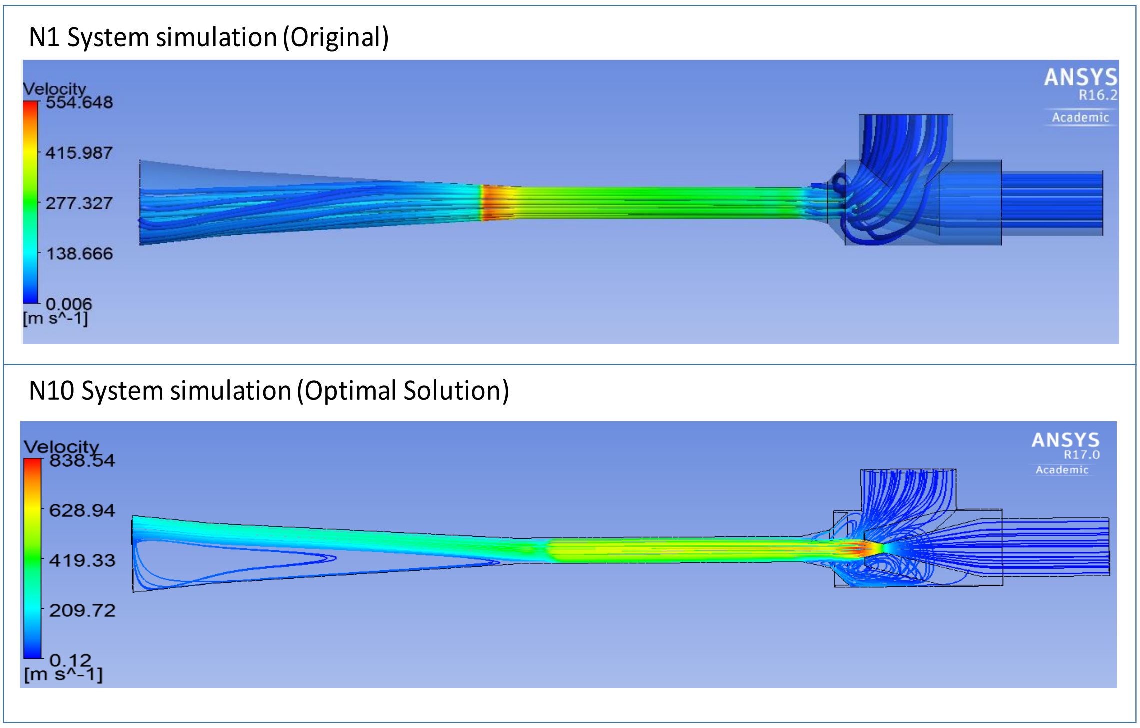


Figure 6-31 Ansys simulations for system N1 and N10

The result of the ANSYS simulation analysis is shown in Table 6-12 below:

Table 6-12 Ansys simulation result comparison for system N1 and N10

No	System Design	Nozzle Outlet Velocity (m/s)	Inlet for Low Pressure (LP) (psig)	HP/LP Pressure Ratio
1	N1 (Original)	485.187	283.34	1.9
2	N10 (Optimal Solution)	772.627	170.63	14.5

From the result, the gas compressor suction pressure has been improved by increasing the nozzle performance velocity from 485.187 m/s in N1 design to 772.627 m/s in N10 design. This could create a vacuum state at the tip of the nozzle which help the gas entrained to the SJP system. Moreover, the LP pressure also simultaneously drops from 283.34 psig (N1 design) to 170.63 psig (N10 design), this gives an advantage for the SJP to revive dead oil and gas well, hence it could further produce the oil and gas. The HP/LP ratio also has been increased from 1.9 to 14.5 which indicate the improvement of the SJP in boosting the pressure of the LP gas entrained. Therefore, the improvement percentage as follows:

- Improvement percentage of compressor suction pressure;

$$\frac{772.627 \text{ m/s (N10 nozzle)} - 485.187 \text{ m/s (N1 nozzle)}}{485.187 \text{ m/s (N1 nozzle)}}$$

$$= 0.592 \times 100\%$$

$$= 59.2\%$$

- Improvement percentage of LP pressure;

$$\frac{283.34\text{psig (N1 nozzle)} - 170.63\text{psig (N10 nozzle)}}{283.34\text{psig}}$$

$$= 0.398 \times 100$$

$$= 39.8\ \%$$

The next benefit gain from the application of the SBCE is the improvement of manufacturing cost. As Caltec Ltd, concern about the manufacturing cost, the SBCE approach has able to reduce the number of part changes by deciding the level of innovation (see Figure 6-16) for the subsystem of the SJP. This visualizes colour coded tool help the designers to communicate simply the level of innovation required for different subsystems of a product. The changes have been made only for the nozzle while another 4 subsystems, namely flange, body, mixing tube, and mount remain same as the current design (each subsystem represents 20% as an average value which contribute to the total sum of 100%). This is involving only 20% of the changes which implicate only one additional operation – a turning process of 35mm deep from the tip of the nozzle.

As refer to the Caltec Ltd. manufacturer, Woodfield System Ltd., the additional process will use the same existing tools, hence no extra cost incurred in the manufacturing. The manufacturer also stresses that the fabrication time also remain 1 week as previous as the additional turning process could be done simultaneously with other machining process. The manufacturing cost given by the manufacturer is based on the estimated cost due to the confidential issue. However, the manufacturers state that the estimation of the manufacturing cost for the N10 is £550.00 plus material cost where the cost remains the same as the current design.

In detail, to define the material cost (Carbon steel), data is gathered from the MEPS international Ltd. which is a source of reference for the Woodfield System Ltd. to estimate the material cost. Due to fluctuating steel price in the market, the carbon steel cost in this case is fixed based on one-year forecast which is £365.00 per tonne for easy comparison. In order to identify the material cost, the equation of material weight estimation is used to identify the weight of the material used for the nozzle. The author expresses the equation as follows;

$$W_{\text{carbon steel use}} = A_{\text{carbon steel}} \text{ x } l_{\text{carbon steel}} \text{ x } \rho_{\text{carbon steel}}$$

Equation 6 Material weight (Round Bar)

Where;

A_{nozzle}= Area of carbon steel used for the nozzle (0.0477 m^2)

$l_{\text{carbon steel}}$ = Length of carbon steel used for the nozzle (0.445 m)

$\rho_{\text{carbon steel}}$ = Density of carbon steel (7850 kg/m^3)

As the result of the equation, the weight of the material need to be used is 166.6 kg.

To identify the cost of the material, the material cost equation is used as described as follows;

$$\text{Material cost}_{\text{nozzle}} = C_{\text{carbon steel}} \text{ x } W_{\text{carbon steel use}}$$ **Equation 7** Material cost

Where;

$C_{\text{carbon steel}}$ = Cost of carbon steel per kg (£0.365/kg based on £365/tonne)

$W_{\text{carbon steel use}}$ = Weight of the carbon steel used for the nozzle (166.6 kg)

Therefore, the cost of the material used for the nozzle is £60.82. As a conclusion, the manufacturing cost for the nozzle N1 and N10 is estimated at £610.82. It is mean that the new N10 nozzle design has been done without any manufacturing cost increase, however it improves the performance significantly compared to the original N1 nozzle.

The probability of having a successful project also has been increased by implementing the SBCE in the product development. In order to understand, probability test has been carried out to identify the risk improvement in the case study. According to Ward et al. (2014), three rules were implied in the probability to identify the risk (see sub-chapter 5.4.2). In the probability test, the comparison was made between three final possible solutions from the SBCE approach and one solution in traditional point-based design approach. The three-final possible solution was taken from the Step 3.3 as each of the subsystem at this stage have a potential to integrate each other (see Figure 6-27-B). Meanwhile, the one solution is taken from the current practice of product development in the company. As refer to the Caltec Ltd., the probability of the subsystem will cause a major problem due to any circumstances is 20%, which explain another 80% is a probability of success as depicted Table 6-13.

Table 6-13 Probability of failure and success for subsystem

Subsystem	Probability of Failure (P_f)	Probability of Success (P_s)
Nozzle	0.2	0.8
Mixing tube	0.2	0.8
Body	0.2	0.8
Flange	0.2	0.8
Mount	0.2	0.8

Therefore, the author applies the probability rules equation (see sub-chapter 5.4.2) as follows;

Firstly, from Table 6-13 the probability of considering 3 design concepts calculated as follows;

<u>Rule 1 and Rule 2</u>

The probability of failure from 3 design concepts is;

$$\mathrm{POF_n} = \mathrm{P_f}^{\mathrm{n}}$$

$$= 0.2^3$$

$$= 0.008$$

$$= 0.8\%$$

The probability that all subsystems will have at least one successful design;

$$\mathrm{POS} = (1 - \mathrm{POF_n})^{\mathrm{m}}$$

$$= (1 - 0.008)^5$$

$$= 0.9606$$

$$= 96\% \text{ succesful rate}$$

Rule 3

The average number of successful designs;

$$\bar{x} = n\ (P_s)$$

$$= 3\ (0.8)$$

$$= 2.4 \text{ sucessful design}$$

Secondly, from Table 6-13 the probability of considering only 1 design concept calculated as follows;

Rule 1 and Rule 2

The probability of failure for 1 design concept is;

$$POF_n = P_f^{\,n}$$

$$= 0.2^1$$

$$= 0.2$$

$$= 20\%$$

The probability that all subsystems will have at least one successful design;

$$POS = (1 - POF_n)^m$$

$$= (1 - 0.2)^5$$

$$= 0.327$$

$$= 33\% \text{ succesful rate}$$

Rule 3

The average number of successful designs;

$$\bar{x} = n\ (P_s)$$

$$= 1\ (0.8)$$

$$= 0.8 \text{ sucessful design}$$

In comparison with the both probability calculations, the success rate has increased from 33% to 96%. This result shows how SBCE approach is much more reliable compared to point-based approach. In addition, the risk of having a failure design also have been reduced from average only 0.8 successful designs (not even 1) to average 2.4 successful designs after SBCE application. The benefits categorisation and improvement (see Figure 6-32) has been achieved through the implementation of the SBCE in the development of new design of Surface Jet Pump (SJP) in Caltec Ltd. The research proves that the SBCE has got the potential in producing high quality successful products on time and in a cost-effective manner.

Step 4.2: Document and present the business case to management

The map of the business case is presented in step 4.2. This step will explain the summary of the business case activity by providing the outcome in short presentable information. The information should contain the tangible benefits gain from the application of the SBCE. This information should not include any formula or calculation. Instead, keep the backup files containing the details in case of someone from the stakeholder need that information for clarification. In this research, a PowerPoint slide has been created to show the value of SBCE application, however the details of the slides are not presented in this thesis, except the summary of the benefits as shows in Figure 6-32. In addition, the steps of the slides are the same as explained in the previous chapter.

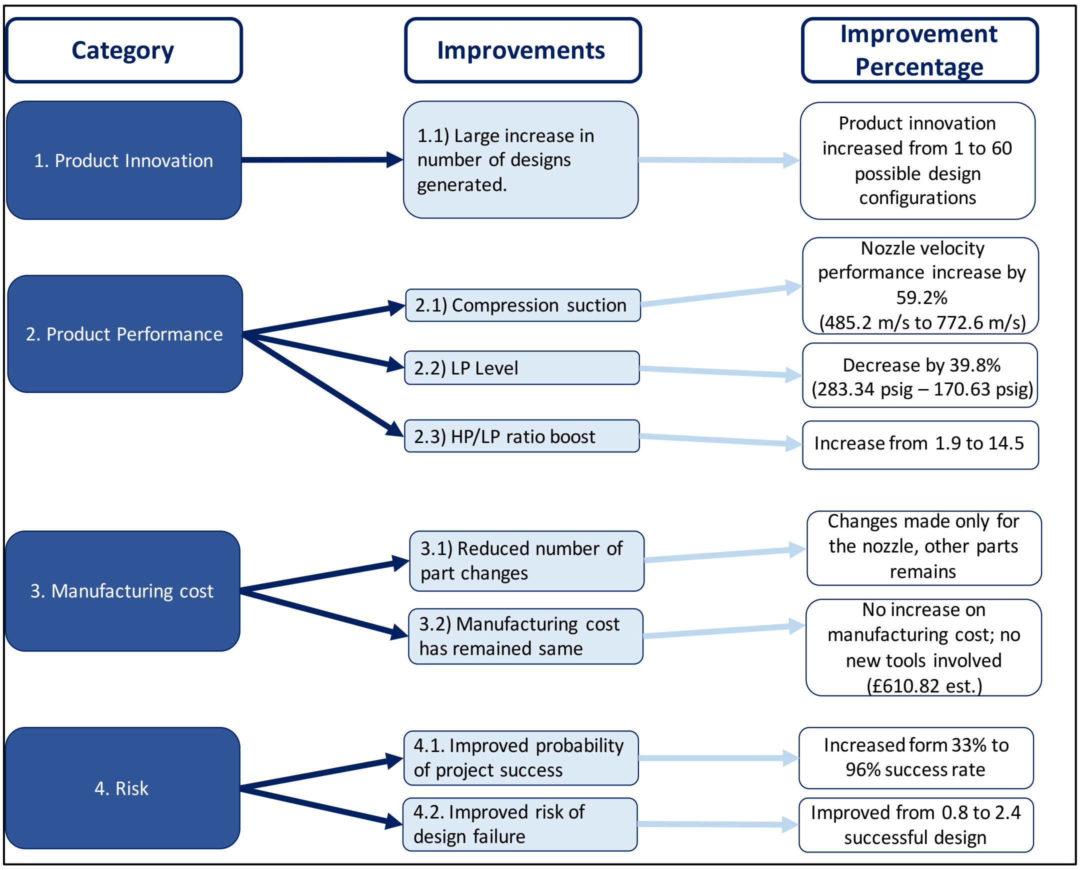


Figure 6-32 Benefits categorisation and improvement achieved in SBCE

6.4 Jaguar Land Rover case study

6.4.1 Overview

The SBCE process model was applied in a case study to demonstrate its ability in addressing the product development challenges faced by the Chassis Engineering Department at JLR. This section explains the detailed application of SBCE business case framework (is illustrated in Figure 5-1) which based on the essence of the SBCE process model. Sensitive information has been deleted or modified during the project to keep in line with the Non-Disclosure Agreement that was signed with the company.

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 6-33 shows the elements of the brake pedal box: 1) Bracket, 2) Pedal arm, 3) Pedal Pad 4) Bushing.

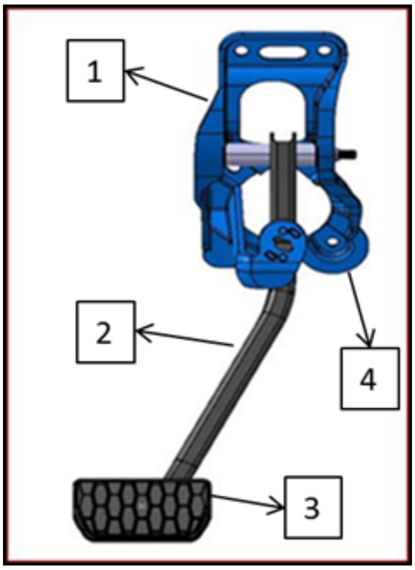


Figure 6-33 The system level of brake pedal box

The most important characteristics of the brake pedal box desired are safety, reliability, and stiffness of the brake pedal box. The SBCE however, has a set of activities that must be carried out to validate its benefits to the PD process. These selected step-by-step SBCE activities have been listed earlier in

Figure 5-2. The next paragraphs explain the application of the SBCE business case framework in the JLR case study.

6.4.2 Application of SBCE Business Case Framework in brake pedal box case study

Phase 1: Driver

<u>Step 1.1: Understand current PD situation</u>

The LeanPD SMART Assessment Tool enables the tracking of the Lean Product Development journey of a company. It allows an assessment of the current Product Development practices against best practices and principles of LeanPD on a SMART scale (Start, Motivate, Apply, Review and Transform) as shown in Figure 6-34. The study used the Lean-PPD SMART Assessment tool consisting of four perspectives: 1) Product Development (PD) Process, 2) Tools and Methods, 3) Knowledge, 4) People and Skills. Each perspective has ten questions where each question has five possible statements to choose from, which are not covered in this thesis. The statements range from the lowest Lean Product Development level to the highest based upon a "SMART" scale of 1-5 as displayed in Figure 6-34. A total of 74 employees from JLR participated in the study, in which they answered the questions individually. The participants came from the 8 functions within the Chassis Engineering Department which is; 1) Suspension Systems Integration, 2) Suspension Systems Architecture, 3) Steering Wheels & Tyres, 4) Suspension Systems Tuning, 5) Driving Dynamics, 6) Brakes Design, 7) Business and Programmes, 8) Motion Control. The results from each section of the assessment have also been analysed independently of each other to look at the results of each question in more detail. In summary of the result, the current lean practices in Chassis Engineering Department at JLR are close to the level 3 (Apply) on the SMART scale of the Lean-PPD Performance Measurement Tool. This means the company is aware of some LeanPD practices and is already doing some lean implementation, but not comprehensively. Furthermore, this means the current lean applications are used in certain activities within the different projects in product development. Thus, there is a space for the company to improve their PD by having the SBCE approach as an enabler towards a successfully transforming from current state to LeanPD environment.

Step 1.2: Established LeanPD milestone

Results from the assessment reveals an overall score of '2.7' for the current AS-IS Lean Product Development practices in JLR, and a score of '4.3' for the desired TO-BE practices. The 'TO-BE' score is 4.3 indicates the common view of a desire to formally implement lean practices in product development processes. The milestone has been established to visualise the journey towards LeanPD as shows in Figure 6-34.

