CRANFIELD UNIVERSITY
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WASIM AHMAD

COST MODELLING SYSTEM TO SUPPORT LEAN PRODUCT AND PROCESS DEVELOPMENT

SCHOOL OF APPLIED SCIENCES

PhD
Academic Year: 2009 - 2012

Supervisors
Dr. Essam Shehab and Prof. Hassan Abdalla

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

ABSTRACT

This PhD project aims to develop a cost modelling system to support lean product and process development. The system enables the designers to assess the design along with associated manufacturing processes and provides decision support at an early development stage. Design assessment at early development stage can help designers to take proactive decisions, eliminate mistakes and enhance product value.

The developed cost modelling system to support lean product and process development incorporates three lean product and process development enablers, namely set-based concurrent engineering, knowledge-based engineering, and mistake-proofing (poka-yoke). To facilitate above explained lean enablers, the system architecture contains six modules, six separate groups of database, a CAD modelling system, and a user interface. The system modules are: (i) value identification; (ii) manufacturing process/machines selection; (iii) material selection; (iv) geometric features specification; (v) geometric features and manufacturability assessment; and (vi) manufacturing time and cost estimation. The group of database includes: (i) geometric features database, (ii) material database, (iii) machine database, (iv) geometric features assessment database, (v) manufacturability assessment database, and (vi) previous projects cost database.

A number of activities have been accomplished to develop the cost modelling system. Firstly, an extensive literature review related to cost estimation, and lean product and process development was performed. Secondly, a field study in European industry and a case study analysis were carried out to identify current industrial practices and challenges. Thirdly, a cost modelling system to support lean product and process development was developed. Finally, validation of the system was carried out using real life industrial case studies.

The system provides a number of benefits, as it enables designers to incorporate lean thinking in cost estimation. It takes into consideration downstream manufacturable process information at an early upstream stage of the design and as a result the designer performs the process concurrently and makes decisions quickly. Moreover, the system helps to avoid mistakes during product features design, material and manufacturing process selection, and process parameters generation; hence it guides toward a mistake-proof product development. The main feature of the system, in addition to manufacturing cost estimation, is set-based concurrent engineering support; because the system provides a number of design values for alternative design concepts to identify the feasible design region.

The major contribution of the developed system is the identification and incorporation of three major lean product and process development enablers, namely set-based concurrent engineering, knowledge-based engineering and poka-yoke (mistake-proofing) in the cost modelling system. A quantification method has been proposed to eliminate the weaker solution among several alternatives; therefore only the feasible or strong solution is selected. In addition, a new cost estimation process to support lean product and process development has been developed which assists above explained three lean product and process development enablers.

Keywords:

Lean product development; Cost Modelling; Set-based concurrent engineering; Knowledge-based engineering; Mistake-proofing (poka-yoke)

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LIST OF PUBLICATIONS

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Alam, R., Wasim, A., Al-Ashaab, A., Shehab, E., and Martin, C. (2011), "Value translation and presentation for lean design", *Proceedings of the 9th International Conference on Manufacturing Research (ICMR 2011), 6th to 8th September, 2011, Glasgow Caledonian University, Scotland*, pp. 1-5.

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Wasim, A., Shehab, E., Abdalla, H., and Al-Ashaab, A., (2012), "Cost modelling to support lean product and process development: Current industrial practices and future research direction", The *International Conference on Manufacturing Research 2012, Aston University, United Kingdom, Sept 11-13,* pp. 262-267.

Shehab, E., Al-Anazi, G., and Wasim, A., (2012) "Recycling cost modelling methodology of carbon fibre composites", The *International Conference on Manufacturing Research 2012, Aston University, United Kingdom, Sept 11-13,* pp. 256-261.

Shehab, E., Ma, W., and Wasim, A., (2012) "Manufacturing cost modelling for aerospace composite applications", The *19th ISPE International Conference on Concurrent Engineering – CE2012, Trier (Germany), Sept 3–7,* pp. 425-433.

Shehab, E., Yatta, D., Hamed, M., and Wasim, A., (2012), “Finite element analysis process in design engineering: Best practice”,The *19th ISPE International Conference on Concurrent Engineering – CE2012, Trier (Germany), Sept 3–7,* pp. 327-338.