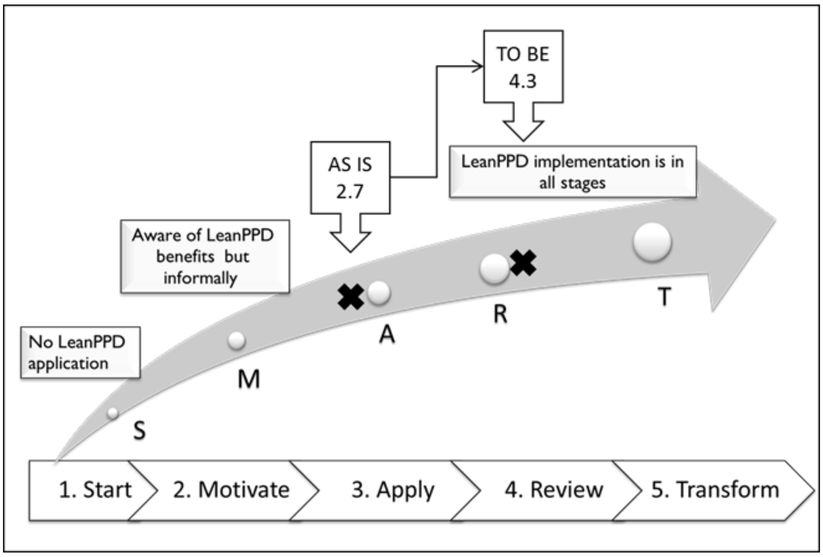


Figure 6-34 Overall result of the Lean-PPD performance assessment of the Chassis Engineering Department at JLR

<u>Step 1.3: Identify current PD challenges</u>

To verify the findings from the Performance Assessment, a face-to-face interview was conducted with 44 respondents. This section summarises the findings of the face-to-face interviews on the PD practices within the Chassis Engineering Department of Jaguar Land Rover. The group of employees that underwent the questionnaire was chosen from the sample of 83 employees that participated in the performance assessment. The main criteria for the selection was the diversity of roles, responsibilities and experience within the function, in order to obtain representative and comprehensive results; as well as the motivation and willingness of the individuals to cooperate and offer extra information during the mentioned Performance Assessment. The main focus of the Semi-Structured Questionnaire was to identify the current product development challenges in the department, with a focus on findings from the SMART performance assessment (Al-Ashaab *et al.*, 2016). From the data analysis of results obtained, 3 key challenges were identified which explained in Table 6-14.

Table 6-14 Key PD challenges from performance assessment and face-to-face interviews

No.	Challenges	Descriptions
1	Design Rework	• The concept of late change is wrong within the department, as it is viewed negatively. This means design changes are currently viewed as rework rather than an iterative process
2	Product not meeting the specification	• Most of the time, the concept phase is not given so much attention because of the pressure to meet targets. This eventually leads to design reworks and quality issue.
3	Creativity and Innovation	• Lack of exploring possible design solutions at the design phase hinders creativity and innovation of design parts

Step 1.4: Appoint Champion

In this case study, champion has been appointed to lead the team and spreading the awareness on LeanPD to the team and management. Level of authority of the champion is a Senior Manager in Chassis Engineering Department.

Step 1.5: Team formation

Prior to the awareness training, a set of teams has been established consists of managers and engineers from 8 different functions in the department. As preparation, all the team members participating in the awareness training to sharpen their knowledge on LeanPD and SBCE.

Step 1.6: Create awareness to build culture

A short seminar was given to the senior management of Chassis Engineering Department of JLR prior the introduction of SBCE application to the organisation. This is in order smooth the buy-in process, gain their confidence and be supportive on the initiatives. Awareness training has been conducted in order to provide the knowledge of SBCE and its application before case study commencement. Awareness training is purposely to provide an essence of the SBCE into the organisation. A short course training was delivered involving top management and engineers of the company. The subject covered the LeanPD and SBCE with theoretical and hands on exercise using real case study.

Phase 2: Demonstrate

Step 2.1: Define pilot project

To address these challenges, a pilot project on a brake pedal box was selected to demonstrate the ability of SBCE within a lean environment in addressing the challenges faced by the company. The selection of the project is based on mutual understanding between research team from Cranfield University and team from Jaguar Land Rover. The mutual understanding includes time limitation, project impact, and data accessibility. The brake pedal box pilot project is explained in the following steps.

Step 2.2: Define aim and objective of pilot project

In Step 2.2, there was a formal template to tabulate the aim and objective of the pilot project. The establishment of the template is crucial as it reflect to the nitty-gritty of the project. A table was created to include all the information such as project name, project aim, duration, and expected end date as shows in Table 6-15.

Table 6-15 Project definition matrix

No	Pilot Project Name	Aim	Objectives	Duration
1	Brake Pedal Box	The aim is to find an improved design of a brake pedal box applying the principles of SBCE.	1. Demonstrate the potential of SBCE addressing the PD challenges 2. Identify the potential benefits from the application of SBCE in the pilot project	• 3 month (This include LeanPPD performance asessment, face-to-face interview, LeanPD short course, and pilot project)

Step 2.3: Explore customer requirement

A 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 as illustrated in Figure 6-35.1. A total of 25 values attributes (refer to Figure 6-35.2) was then classified into 10 categories for easier handling of the analysis as shows in Figure 6-35.3. For example, these five (5,6,7,9,10) values were classified as a single value attributes tagged 'Stiffness'. In this same way, the rest of the values were classified based on the similarity of their objectives. Furthermore, to identify the most relevant attributes for the assembly, the loads of importance of each of them had to be evaluated and compared with the rest. This was achieved using the Analytic Hierarchy Process (AHP) matrix (Bhushan and Rai, 2007; Schuh and Drescher, 2014) which is not covered in this thesis. The AHP matrix helps to identify the relevance of each value attribute for the pedal brake box. Additionally, since the design cannot be based on all the value attributes, the top three designs with the highest relevance scores were chosen which are; 1) Safety, 2) Reliability, and 3) Stiffness as depicted in Figure 6-35.4. Finally, the loads of importance are calculated respectively by the AHP value in Figure 6-35.5. The result of the key value attributes (KVA) are; 1) Safety; 39%, 2) Reliability; 35%, and 3) Stiffness; 26%. Other values had low loads of importance because of several reasons, but most importantly, because they were no need to make improvements on them. Moreover, the system targets also should be specified in this phase in order to explain how the KVA will be reached. The system targets are measurable values which represent the target for the key value attributes as illustrated in Table 6-16.

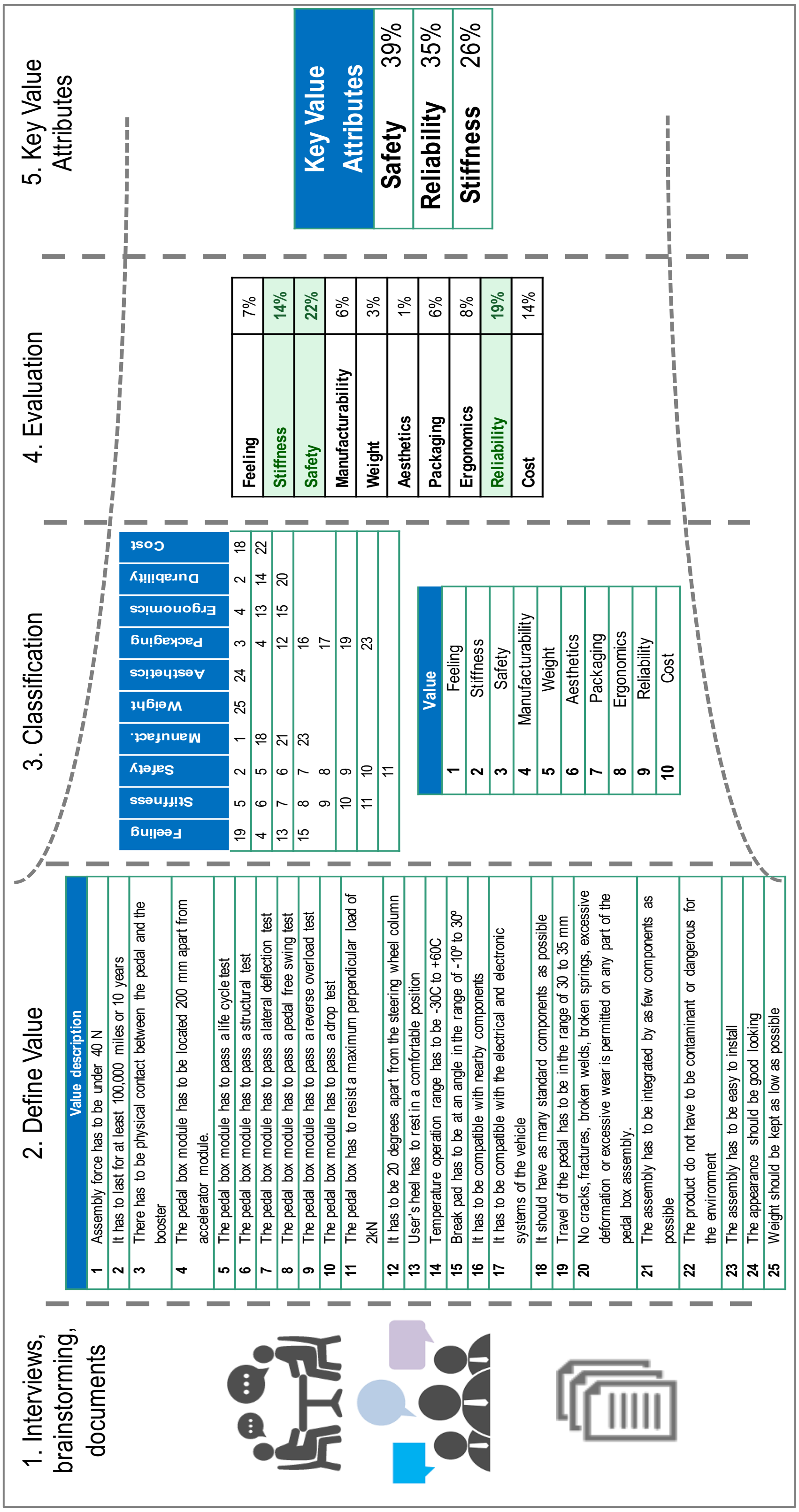


Figure 6-35 The process of identifying Key Value Attributes (KVA)

Table 6-16 System target for KVA

No	KVA	System targets
1	Safety	1. The pedal box has to pass a life cycle test 2. The pedal box has to pass a structural test 3. The pedal box has to pass a lateral detection test 4. The pedal box has to pass a pedal free swing test 5. The pedal box has to pass a reverse overload test 6. The pedal box has to pass a drop test
2	Reliability	1. It has to last for at least 100,000 miles or more 2. Temperature operation range has to be -30C 3. No defects or excessive wear permitted
3	Stiffness	1. Pedal arm has to be at an angle of 30 to 35mm 2. The pedal box has to resist a maximum perpendicular load of 2kN 3. The pedal box has to pass a life cycle test 4. The pedal box has to pass a structural test 5. The pedal box has to pass a lateral detection test 6. The pedal box has to pass a pedal free swing test 7. The pedal box has to pass a reverse overload test 8. The pedal box has to pass a drop test

<u>Step 2.4: Define scope of design work</u>

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 were used at this phase. The Level of Innovation tool is a colour coded tool which is used to simply communicate the innovation levels: providing the scale of levels of innovation considered. Figure 6-36 below illustrates an engineering drawing of the brake pedal box assembly, the components and their respective level of innovation. The level of innovation is a colour-coded tool that is used to visualise the level of innovation needed for each of the component or subsystem of a product (Ward, 2007; Oosterwal, 2010). This could promote a systematic communication that help companies to allocate their necessary resources in order to prevent over engineering and under engineering in developing a product. A high level of the innovation (red colour coded) 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 (yellow colour coded) was required for the pedal arm while the pedal pad and bushing are needed “no changes” in the design.

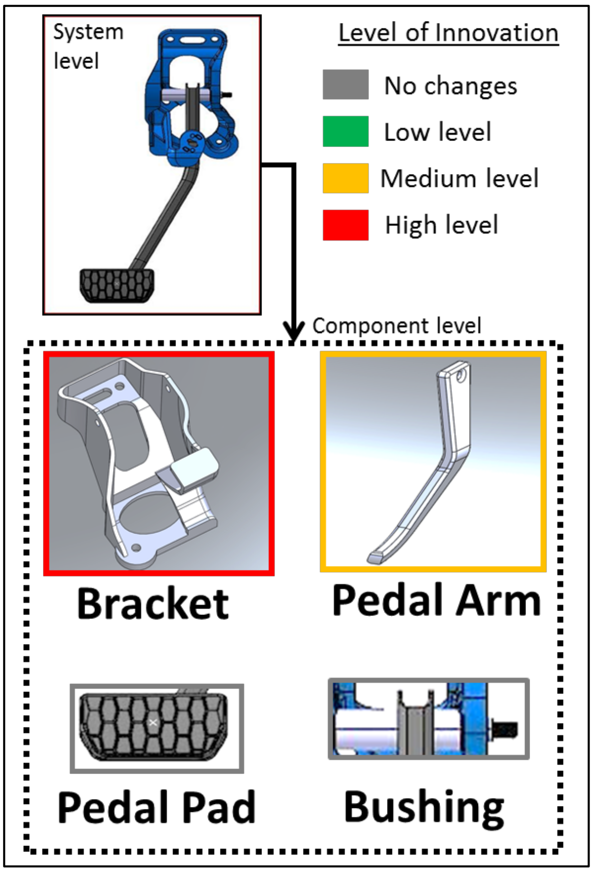


Figure 6-36 Level of Innovation

To have clear objectives for the design and then to evaluate those different design alternatives, it was 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 6-37.

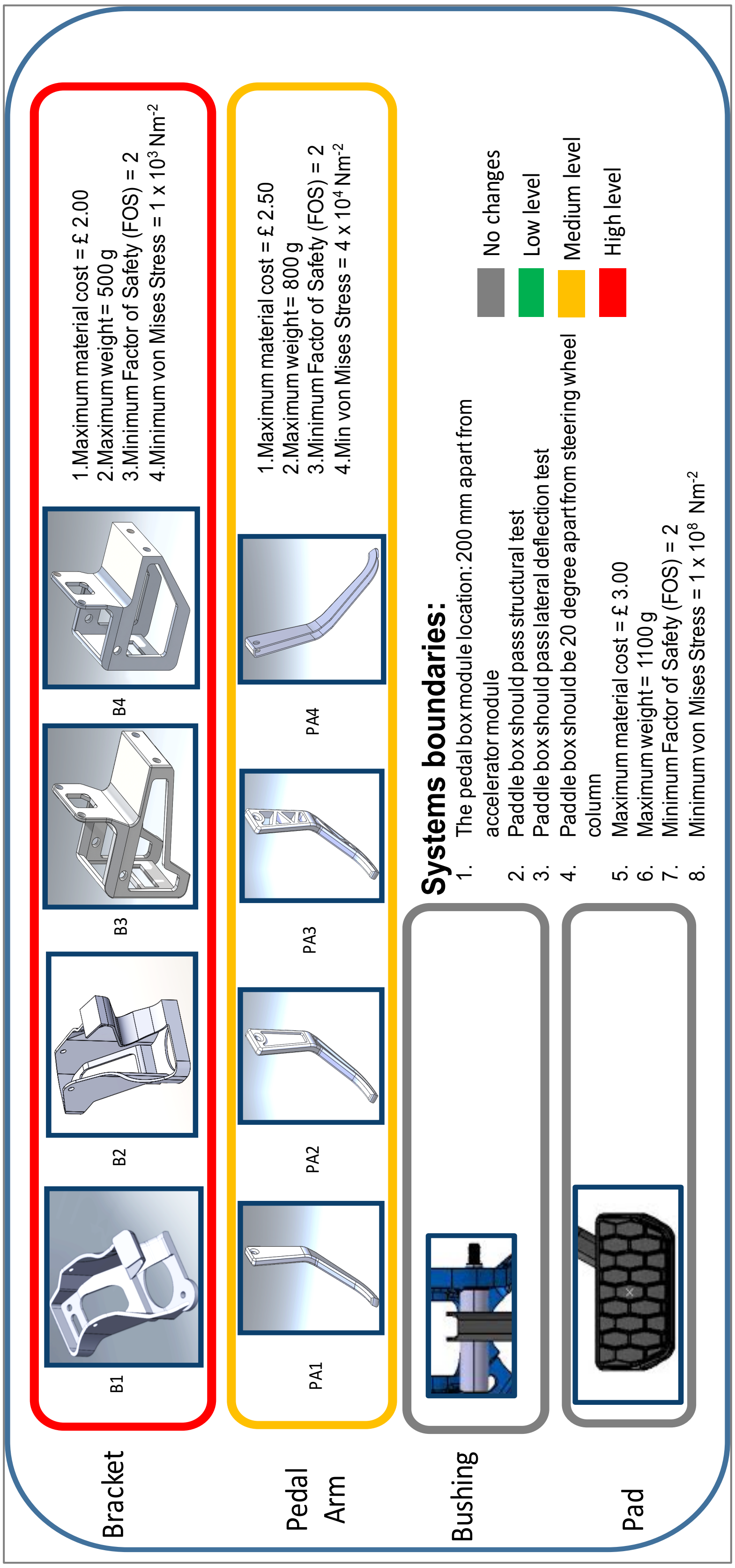


Figure 6-37 System and component boundaries

Phase 3: Evaluate

Step 3.1: Generate multiple alternative solution

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. Provided sufficient time for it, the same process would be followed for pulling and further exploring different designs for the bushing.

As described in Figure 6-38, four designs were found for both the bracket and the pedal arm; and three different materials were considered for each of them. This gives a total of 4x3=12 possible designs for each of them. When combined, it gives a total of 144 (12x12=144) different possible design solutions for the brake pedal, and therefore, potential solutions.

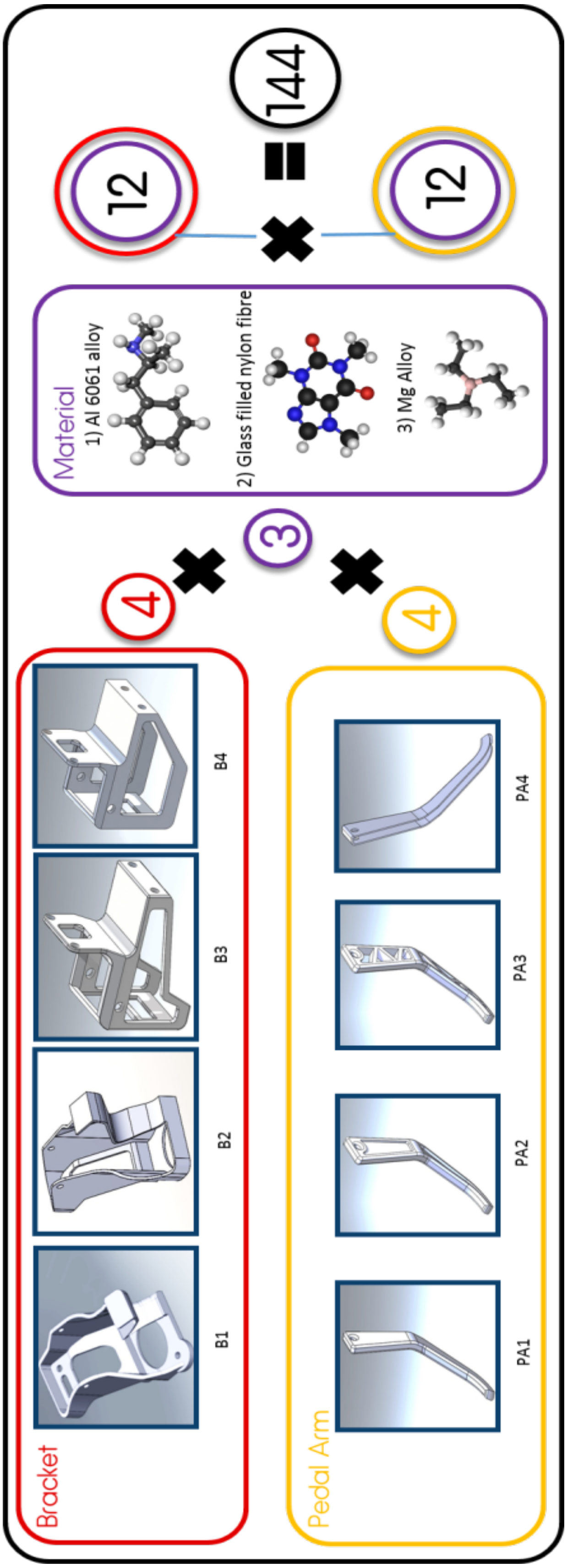


Figure 6-38 Possible design solutions

Step 3.2: Analyse, evaluate, and narrowing the solutions

The purpose of this activity is to analyse the conceptual solutions to ascertain their reliability. The simulation analysis in Solidworks software was used to create virtual prototypes of the parts that had the desired level of innovation i.e. the bracket and pedal arm. The stress analysis and factor of safety test analysis were carried out for the bracket (4 alternative designs) and pedal arm (4 alternative designs). The tests for both component alternatives design use three different alternative materials which is Aluminium Alloy 6061, Glass filled Nylon Fibre, and Magnesium Alloy. These materials were selected due to their characteristic ability to address the KVA which is safety, reliability, and stiffness. With 4 alternative designs combining with 3 material selection for bracket and pedal arm, 144 possible design solutions were generated, and calculation are as follows: [4 (bracket) x 3 (material)] x [4 (pedal arm) x 3 (material)] = 144 possible solutions. However, the numbers are too high to be analysed. Therefore, the possible solutions are simulated individually at the component level (bracket and pedal arm) to generate the stress and factor of safety values as shows in Figure 6-39.

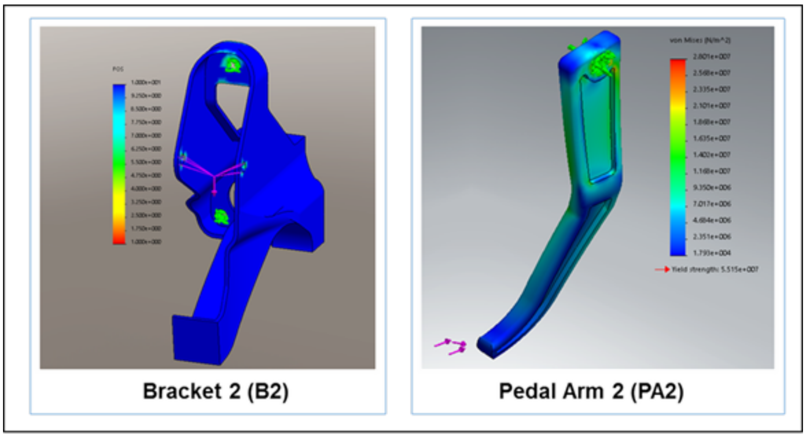


Figure 6-39 Example of the simulation analysis using Aluminium Alloy 6061

From the result of the simulation, the trade-off curves (ToCs) were used to aggressively narrow down the solutions (Araci, 2017). The ToCs were generated based on the component target in Table 4 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 equation. Figure 6-40, Figure 6-41, and Figure 6-42 illustrates the ToCs for the bracket while Figure 6-43, Figure 6-44, and Figure 6-45 illustrates the ToCs for pedal arm. 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. For instance, bracket "2.3" has a perfect relation as the values of stress (Figure 6-40), factor of safety (Figure 6-41), and material cost and weight (Figure 6-42) are within the feasible area in the ToCs. Contrary on the bracket "1.1", where not all values are within the feasible area in the ToCs hence, it will be discarded from the list of solutions. Similarly, the rest of the bracket and pedal arm were evaluated with the same method. As the result, the configuration was reduced from 144 to 6. The calculation is below:

- 2 (bracket: B2.1, B2.3) x 3 (pedal arm: PA2.1, PA2.3, PA3.1) x 1 (pedal pad) x 1 (bushing) = 6

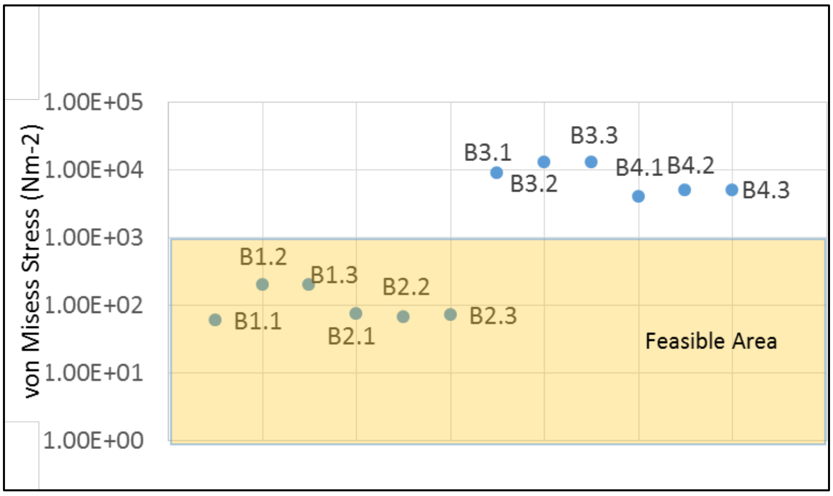


Figure 6-40 ToCs for von Misess Stress (Bracket)

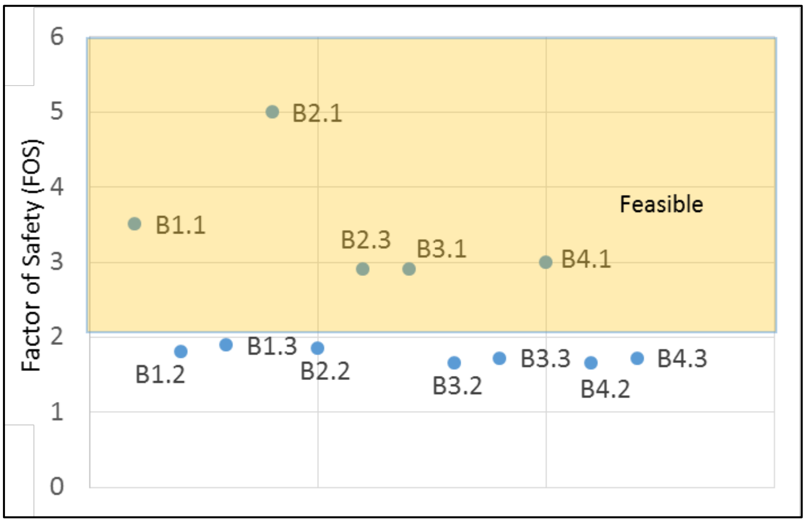


Figure 6-41 ToCs for Factor of Safety (Bracket)

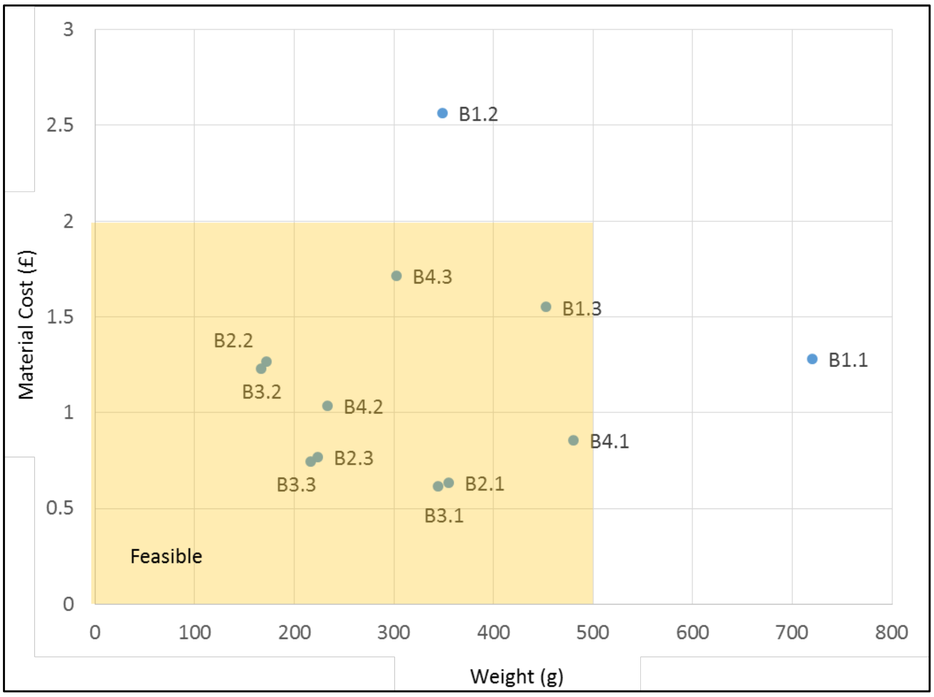


Figure 6-42 ToCs for Material cost vs. Weight (Bracket)

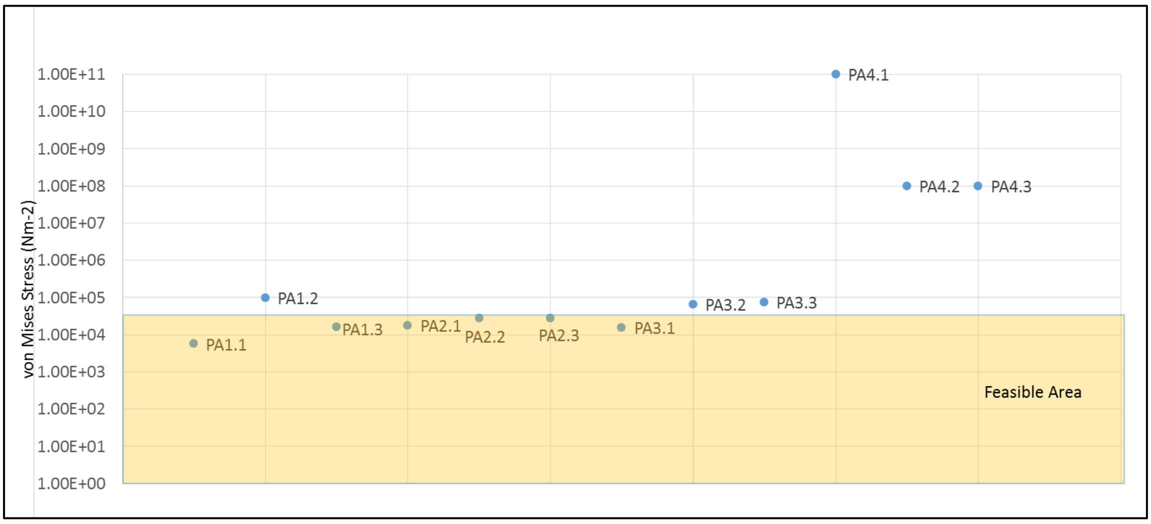


Figure 6-43 ToCs for von Mises Stress (Pedal Arm)

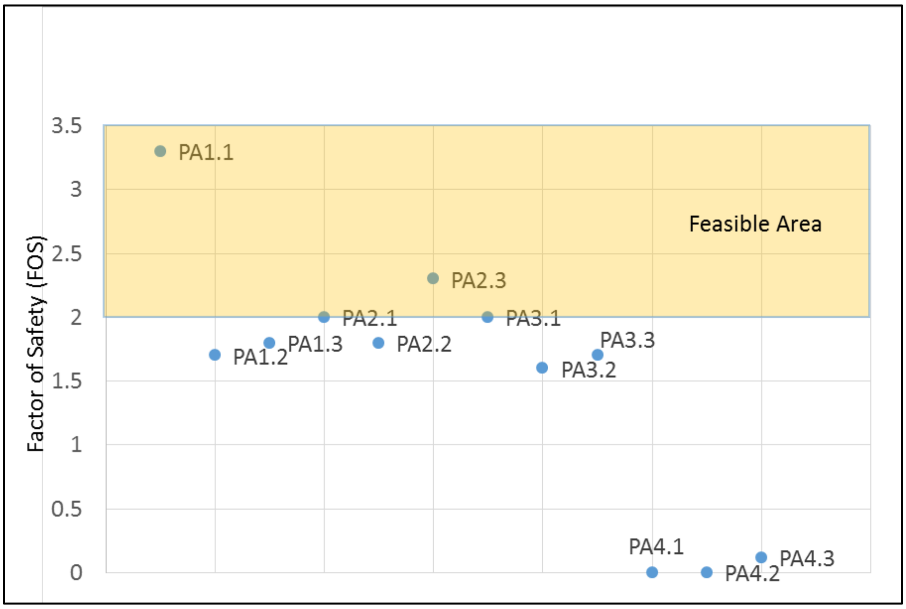


Figure 6-44 ToCs for Factor of Safety (Pedal Arm)

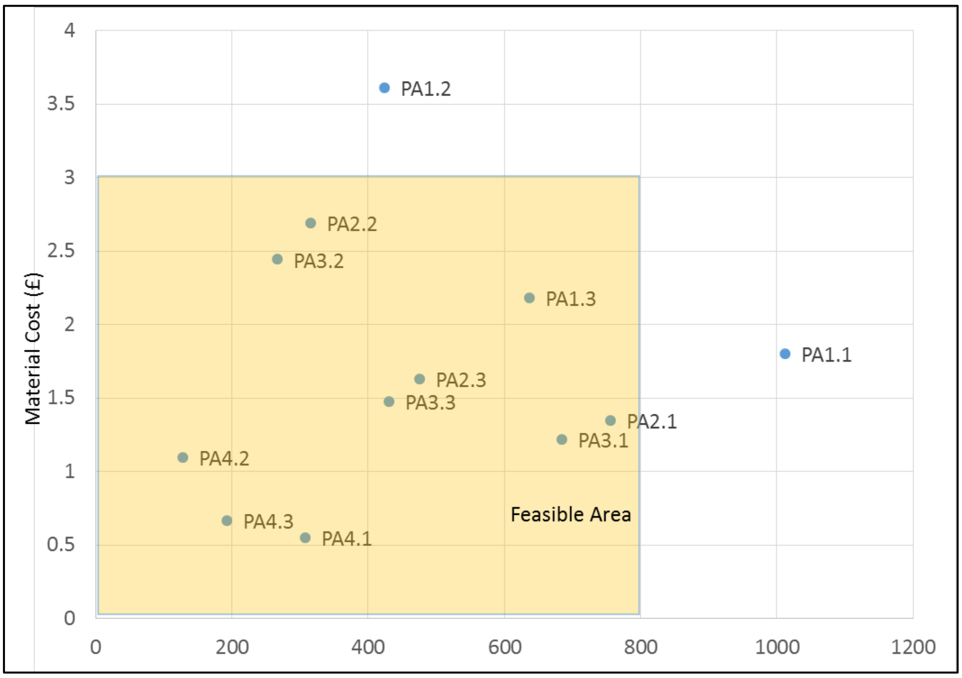


Figure 6-45 ToCs for Material Cost vs. Weight (Pedal Arm)

<u>Step 3.3: Select the optimum solution</u>

To obtain the optimal brake pedal box design, alternatives which were not increasing the design performance were discarded and the rest of the possibilities were developed until the optimum design solution was achieved.

The total number of combinations was reduced from 144 to 6. These were then intersected, and simulations were performed on these sets (load simulation of assemblies). In the step 3.3 activity "select optimum solution", the final brake pedal designs were generated using feasible component set of solutions. From 6 possible combinations, this number was narrowed down by using a lateral test simulation, as shown in Figure 6-46. From the lateral test simulation result, again the ToCs were used to narrow down the solutions as depicted in Figure 6-47, Figure 6-48, and Figure 6-49. With the same method used in step 3.2 "Analyse, evaluate, and narrowing the solutions", the focus was to identify the solutions that could satisfy each of the ToCs values in the feasible area. A combination that does not satisfy any of the ToCs values will be discarded from consideration. As a result, the design solutions were reduced from 6 to 3 which is; 1) B2. 3+PA2.1, 2) B2.3+PA2.3, and 3) B2.3+PA3.1.

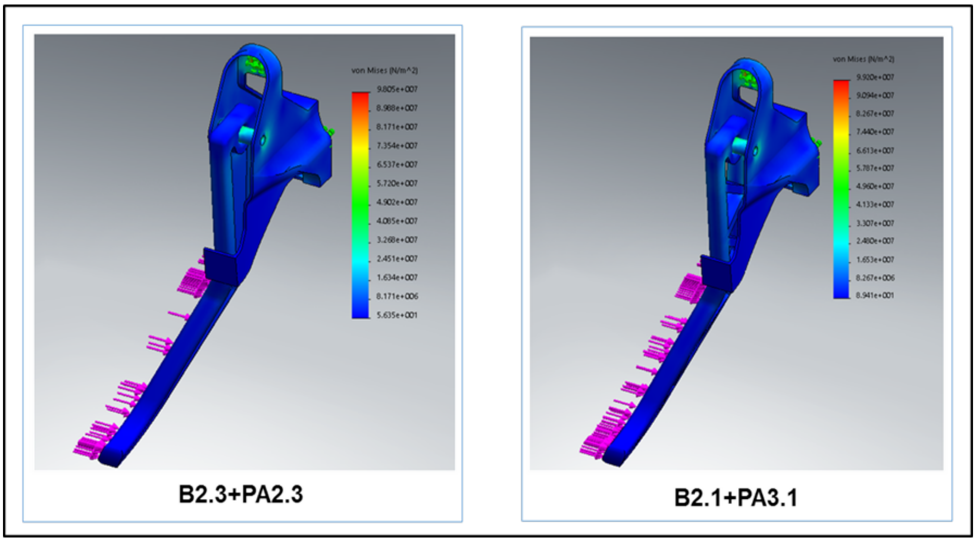


Figure 6-46 Example of lateral test simulation

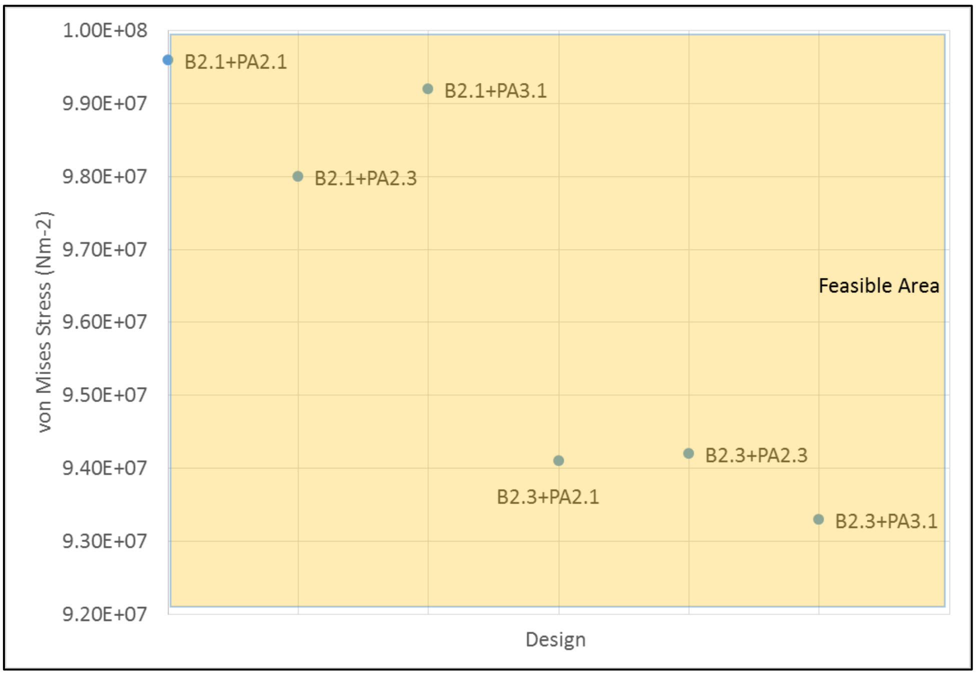


Figure 6-47 ToCs for von Mises Stress (Bracket with Pedal Arm)

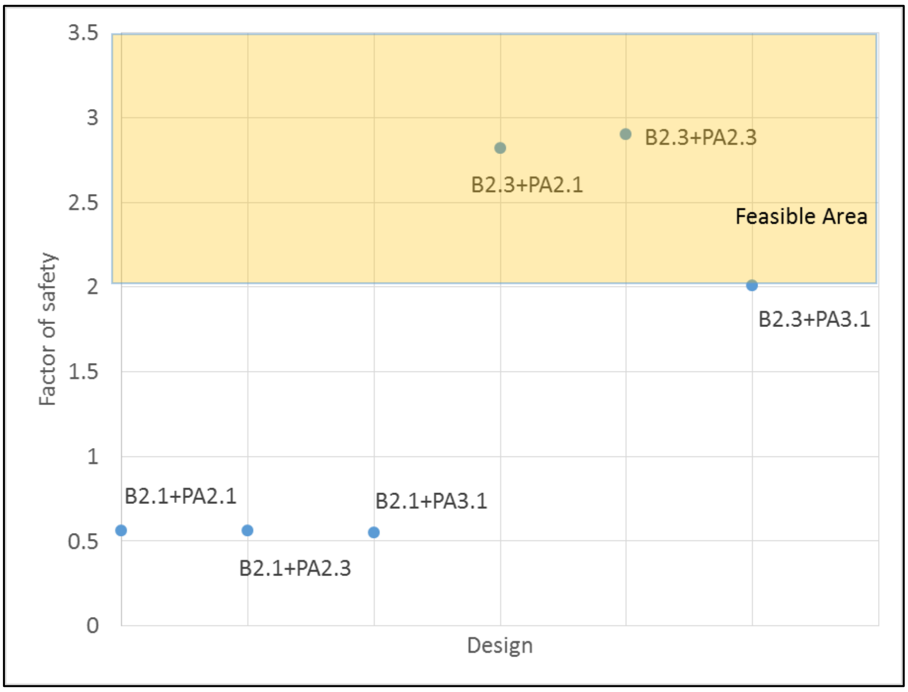


Figure 6-48 ToCs for Factor of Safety (Bracket with Pedal Arm)

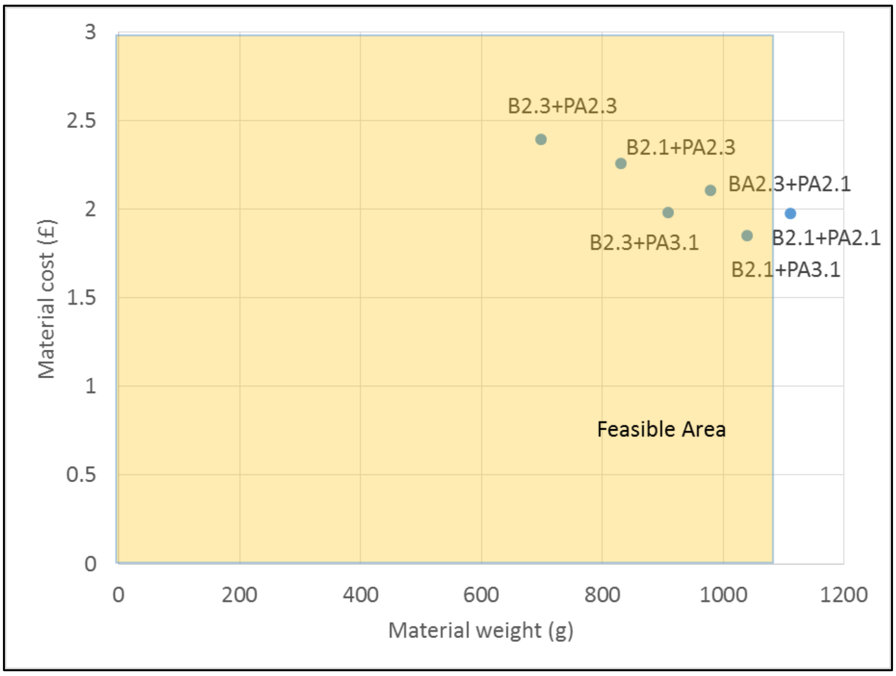


Figure 6-49 ToCs for Material cost Vs. Material weight (Bracket with Pedal Arm)

Furthermore, a narrowing process was performed based on the loads of importance from the KVAs. To achieve the final optimal solution for the brake pedal box, a Pugh Matrix (Ward and K. Sobek II, 2014) was used to compare the characteristics and degree of targets met of the last 3 design solutions from the intersection of sets with the weightings of the key value attributes. The performance scale was from 1-4, with 4 being the best in terms of targets met and 1 being the worst in terms of targets met as illustrated in Figure 6-50-A. The ratings of each design were then multiplied by the loads of the importance of the KVAs in Figure 6-50-B. The design solution with the highest total weighting was then selected as an optimal design solution. For instance, design "B2.3 + PA2.3" had a rating of 4 for safety, 3 for reliability and 2 for stiffness. These total weighting was then evaluated as follows:

$$(39\% \times 4) + (35\% \times 3) + (26\% \times 2) = 3.13$$

The weighting calculations for the other 3 concepts was done the same way as above. As a result, the optimal solution of the brake pedal is the B2.3+PA2.3 system which gives the highest score of 3.13 as depicted in Figure 6-50-B. Thus, this solution will be chosen to be the final optimal solution which then will be released to the final specification in the detailed design. The detailed design of the final optimal solution shown in Figure 6-51.

A

Scale	
4	The Best
3	Good
2	Moderate
1	The worst

B

Key Value Attributes	Loads of importance	B2.3+PA2.1	B2.3+PA2.3	B2.3+PA3.1
Safety	39%	3	4	1
Reliability	35%	2	3	1
Stiffness	26%	1	2	4
Weighted Total		2.13	3.13	1.78

Figure 6-50 Pugh Matrix for the brake pedal

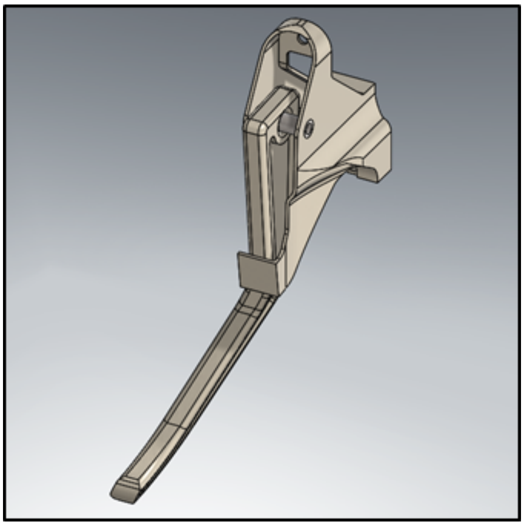


Figure 6-51 Final Optimal Solution for brake pedal box

Phase 4: Justify

Step 4.1: Identify tangible benefits from pilot project

The brake pedal case study shows the detailed application of the SBCE process model in the real scenario. This case study has benefitted the company by enhancing its current product development process as it provides an opportunity to explore alternative designs from different angles like the product performance, product innovation, and cost. The SBCE approach guided the development of a brake pedal box with the right design and engineering activities as well as the associated tools and method to enable the application of the different activities. In addition, the SBCE approach provided a suitable knowledge environment to support decision making throughout the development process.

There are several tangible benefits which could be seen as an evidence in addressing the challenges in Table 6-14. Typically, a business case is built on the return on investment, However, during the early stage of SBCE introduction, the business case is based on the potential tangible benefits in a few key areas which is;

1. Improved product innovation
2. Improved product performance
3. Minimised impact of material cost
4. Maximized probability of project success

The innovation and knowledge creation level has increased: 144 system design configurations were identified through the application of the SBCE process model in the case study. This could give an opportunity for the designers and engineers in JLR to explore the possible designs within the design space without any difficulties from the current product development practices. The 144 design solutions have been generated based on creativity which corresponds to the key value attributes; safety, reliability, and stiffness.

Secondly, product performance has improved through an implementation of the SBCE. Improvements were achieved in four areas which are stiffness, weight, material cost, and, factor of safety (reliability). These improvements have been gained through an analysis using Solidwork software for the bracket and pedal arm. The analysis was based on the comparison of the component boundary data as shown in Figure 6-37.

The analysis of the stiffness originated from the equation of von Mises Stress which connected using distortion energy failure theory (Segalman *et al.*, 2000). The distortion energy required per unit volume, therefore the equation was derives as follows:

$$\left[\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}\right]^{1/2} \geq \sigma_y$$

Equation 8 Distortion energy

The left side of the above equation represents the von Mises stress, where the right side (σ_y) is the yield strength of the material. To simplify, the von Mises stress value is expressed as σ_v in the following equation:

$$\left[\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}\right]^{1/2}=\sigma_v$$

Equation 9 von Mises stress

Therefore, if the von Mises stress induced in the material surpasses yield strength of the material, the product will fail. Thus, the lower von Mises stress will give the best result which describes as follows:

$$\sigma_v \leq \sigma_y$$

These could be analysed quickly through a simulation of von Mises stress in Solidwork software. From the analysis, the von Mises stress was carried out at component level, which is the bracket and pedal arm. The comparison of the result is between the component target and final solution. The von Mises stress for the bracket and pedal arm was improved (decrease) by 92.7% and 32% respectively. The percentage is calculated as follows;

- Improvement percentage for the von Mises stress (Bracket);

$$\frac{1 \times 10^{3}\ Nm^{-2}\ \text{(Original)} - 7.33 \times 10^{1}\ Nm^{-2}\ \text{(Bracket 2.3)}}{1 \times 10^{3}\ Nm^{-2}\ \text{(Original)}}$$

$$= 0.927 \times 100\%$$

$$= 92.7\%$$

- Improvement percentage for the von Mises stress (Pedal Arm);

$$\frac{4 \times 10^{4}\ Nm^{-2}\ \text{(Original)} - 2.72 \times 10^{4}\ Nm^{-2}\ \text{(Pedal Arm 2.3)}}{4 \times 10^{4}\ Nm^{-2}\ \text{(Original)}}$$

$$= 0.32 \times 100\%$$

$$= 32\%$$

- Improvement percentage for the von Mises stress (Bracket + Pedal Arm);

$$\frac{1 \times 10^{8}\ Nm^{-2}\ \text{(Original)} - 9.42 \times 10^{7}\ Nm^{-2}\ \text{(B2.3+PA2.3)}}{1 \times 108\ Nm\text{-}2\ \text{(Original)}}$$

$$= 0.58 \times 100\%$$

$$= 58\%$$

The weight of the brake pedal box was reduced by 39.1%. The percentage are calculated as follows;

- Improvement percentage for the weight (Bracket + Pedal Arm)

$$\frac{\text{1100 gram (Original)} - \text{669.76 gram (B2.3+PA2.3)}}{\text{1100 gram (Original)}}$$

= 0.391 x 100%
= 39.1%

As the weight reduced, the material cost also reduced by 45%. This was achieved through an alternative material selection of magnesium alloy instead of steel in the original design. The percentage are calculated as follows;

- Improvement percentage for the material cost (Bracket + Pedal Arm)

$$\frac{\text{£3.00 (Original) - £2.391(B2.3+PA2.3)}}{\text{£3.00 (Original)}}$$

= 0.203 x 100%
= 20.3%

In addition, the factor of safety of the brake pedal box has improved by 45% which increase its reliability and performance. The percentage are calculated as follows;

- Improvement percentage for the factor of safety (Bracket + Pedal Arm)

$$\frac{\text{2.9 (B2.3+PA2.3)} - \text{2 (Original)}}{\text{2 (Original)}}$$

= 0.45 x 100%
= 45%

The probability of having a successful project also was increased by implementing the SBCE in the product development. The test is to show how SBCE was able to eliminate the rework activities in product development by having the highest rate of successful designs and least percentage of failure risk. As explained in sub-chapter 5.4.2, Ward and K. Sobek II (2014) described three rules employed in the probability test to identify the risk. In the probability test, the comparison was made between 3 final possible solutions obtained from using the SBCE approach and one solution in traditional point-based design approach.

The possible solutions were taken from the step 3.3 "Select the optimum solution" as each of the subsystems at this stage has a potential to integrate with each other. Meanwhile, the one solution is taken from the current practice of product development in the company.

Due to confidentiality, the probability value of the component will cause a major problem is taken from average fraction values of the number of components represents in brake pedal box. It means that 25% of each of the components might have a potential of having a problem while another 75% of the components have the probability of success as depicted in Table 6-17.

Table 6-17 Probability of failure and success for subsystem

Component	Probability of Failure (P_f)	Probability of Success (P_s)
Bracket	0.25	0.75
Pedal Arm	0.25	0.75
Bushing	0.25	0.75
Pedal Pad	0.25	0.75

Therefore, the author applies the probability rules equation (see sub-chapter 5.4.2) as follows;

Firstly, from Table 6-17, the probability of considering 3 design concepts calculated as follows;

<u>Rule 1 and Rule 2</u>

The probability of failure from 3 design concepts is;

$$POF_n = P_f^{\,n}$$

$$= 0.25^3$$

$$= 0.0156$$

$$= 1.56\%$$

The probability that all subsystems will have at least one successful design;

$$\mathrm{POS} = (1 - \mathrm{POF_n})^{\mathrm{m}}$$

$$= (1 - 0.0156)^4$$

$$= 0.939$$

$$= 93.9\%\ \text{succesful rate}$$

<u>Rule 3</u>

The average number of successful designs;

$$\bar{\mathrm{x}} = \mathrm{n}\ (\mathrm{P_s})$$

$$= 3\ (0.75)$$

$$= 2.25\ \text{sucessful design}$$

Secondly, from Table 6-17, the probability of considering only 1 design concept calculated as follows;

<u>Rule 1 and Rule 2</u>

The probability of failure for 1 design concept is;

$$\mathrm{POF_n} = \mathrm{P_f}^{\mathrm{n}}$$

$$= 0.25^1$$

$$= 0.25$$

$$= 25\%$$

The probability that all subsystems will have at least one successful design;

$$\mathrm{POS} = (1 - \mathrm{POF_n})^{\mathrm{m}}$$

$$= (1 - 0.25)^4$$

$$= 0.316$$

$$= 31.6\%\ \text{succesful rate}$$

Rule 3

The average number of successful designs;

$$\bar{x} = n\,(P_s)$$

$$= 1\,(0.75)$$

$$= 0.75 \text{ sucessful design}$$

From the probability tests, the success rate has increased from 31.6% to 93.9%. This result shows how SBCE approach is much more reliable compared to point-based approach. In addition, the risk of having a failure design also have been reduced from average only 0.75 successful designs (not even 1) to average 2.25 successful designs after SBCE application. As summarised, the research proves that the SBCE has the potential to produce high quality products on time and in a cost-effective manner.

Step 4.2: Document and present the business case to management

The map of the business case is presented in step 4.2. This step will explain the summary of the business case activity by providing the outcome in short presentable information. The information should contain the tangible benefits gain from the application of the SBCE. This information should not include any formula or calculation. Instead, keep the backup files containing the details in case of someone from the stakeholder need that information for clarification. In this research, a PowerPoint slide has been created to show the value of SBCE application, however the details of the slides are not presented in this thesis except the summary of the benefits as shows in Figure 6-52. In addition, the steps of the slides are the same as explained in the previous chapter.

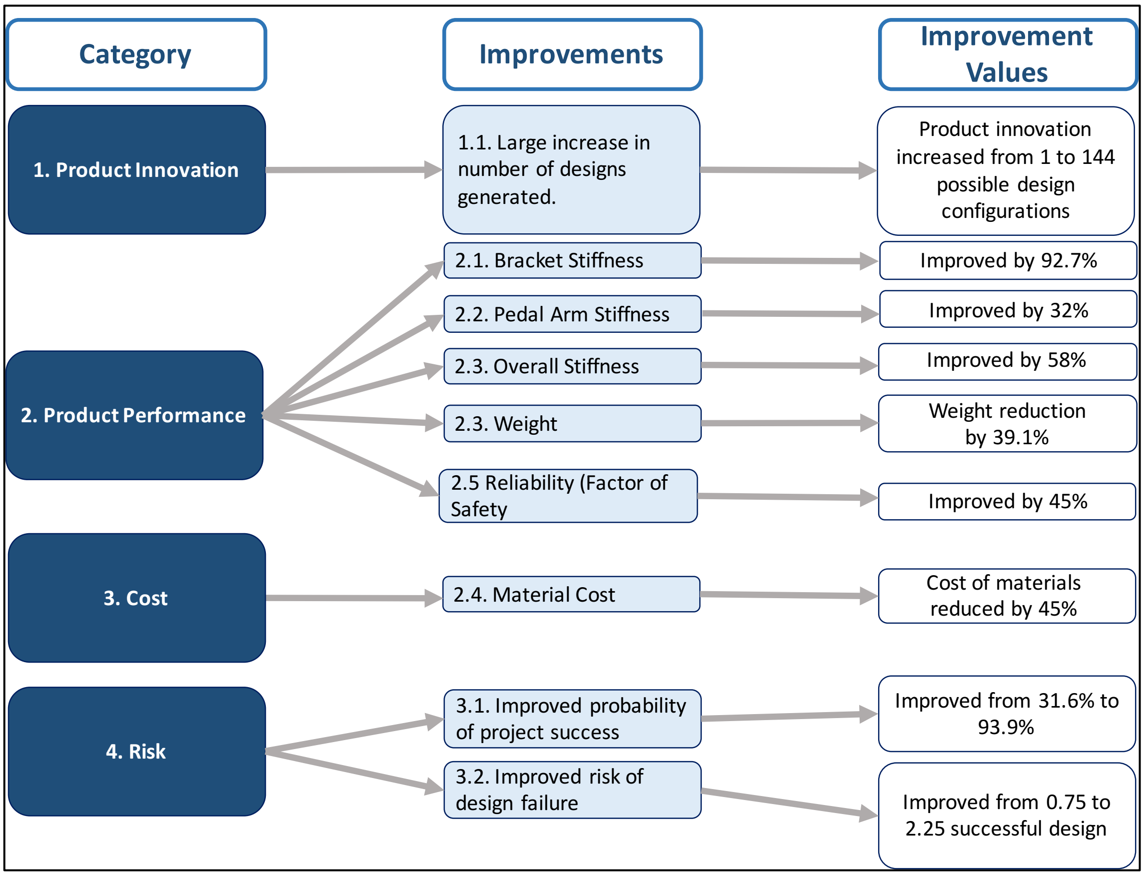


Figure 6-52 Example of the slides; mapping the tangible benefits of SBCE

7 DISCUSSION, CONTRIBUTION TO KNOWLEDGE, RESEARCH LIMITATION, CONCLUSION, AND FUTURE WORK

7.1 Introduction

In this chapter, the discussion, conclusion, and future work for this research will be presented. The structure of this chapter includes 7.1) Introduction, 7.2) Discussion of research findings, 7.3) Contribution to knowledge, 7.4) Research Limitation, 7.5) Conclusion, and 7.6) Future work as described in Figure 7-1

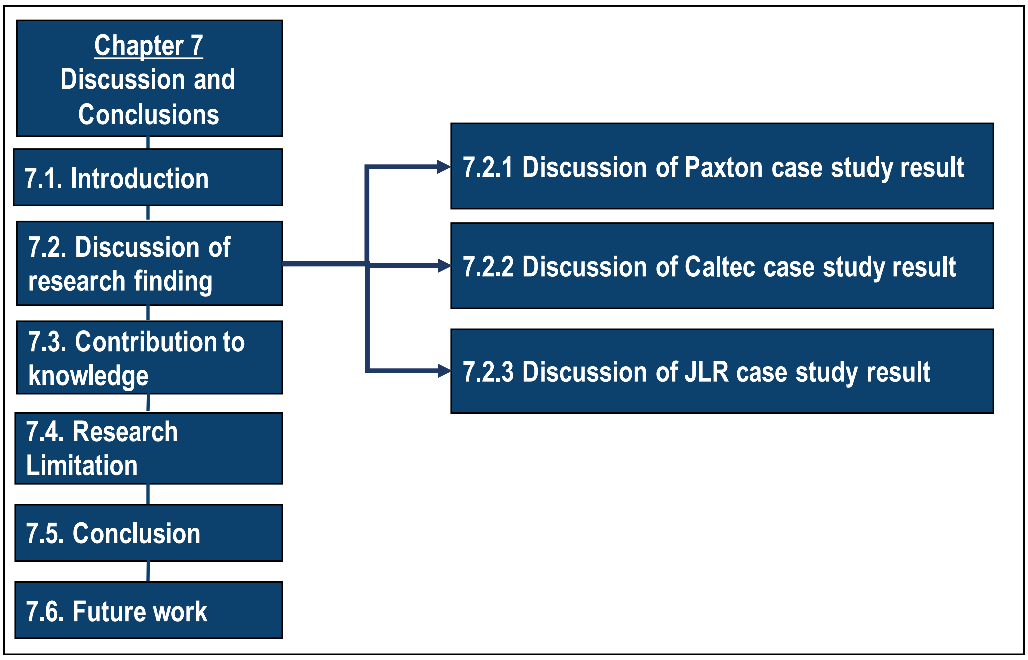


Figure 7-1 The structure of chapter 7

7.2 Discussion of research findings

This sub-chapter 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.

Towards developing a business case for the SBCE, a literature on product development challenges was captured from various articles and theses. A total of nine challenges were obtained where each of the challenges was supported by various reliable literatures. These findings were used as a foundation to demonstrate the ability of applying SBCE to address those challenges. This was explained in sub-chapter 3.3 in the thesis.

Through the analysis of the literature, the SBCE is the core enabler of LeanPD as it represents the process model that should be followed in developing a product. The SBCE focuses on value creation, provision of a knowledge environment, continuous improvement, and process that encourage innovation through the exploration of sets of alternative solutions. A systematic review has been conducted in which the various approaches of lean PD have been analysed to evaluate their adoption and application of lean principles, as well as the importance of applying SBCE. The review showed two main groups; which at first, mentions and emphasises the importance of SBCE without presenting any detailed work. While the second group developed and acclaimed LeanPD frameworks without addressing SBCE application. Both groups are described in detail in sub-chapter 3.4. In the event of introducing SBCE, not all of the activities in Figure 3-4 were used. The selected activities used in this research are the activities that lead the development of the business case as it could demonstrate the tangible benefits of the application of the SBCE.

The analysis of extensive literature, industrial perspective, and case studies has provided a foundation in developing a SBCE business case framework and its following implementation. The aim of the framework is to provide a guideline in developing a business case for the introduction and applications of the Set-Based Concurrent Engineering (SBCE). Having a business case would not only help the company identify the potential solution, but also help sell the idea to the stakeholders with valid justification. A number of phases defined in the framework represent the top-level process. The framework was established in a four-phase approach where each of the phases consists of a series of activities that are unique to the purpose of developing the business case for introducing the SBCE. These were aligned with the principles of SBCE. The framework is categorised as follows; Phase 1: Driver, Phase 2: Demonstrate, Phase 3: Evaluate, and Phase 4: Justify. Each of the phases is explained in detail in sub-chapter 5.4.

In order to measure the success of the business case for introducing the SBCE, metrics have been assigned. The purpose of having these metrics is to track and assess the effectiveness of SBCE. The SBCE metrics development is built on quantifiable measurements that could measure the effectiveness of SBCE applications. During the extensive literature review, field study, and performing the case study, the key SBCE metrics are identified and considered as “should be monitored” in introducing the SBCE which is- 1) Knowledge and learning metric, 2) Product performance metric, 3) Cost metric, and 4) Risk metric.

The following sub-chapter will discuss the results of the case studies from chapter 6 using the SBCE business case framework that has been constructed.

7.2.1 Case Study 1

Case study 1 was performed in Paxton Access Limited, a leading company in the manufacturing of electronic access control systems. The company has been selected due to its continuous production of innovative products that add value to the customer and the range of services. The case study was set up to develop a new design of a vandal-resistant “Reader” that has the ability to resist vandals using the principles and processes of SBCE, which means, it is resistant to different types of damage; for instance, removal of the “Reader” by hand, striking the “Reader” with any object, burning the case with fire, and spoil with liquid, sand or stones. Other important features in this reader are the ability to capture a wide range of credentials and the ease of installation and maintenance.

The implementation of the SBCE business case framework which is shown in Figure 5-1, helped the company to smooth their PD processes and improved their confidence level by having the optimal solution through the application of SBCE. There are a number of findings derived in case study 1:

1. There is an available time to demonstrate the power of SBCE in the case study, however, to see the journey of the company towards LeanPD required a longer time as well as necessity to have a full implementation of SBCE in their PD process.

2. The culture and learning have been embedded in the organisation through an awareness training session, however the most important outcome is to develop the culture change. By doing so, the impact will be greater in the organisation.
3. The phase is categorised into structured step-by-step activities in order to create a smooth flow during the process of developing the business case for introducing the SBCE.
4. The process of narrowing down the number of the solution uses a subjective judgement rather than objective judgement for instance through the process of ToCs.
5. The visualisation method does help the company to understand easily and effectively during the evaluation of design options, until reaching the optimal solution.
6. The weaker solutions are not considered as waste, rather they are kept for future projects.
7. Tangible benefits were obtained through a constructed and systematic approach.

7.2.2 Case study 2

The aim of the case study 2 is to present a novel application of the SBCE in order to generate a new design to enhance the efficiency of the Surface Jet Pump (SJP) in terms of its productivity and performance in producing the oil and gas in an oil and gas well. The main feature of SJP is to enhance the performance of gas extraction that could be understood as an increase of pressure at the output or High Pressure (HP) source and the reduction in pressure on Low Pressure (LP) source by maintaining output parameters.

The implementation of the SBCE business case framework which is shown in Figure 5-1, helped Caltec to smoothen their analysis process and improve their confidence level by selecting the optimal solution through the application of SBCE. A number of findings were derived in case study 2:

1. There is an available time to demonstrate the power of SBCE in the case study, however to understand the PD practices in the Caltec organisation, a LeanPD performance assessment needs to be performed.
2. The analysis has been performed using the low fidelity data to speed up the process of selecting the optimal solution as opposed to using the high-fidelity data which requires a longer time to complete. However, the result's reliability from the analysis is still not compromised.
3. Visualisation method helps Caltec to understand easily and effectively during the evaluation of design options until reaching the optimal solution.
4. The weaker solution is not considered as waste, rather it is kept for future projects.
5. The phase is categorised into structured step-by-step activities in order to create a smooth flow during the process of developing the business case for introducing SBCE.
6. The process of narrowing down the number of the solutions uses an objective judgement through the process of ToCs that include 2-dimensional and 3-dimensional ToCs.
7. Tangible benefits were obtained through a constructed and systematic approach.
8. The new design of SJP from the case study has been used by a Malaysian oil and gas company called Petronas. This has been acknowledged by the Director of Technology at Caltec where the physical product is shown in Figure 7-2.

Figure 7-2 The new SJP design with N10 nozzle ready to be installed

7.2.3 Case study 3

The SBCE process model was applied in case study 3 to demonstrate its ability in addressing the product development challenges faced by the Chassis Engineering Department at JLR. The brake pedal box is one of the most important parts in a car which functions to assist a car driver with control over the car while driving. The most important characteristics of the brake pedal box desired are safety, reliability, and stiffness of the brake pedal box.

The implementation of the SBCE business case framework which is shown in Figure 5-1, helped JLR to smoothen their PD process and improved their confidence by selecting the optimal solution through the application of SBCE. A number of findings were derived in the case study 3:

1. There is an available time to demonstrate the power of SBCE in the case study, however to see the journey of the company towards LeanPD required a longer time as well as necessity to have a full implementation of SBCE in their PD process.
2. Access to the data is limited due to confidentiality, only basic data is provided for the case study.
3. The culture and learning have been embedded in the organisation through an awareness training, however the most important outcome is to develop

the culture change. By doing so, the impact will be greater in the organisation.

4. The analysis has been performed using the low fidelity data to speed up the process of selecting the optimal solution as opposed to using the high-fidelity data which requires a longer time to complete. However, the result's reliability of the analysis is still not compromised.
5. Visualisation method helps JLR understand easily and effectively during the evaluation of design options until reaching the optimal solution.
6. The weaker solution is not considered as waste rather it is kept for the future projects.
7. The phase is categorised into structured step-by-step activities in order to create a smooth flow during the process of developing the business case for introducing the SBCE.
8. The process of narrowing down the number of the solutions uses an objective judgement through the process of ToCs; a 2-dimensional ToCs.
9. Tangible benefits were obtained through a constructed and systematic approach.

7.3 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 business case framework for introducing the SBCE. This means that the scope is tailored to focus on introducing the SBCE which led to an adoption only on selected activities which could deliver an immediate impact in obtaining the tangible benefits as described in sub-chapter 5.2. Thus, 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. Since the business case in SBCE is a novelty topic, the scope of business case has gone through benchmarking from several other initiatives such as information technology, quality, knowledge management, safety, and business. However, commonalities of each of the initiatives are later tailored to suit the need for SBCE.

The reason for this limitation is;

a. It is important to have a specific and certain topic for the research
b. It is important that the research could be done in a specified time period.

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 generating the ToCs for the evaluation process. This is due to the situation where the company does not have a properly established data platform. 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. Due to this limitation, some data are collected from open data available in the market for instance, in product specification or technical specification. Although using an open data access, the result of the research is not compromised in any way.

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. However, this time limitation has been minimised through a mitigation of the time constraint among research team.

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.

7.4 Research Contributions

The research that has been carried out contributes to the scientific knowledge in many ways. The research contributions are as follows:

1. The key research contribution is the development of business case framework for introducing the SBCE. Having this would not only help the company identify the potential solution, but also help to sell the idea to the stakeholders with valid justifications on tangible benefits.
2. Clarify the gap in the application of details and well-structured SBCE process model and the business case.
3. Establish a structured guideline on developing business case for introducing SBCE in the company.
4. Establish the potential metrics that should be used to measure the performance of SBCE application in product development.
5. A new conceptual design for the front cover of a card Reader that is resistant to vandalism
6. A new conceptual design for the Surface Jet pump (SJP) that has better performance compared to existing product.
7. A new design for SJP in the case study has been manufactured and used by the Malaysian oil and gas company called Petronas.

8. A new conceptual design for the brake pedal box that has better stiffness and reliability compared to existing product.

7.5 Conclusion

As the research comes up to an end, the following conclusion was listed:

1. The literature review highlighted the importance of the Set-based Concurrent Engineering approach in supporting the development of an innovative product, however, there is a lack of a real industrial case studies with real tangible benefits of the application which this thesis has contributed to.
2. There are several acclaimed SBCE process models, but there is no guide on how to justify its introduction, therefore, there is a need for this framework. Therefore, this thesis contributed to the development of the business case framework
3. When having a business case, it is important to have a framework that is focused on measuring the tangible benefits from company to company or sector to sector.
4. While working with the industry, it is very important to have a real pilot project from within the company's business rather than a hypothetical project. This enables the company to be engaged in the actual SBCE application rather than have only a theory based SBCE.
5. Constructing a business case framework does help the companies to identify the potential solution and justify the tangible benefits in a structured way.

7.6 Future Work

Based on the findings of the research, a number of suggestions for future work are listed below:

1. The knowledge obtained from the SBCE application should be captured and stored in a well-established database for future projects, hence it could help to reduce the iteration or reinvent processes that may occur when a new project commences.
2. Further industrial applications of the SBCE business case framework should be investigated not only at different sectors, but also on complex integrations such as system to system or function to function.
3. Full implementation of the SBCE process model should be investigated for future work.
4. There is a requirement to extend the SBCE business case framework from focusing on introducing the SBCE to a full implementation. Thus, the impact on the business will be more significant to the company.
5. A well-structured team led by a Lean Champion should be developed in order to steer the organisation towards full implementation of SBCE.

LIST OF PUBLICATION

Journal

1. Mohd Maulana, M.I.I, Sherrey, G., Al-Ashaab, A., Martin, A.J., Vats, K., Omoloso, O., Masson, T., Leigh, T., Perramon, T.G., Moreno, V.R., Zhang, Y., 2017. “Developing Business Case Framework for The Introduction of The Set-Based Concurrent Engineering; A Case Study at Jaguar Land Rover”, International Journal Of Systems Applications, Engineering & Development, v.11, p. 128-137.
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4. Mohd Maulana, M.I.I., Al-Ashaab, A., Sherrey, G., Martin, A.J., Vats, K., Omoloso, O., Masson, T., Leigh, T., Perramon, T.G., Moreno, V.B., Zhang, Y., “Business Case for Introducing Set-Based Concurrent Engineering; A Case Study at Automotive Company”. (In review)

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1. Maulana, M.I.I.B.M., Al-Ashaab, A., Flisiak, J.W., Araci, Z.C., Lasisz, P.W., Shehab, E., Beg, N. and Rehman, A., 2017. The Set-based Concurrent Engineering application: a process of identifying the potential benefits in the Surface Jet Pump case study. Procedia CIRP, 60, pp.350-355.
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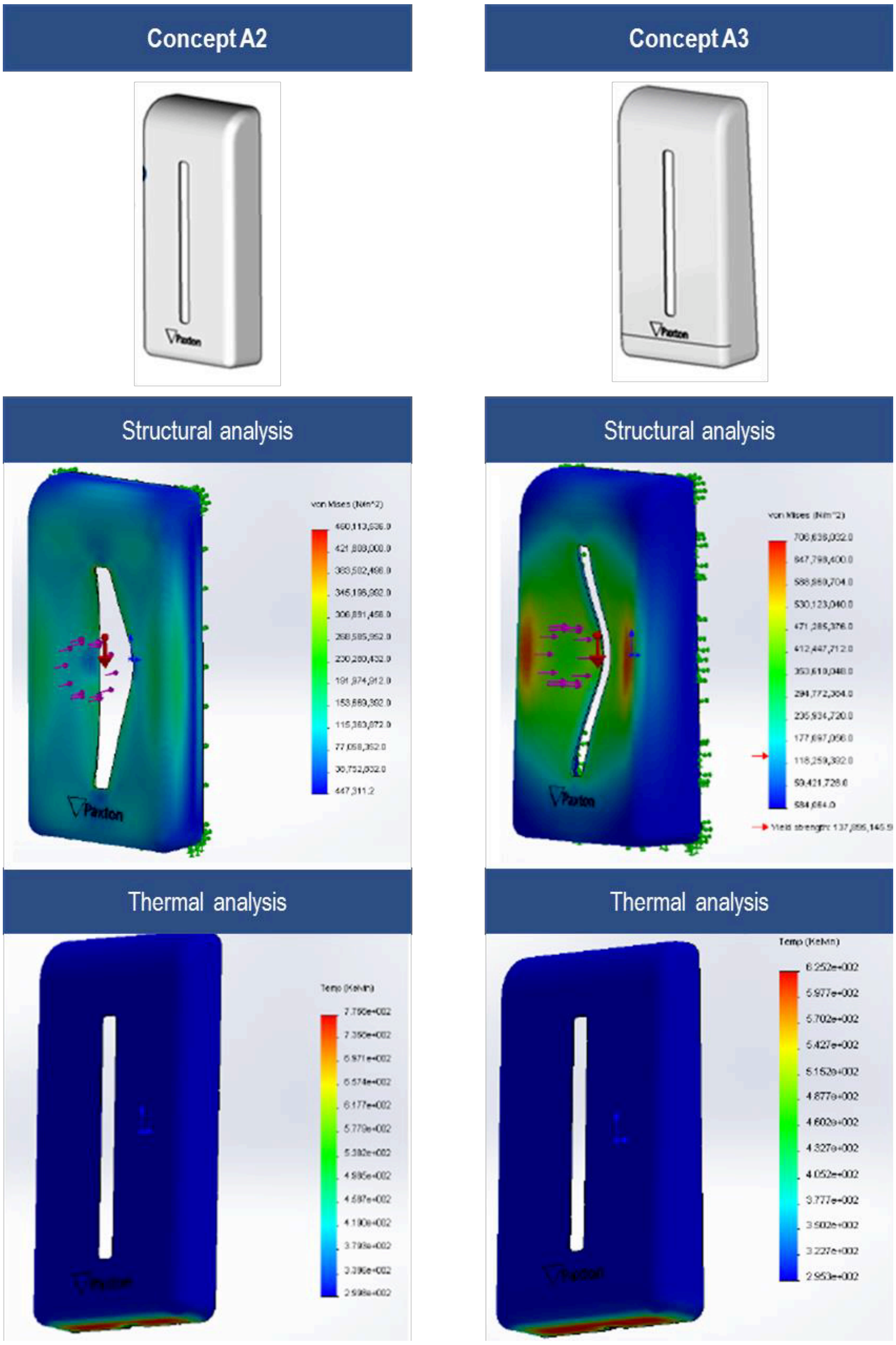
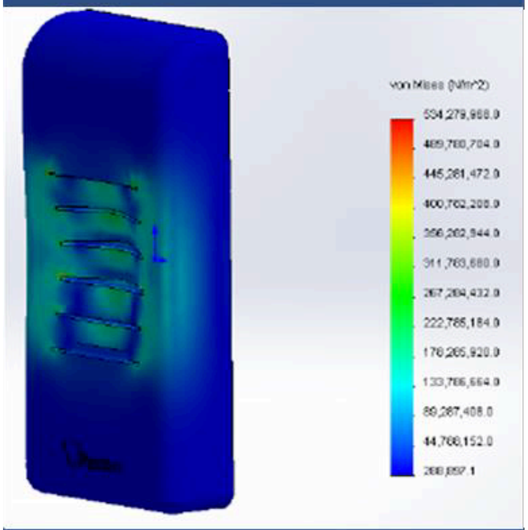
APPENDICES

Appendix A Paxton Case Study: Structural and Thermal Analysis

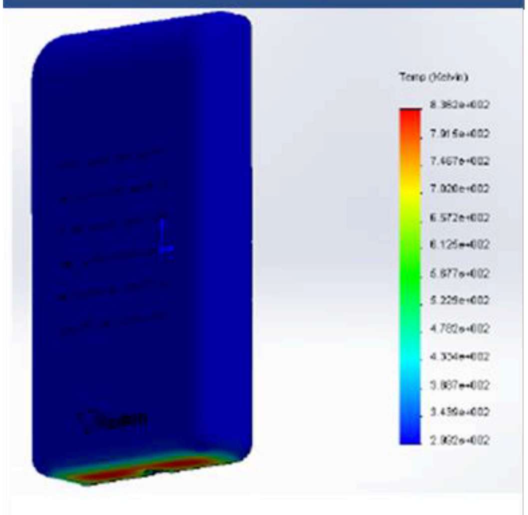


Concept A4

Structural analysis

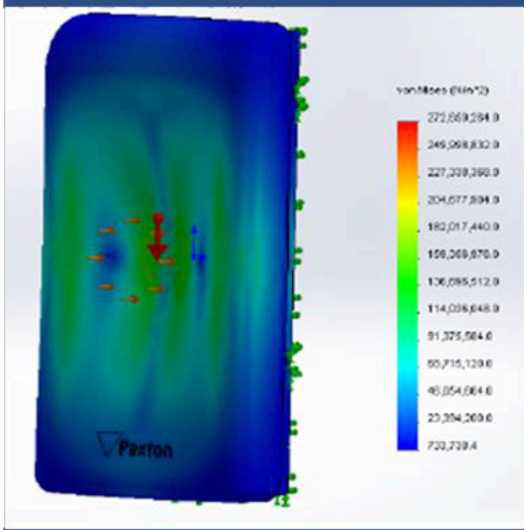


Thermal analysis

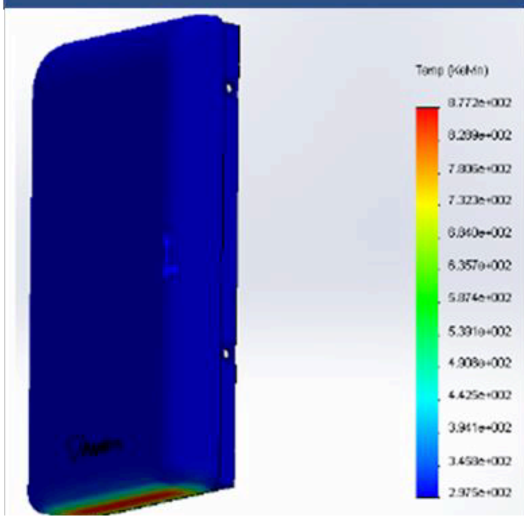


Concept A5

Structural analysis

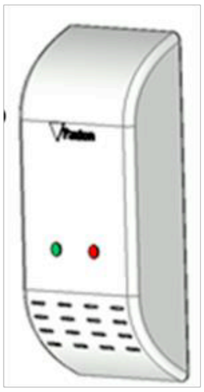


Thermal analysis

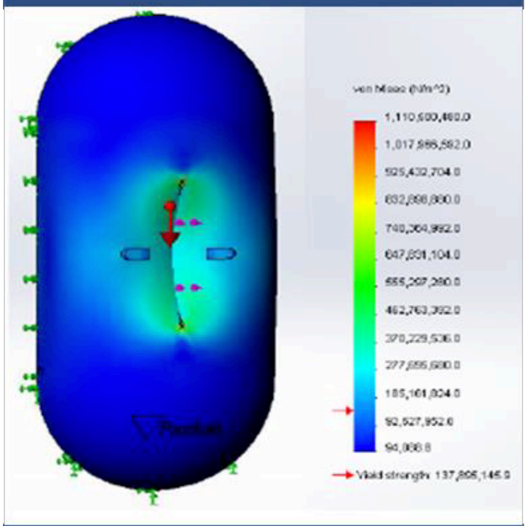


Concept A6

Concept A7



Structural analysis



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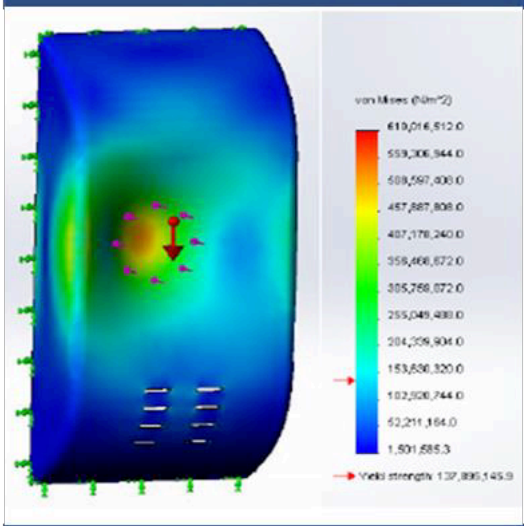
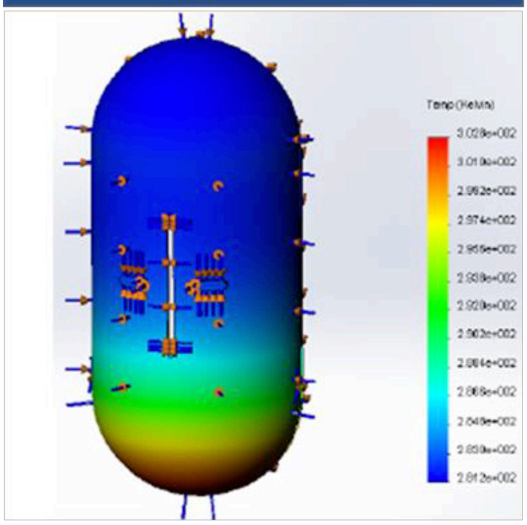


Thermal analysis



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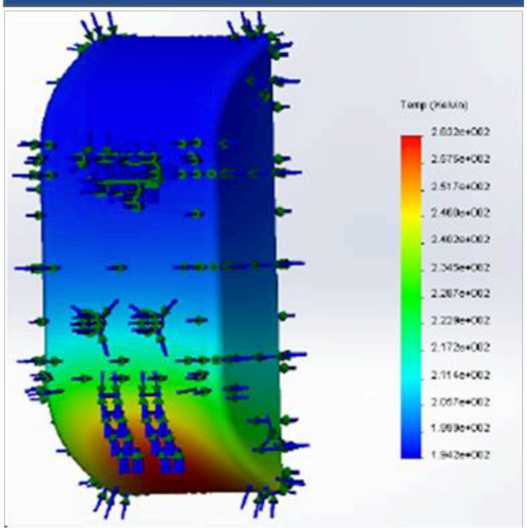
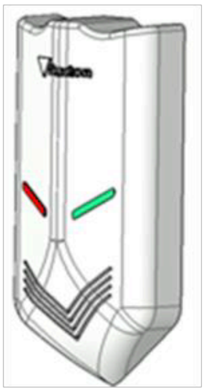


Concept A8

Concept A9



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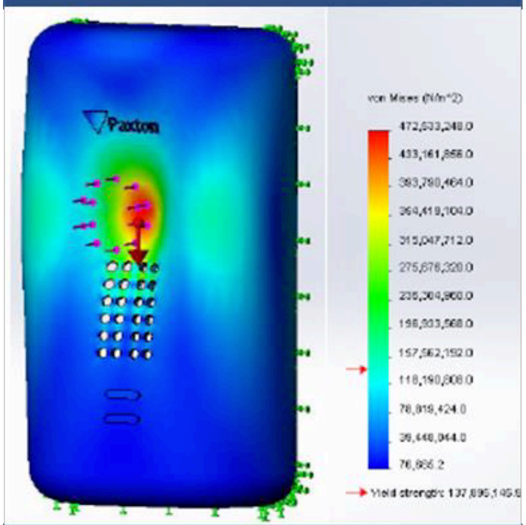

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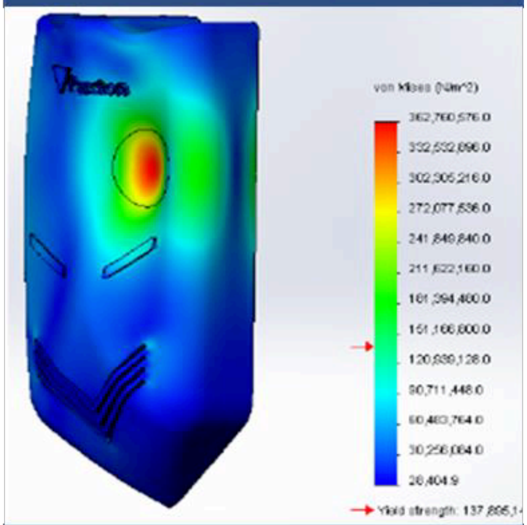
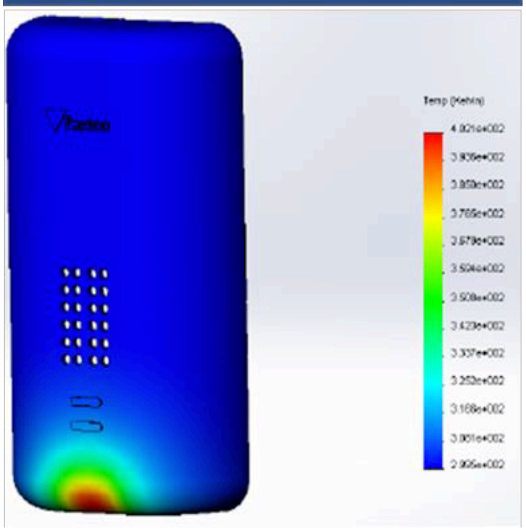
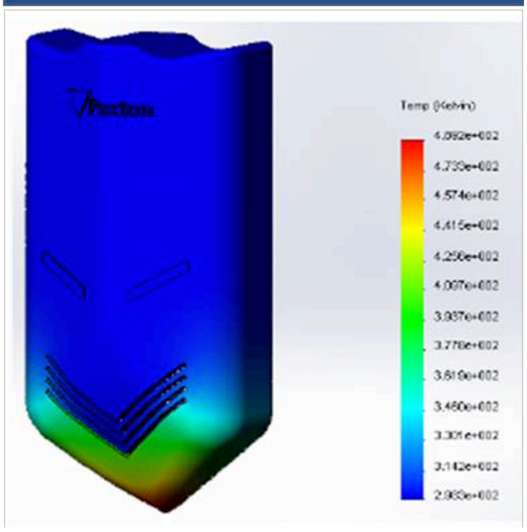


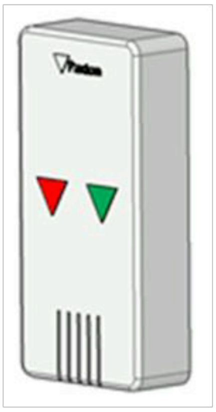
Thermal analysis



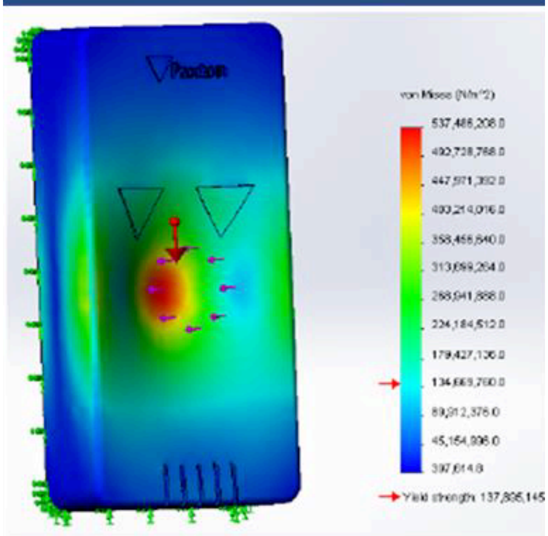
Thermal analysis



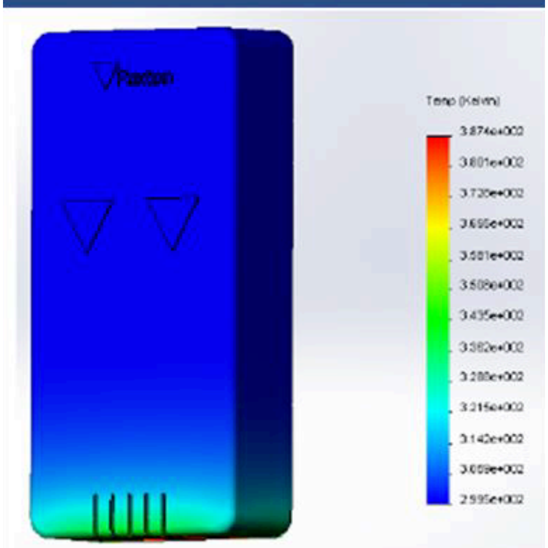
Concept A10



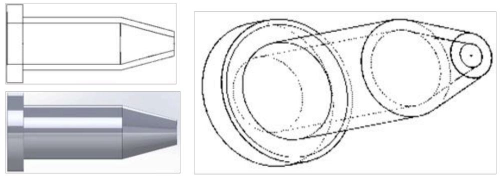
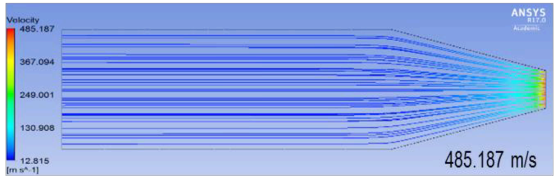
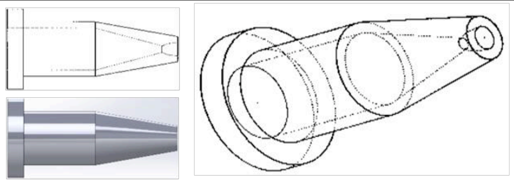
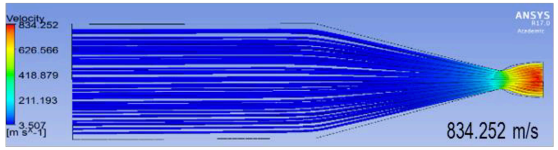
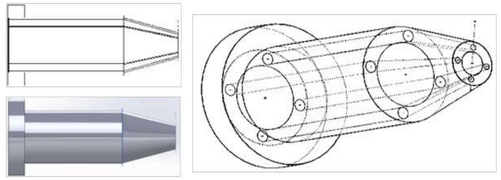
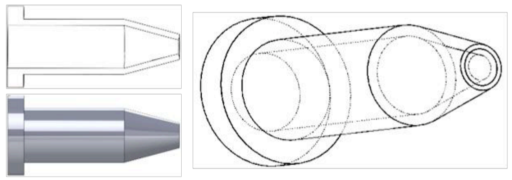
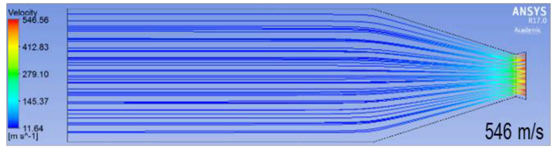
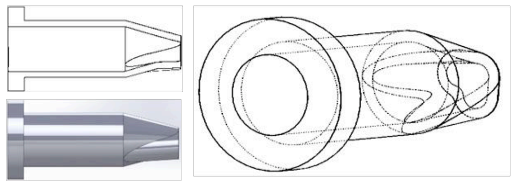
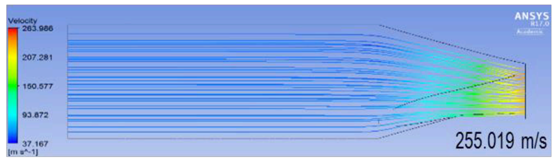
Structural analysis

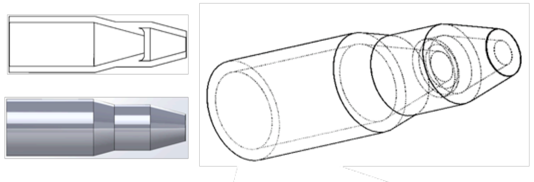
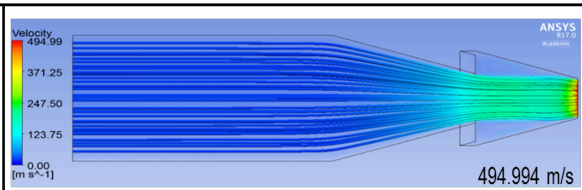
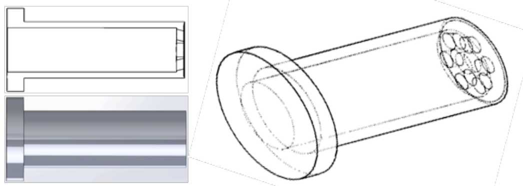
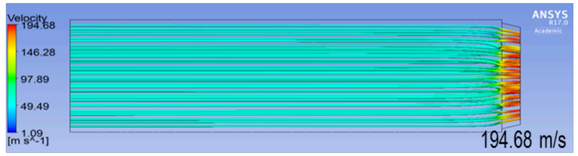
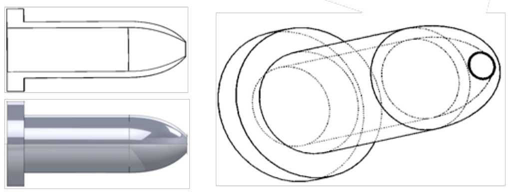
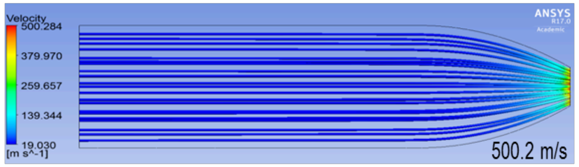
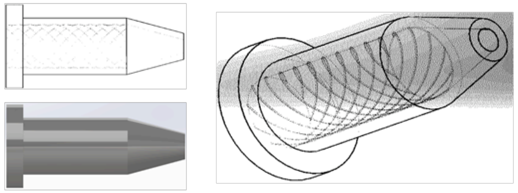
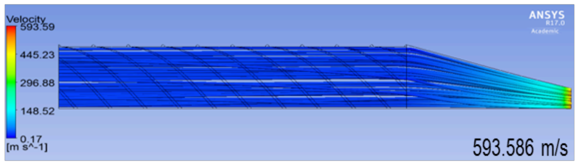
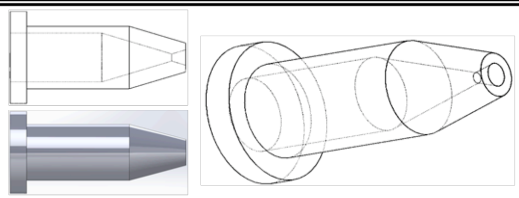
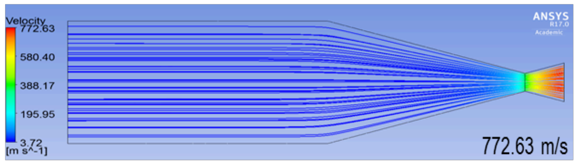


Thermal analysis



Appendix B Caltec Case Study: CFD simulation

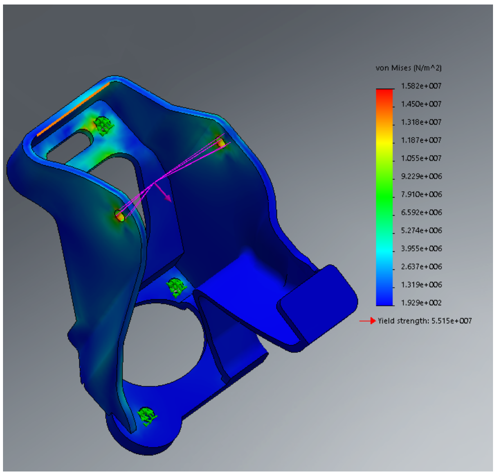
No	Nozzle Designs	CFD Simulation Results (Velocity [m/s])	Details About the Nozzle Design
N1			• Existing solution (original nozzle design)
N2			• No moving parts • Replaceable nozzle • N2 could increase velocity by generating a supersonic flow at the tip of nozzle • Concept inspired from the space rocket launcher nozzle
N3		 429 m/s	• No moving parts • Easy to manufacture • Replaceable nozzle • Clog resistant • 4 holes reduce the energy-flow-loss at the tip of the nozzle
N4			• No moving parts • Replaceable nozzle • Small modification to the current design • Lighter in weight • The angle could reduce the energy flow loss and maintain the flow geometry.
N5			• No moving parts • Replaceable nozzle • Reduced backpressure due to its clog resistant ability • N5 could increase penetration rate hence improve flow energy • Clog resistant due to higher penetration flow

No	Nozzle Designs	CFD Simulation Results (Velocity [m/s])	Details About the Nozzle Design
N6			• No moving part • Replaceable nozzle • Increase velocity of the fluid by 2 times • Stabilize the flow of the fluid • Reduce backpressure due to its clog resistant ability
N7			• No moving parts • Replaceable nozzle • Easy to manufacture • The multi jet could increase velocity of the gas or liquid due to its multi holes design.
N8			• No moving parts • Replaceable nozzle • N8 could maintain the flow of gas or liquid based on develop flow geometry • N8 could stabilize the flow of the fluid
N9			• No moving parts • Replaceable nozzle • N9 could generate a vortex flow energy to increase the velocity. • N9 could stabilize the vortex flow of the gas or fluid
N10			• No moving parts • Replaceable nozzle • N10 could increase velocity by generating a supersonic flow • The supersonic flow achieve early at the outlet nozzle tip.

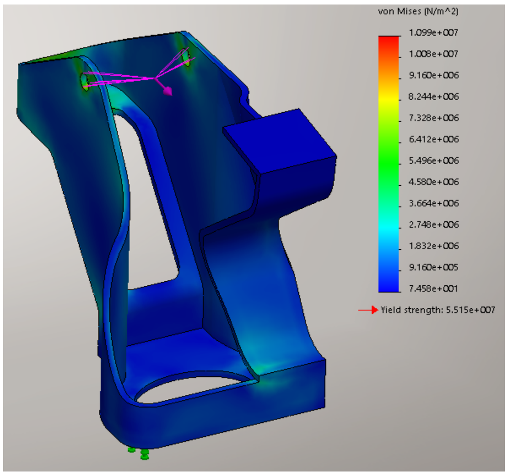
Appendix C JLR Case Study: von Mises Stress simulation

Bracket

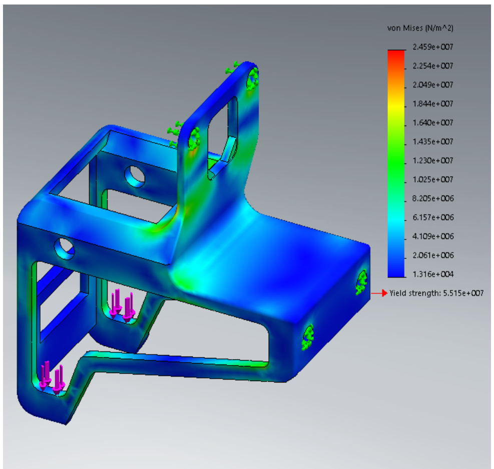
B1



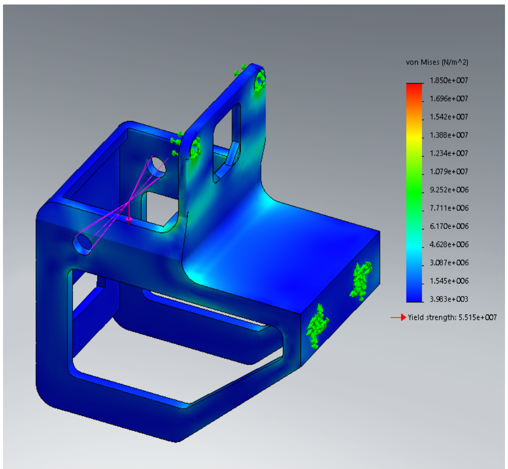
B2



B3

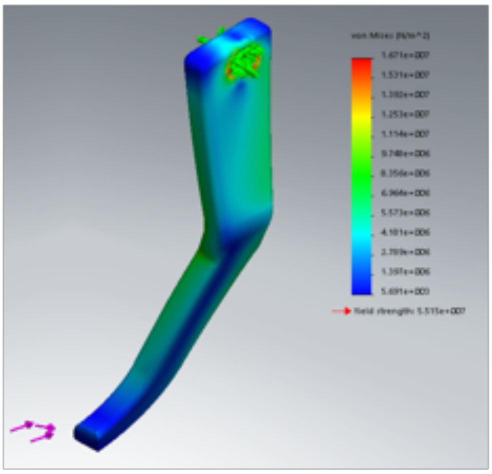


B4

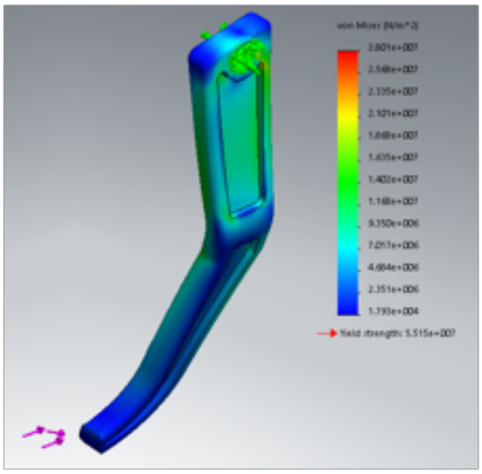


<u>Pedal Arm</u>

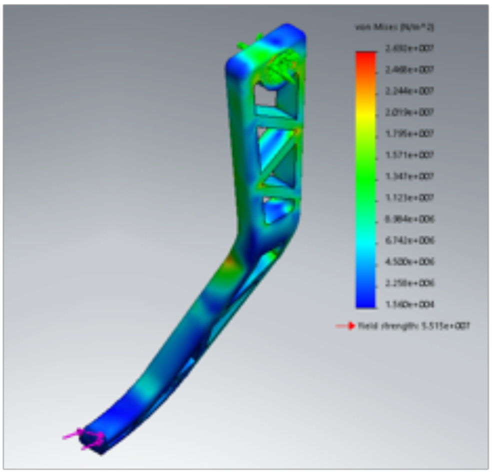
PA1



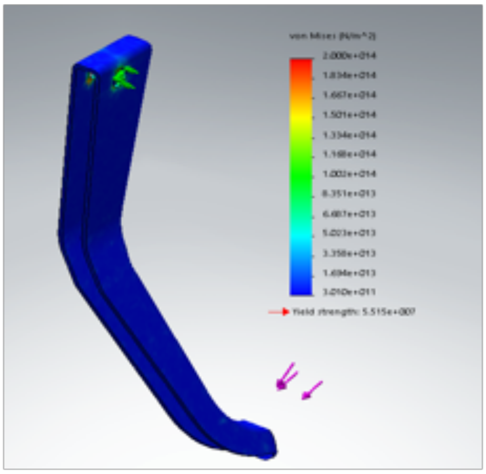
PA2



PA3



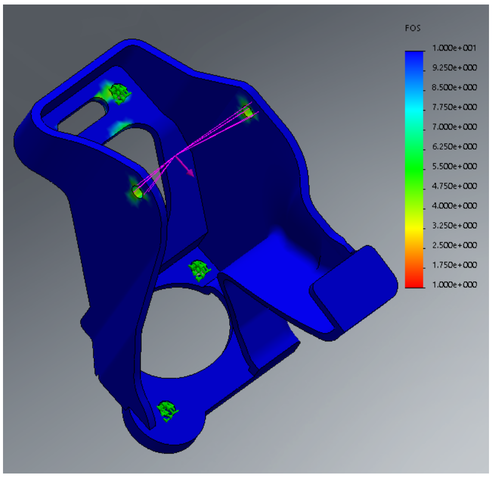
PA4



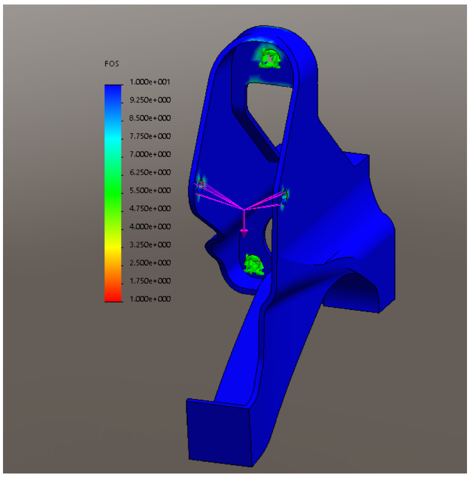
Appendix D JLR Case Study: Factor of Safety simulation

Bracket

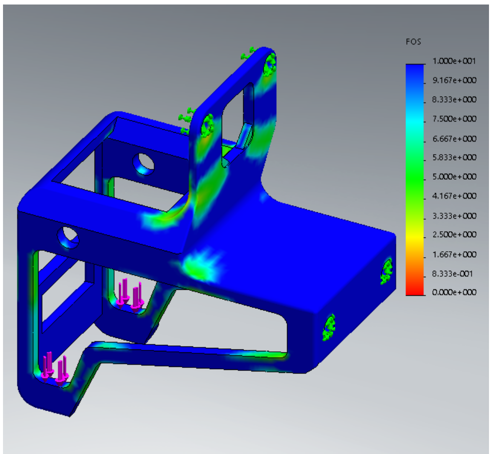
B1



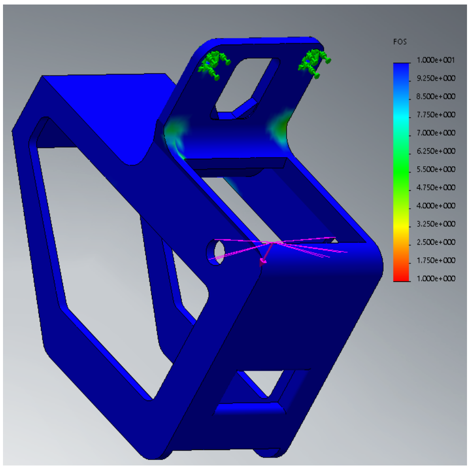
B2



B3

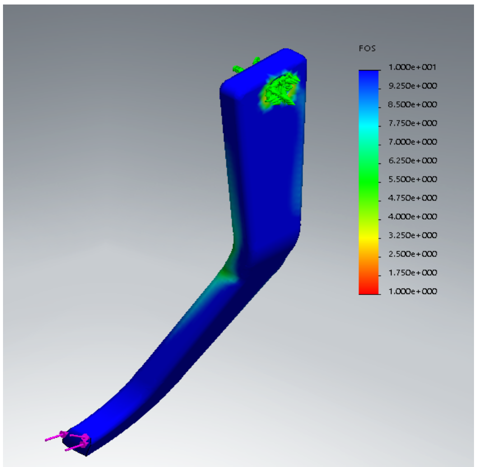


B4

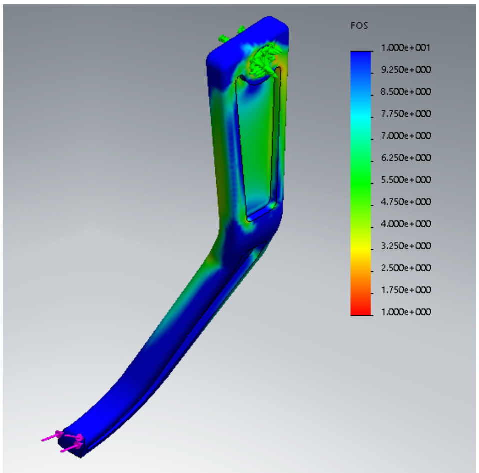


Pedal Arm

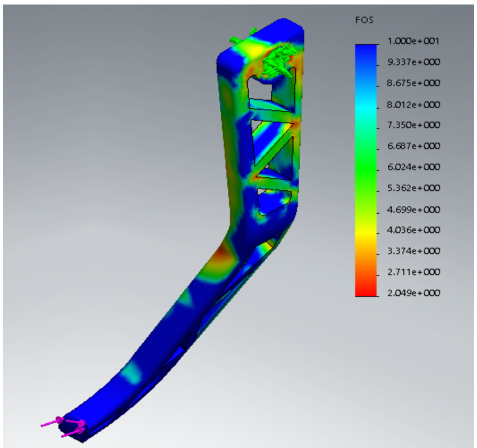
PA1



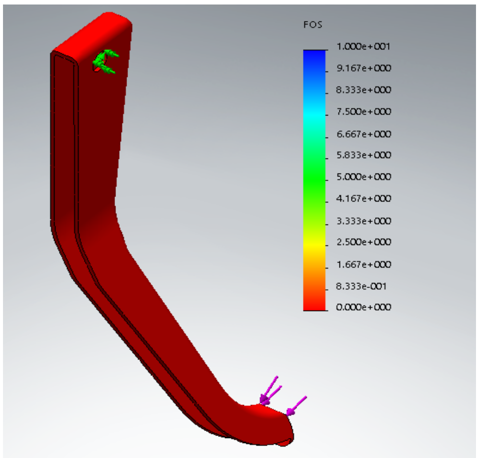
PA2



PA3



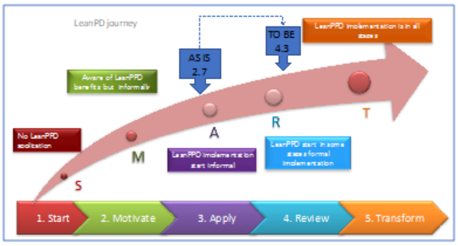
PA4



Appendix E Map the Business Case Example

The opportunity statement

1) Understand current PD practices

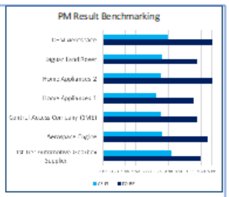


Jaguar Land Rover

Chassis Engineering Department

AS-IS 2.7 TO-BE 4.3

- No surprise in the overall scores.
- No significant variation between the scores of each function.
- The TO-BE score is not closer to 5 as participants were realistic with their expectations of change at a large company.
- The results are comparable to those of other companies who have previously completed the study.

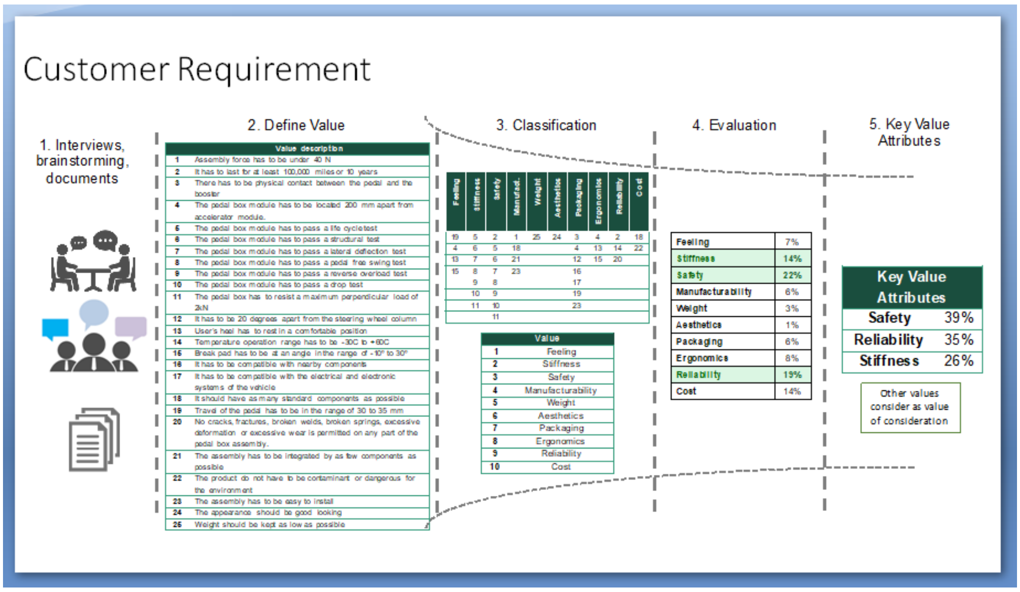


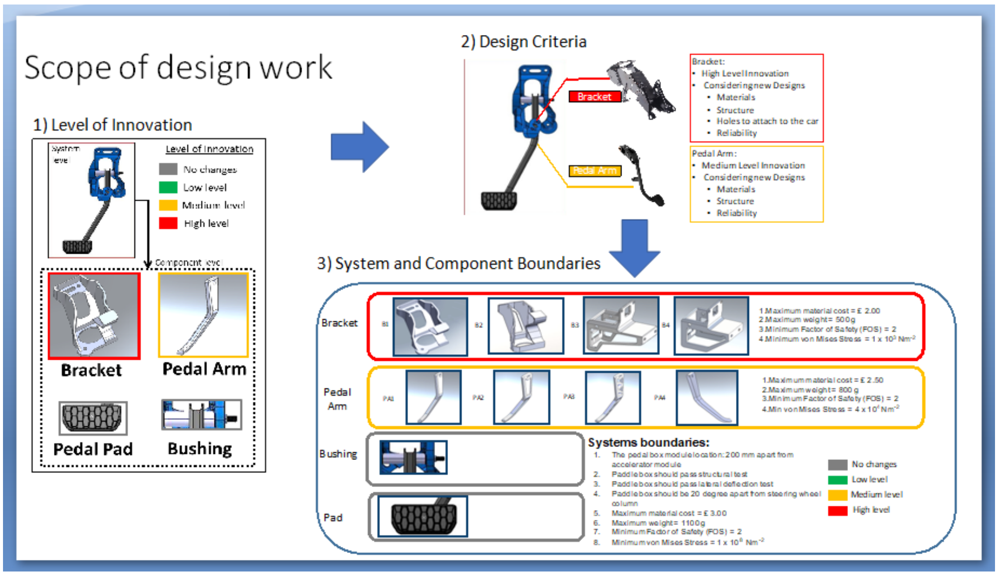
2) Identifying key PD challenges

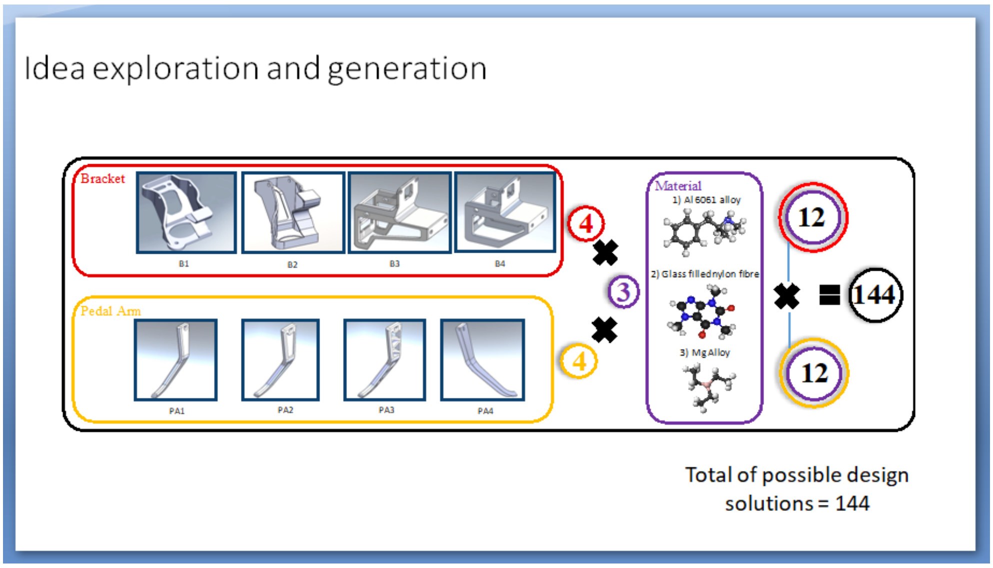
No.	Challenges	Descriptions
1	Design Rework	• The concept of late change is wrong within the department, as it is viewed negatively. This means design changes are currently viewed as rework rather than an iterative process
2	Product not meeting the specification	• Most of the time, the concept phase is not given so much attention because of the pressure to meet targets. This eventually leads to design reworks and quality issue.
3	Creativity and Innovation	• Lack of exploring possible design solutions at the design phase hinders creativity and innovation of design parts

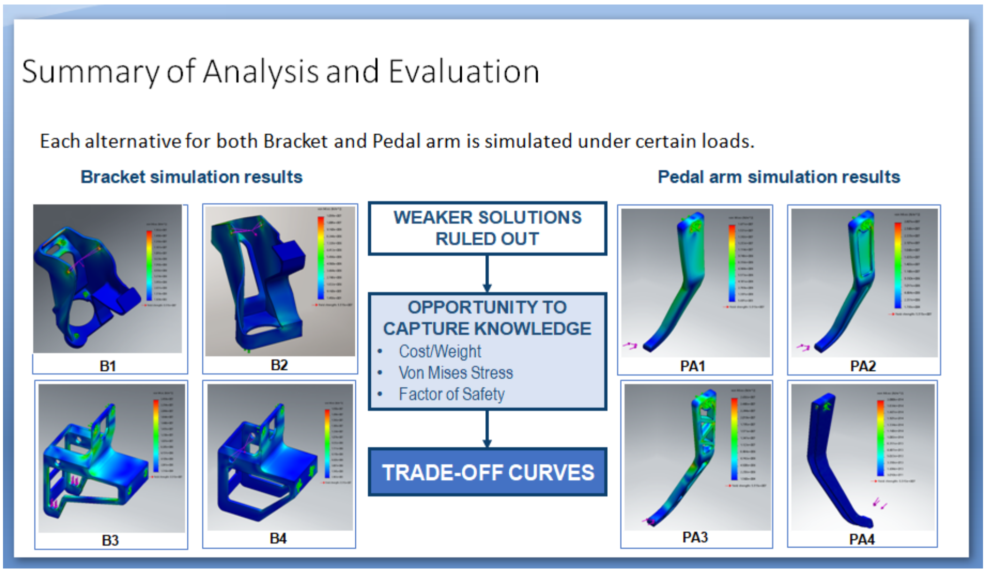
Pilot Project Overview

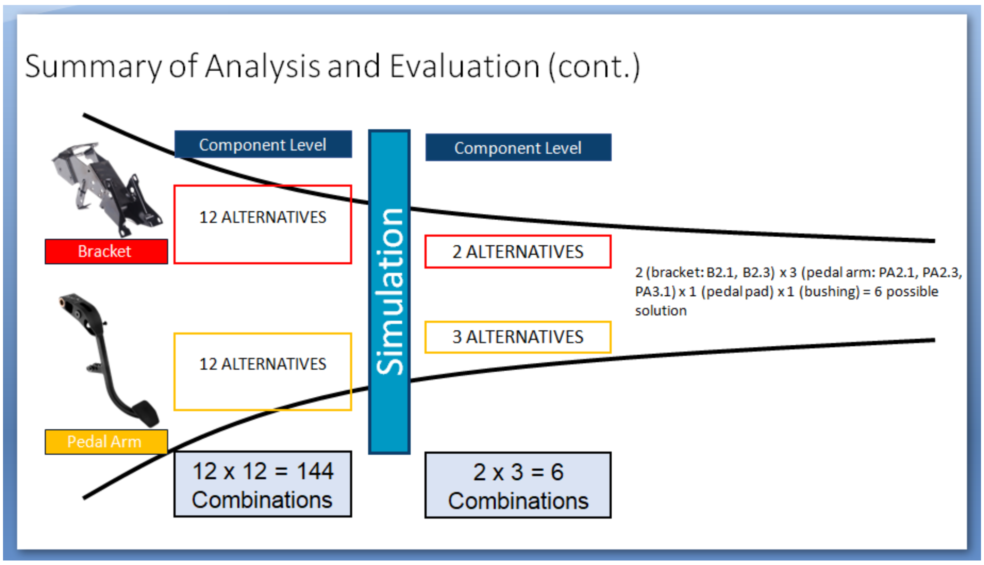
No	Pilot Project Name	Aim	Objectives	Duration	Estimated Dateline
1	Brake Pedal Box	The aim is to find an improved design of a brake pedal box applying the principles of SBCE.	1. Demonstrate the potential of SBCE addressing the PD challenges 2. Identify the potential benefits from the application of in the pilot project	3 month (including LeanPPD Performance measurement assessment, Face to face interview, LeanPD short course, and pilot project)	26/4/2017


Customer Requirement
1. Interviews, brainstorming, documents
2. Define Value
Value description
1 Assembly force has to be under 40 N
2 It has to last for at least 100,000 miles or 10 years
3 There has to be physical contact between the pedal and the booster
4 The pedal box module has to be located 200 mm apart from accelerator module.
5 The pedal box module has to pass a life cycle test
6 The pedal box module has to pass a structural test
7 The pedal box module has to pass a lateral deflection test
8 The pedal box module has to pass a pedal free swing test
9 The pedal box module has to pass a reverse overload test
10 The pedal box module has to pass a drop test
11 The pedal box has to resist a maximum perpendicular load of 2kN
12 It has to be 20 degrees apart from the steering wheel column
13 User's heel has to rest in a comfortable position
14 Temperature operation range has to be -30C to +60C
15 Break pad has to be at an angle in the range of -10° to 30°
16 It has to be compatible with nearby components
17 It has to be compatible with the electrical and electronic systems of the vehicle
18 It should have as many standard components as possible
19 Travel of the pedal has to be in the range of 30 to 35 mm
20 No cracks, fractures, broken welds, broken springs, excessive deformation or excessive wear is permitted on any part of the pedal box assembly.
21 The assembly has to be integrated by as few components as possible
22 The product do not have to be contaminant or dangerous for the environment
23 The assembly has to be easy to install
24 The appearance should be good looking
25 Weight should be kept as low as possible
3. Classification
Feeling | Stiffness | Safety | Manufact. | Weight | Aesthetics | Packaging | Ergonomics | Reliability | Cost
19 | 5 | 2 | 1 | 25 | 24 | 3 | 4 | 2 | 18
4 | 6 | 5 | 18 | | | 4 | 13 | 14 | 22
13 | 7 | 6 | 21 | | | 12 | 15 | 20 |
15 | 8 | 7 | 23 | | | 16 | | |
9	8				17		
10	9				19		
11	10				23		
	11						
Value
1 Feeling
2 Stiffness
3 Safety
4 Manufacturability
5 Weight
6 Aesthetics
7 Packaging
8 Ergonomics
9 Reliability
10 Cost
4. Evaluation
Feeling 7%
Stiffness 14%
Safety 22%
Manufacturability 6%
Weight 3%
Aesthetics 1%
Packaging 6%
Ergonomics 8%
Reliability 19%
Cost 14%
5. Key Value Attributes
Key Value Attributes
Safety 39%
Reliability 35%
Stiffness 26%
Other values consider as value of consideration


Scope of design work
1) Level of Innovation
Level of innovation
No changes
Low level
Medium level
High level
Bracket
Pedal Arm
Pedal Pad
Bushing
2) Design Criteria
Bracket
Pedal Arm
Bracket:
• High Level Innovation
• Considering new Designs
• Materials
• Structure
• Holes to attach to the car
• Reliability
Pedal Arm:
• Medium Level Innovation
• Considering new Designs
• Materials
• Structure
• Reliability
3) System and Component Boundaries
Bracket
B3
B4
1.Maximum material cost = £ 2.00
2.Maximum weight= 500g
3.Minimum Factor of Safety (FOS) = 2
4.Minimum von Mises Stress = 1 x 10^3 Nm^{-2}
Pedal Arm
PA3
PA4
1.Maximum material cost = £ 2.50
2.Maximum weight= 800 g
3.Minimum Factor of Safety (FOS) = 2
4.Min von Mises Stress = 4 x 10^4 Nm^{-2}
Bushing
Pad
Systems boundaries:
1. The pedal box module location: 200 mm apart from accelerator module
2. Paddle box should pass structural test
3. Paddle box should pass lateral deflection test
4. Paddle box should be 20 degree apart from steering wheel column
5. Maximum material cost = £ 3.00
6. Maximum weight= 1100g
7. Minimum Factor of Safety (FOS) = 2
8. Minimum von Mises Stress = 1 x 10^8 Nm^{-2}
No changes
Low level
Medium level
High level


Idea exploration and generation
Bracket
B1
B2
B3
B4
4
Pedal Arm
PA1
PA2
PA3
PA4
4
3
Material
1) Al 6061 alloy
2) Glass filled nylon fibre
3) Mg Alloy
12
144
12
Total of possible design
solutions = 144


Summary of Analysis and Evaluation
Each alternative for both Bracket and Pedal arm is simulated under certain loads.
Bracket simulation results
Pedal arm simulation results
B1
B2
B3
B4
WEAKER SOLUTIONS RULED OUT
OPPORTUNITY TO CAPTURE KNOWLEDGE
Cost/Weight
Von Mises Stress
Factor of Safety
TRADE-OFF CURVES
PA1
PA2
PA3
PA4


Summary of Analysis and Evaluation (cont.)
Component Level
12 ALTERNATIVES
Bracket
12 ALTERNATIVES
Pedal Arm
12 x 12 = 144
Combinations
Simulation
Component Level
2 ALTERNATIVES
3 ALTERNATIVES
2 (bracket: B2.1, B2.3) x 3 (pedal arm: PA2.1, PA2.3, PA3.1) x 1 (pedal pad) x 1 (bushing) = 6 possible solution
2 x 3 = 6
Combinations

Optimal solution obtained

Using Trade-Off Curves only 3 combinations remaining. To evaluate these, Pugh Matrix is used. In it, the Key Value Attributes are evaluated to make the final selection.

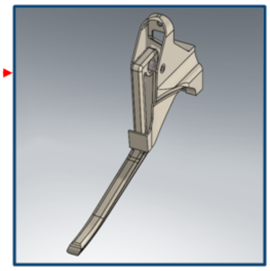
A

Scale	
4	The Best
3	Good
2	Moderate
1	The worst

B

Key Value Attributes	Loads of importance	B2.3+PA2.1	B2.3+PA2.3	B2.3+PA3.1
Safety	39%	3	4	1
Reliability	35%	2	3	1
Stiffness	26%	1	2	4
Weighted Total		2.13	3.13	1.78

This solution has been identified as the optimal



Final Combination = B2.3+PA2.3

Material:

1) B2.3 = Magnesium Alloy
2) PA2.3 = Magnesium Alloy

Justification of measurable benefits.