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LIST OF ACRONYMS

AACE	Association of Advancement of Cost Engineering
ABC	Activity-Based Costing
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CAPP	Computer Aided Production Planning
CBR	Case-Based Reasoning
CEF	Cost Estimation Formulae
CER	Cost Estimation Relationship
DB	Database
DFMA	Design for Manufacture and Assembly
DIS	Design Information Solid-model
DOE	Design of Experiment
ERP	Enterprise Resource Planning
EU-FP7	European Seventh Framework Program
FEA	Finite Element Analysis
FMEA	Failure Mode Effective Analysis
FNN	Fuzzy Neural Network
HAZ	Heat Affected Zone
JIT	Just in time
KBE	Knowledge-Based Engineering
KLC	Knowledge Life Cycle
KM	Knowledge Management

KNOMAD	Knowledge Nurture for Optimal Multidisciplinary Analysis and Design
LeanPPD	Lean Product and Process Development
MML	MOKA Modelling Language
MOKA	Methodology and tools Oriented to Knowledge-based engineering Application
MRP	Material Requirement Planning
MRP-I	Material Requirement Planning
MRP-II	Manufacturing Resource Planning
Nd:YAG	Neodymium Yttrium Aluminium Garnet
OEM	Original Equipment Manufacturer
PDM	Product Data Management
PLM	Product Lifecycle Management
PSD	Preference Set-based Design
QCD	Quality Cost and Delivery
RBR	Rule-Based Reasoning
RSW	Resistance Spot Welding
SBD	Set-Based design
SBPD	Set-Based Parametric Design
SCAF	Society of Cost Analysis and Forecasting
SMEs	Small and Medium Enterprises
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TQM	Total Quality Management
UML	Unified Modelling Language
VA/VE	Value Analysis/Value Engineering

CHAPTER 1

1 INTRODUCTION

1.1 Research Background

In today's competitive global market, companies strive to provide value products at low cost and therefore employ best product development strategies. Lean thinking is a philosophy that aims to both enhance value and reduce waste. World leading companies, especially European companies are motivated to apply lean thinking in their product development process. Figure 1-1 illustrates an overview of the lean journey as understood by the researcher.

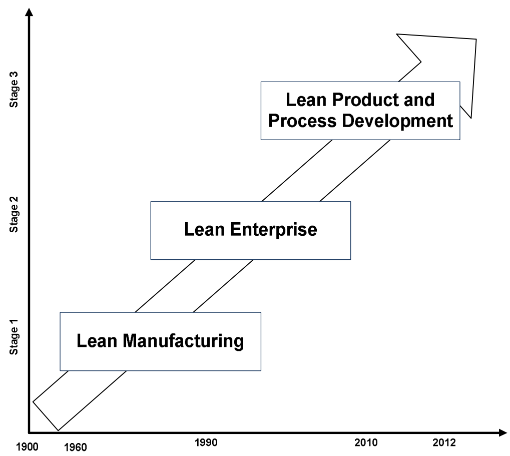

Figure 1-1: An overview of the lean journey

The lean journey was initiated with lean manufacturing for the shop floor, also known as the Toyota production system. Lean principles, models, tools and techniques for the shop floor were developed in this stage. After realising the success of lean thinking, Lean Aerospace Initiatives (LAI) projects were started by US and UK aerospace companies (Al-Ashaab et al., 2010). The aim of these projects was the transformation of organisations into lean enterprises. This stage of lean implementation is recognised as the Lean Enterprise, which supports the top management. The major problems associated with Lean Enterprise are that only the aerospace industry is concerned with it, and the projects members are the only ones who know the project information (Al-

Ashaab et al., 2010). After realising the problems associated with Lean Enterprise, European product development companies initiated the third stage of lean thinking in 2008 and named it Lean Product and Process Development (LeanPPD). LeanPPD project is funded by the European Union EU-FP7 (www.leanppd.eu) and aims to develop a new model for European companies which goes beyond lean manufacturing to ensure the transformation of enterprise into a lean environment (Al-Ashaab et al., 2010). The foundations of the LeanPPD project are based on initial work performed in the area of lean in product design and development. Kennedy et al. (2008), Mascitelli (2004), Morgan and Liker (2006), Nahm and Ishikawa (2006a), Sobek and Liker (1998), Sobek et al. (1999), Ward (2007) and Ward et al. (1995) are well known researchers in this area. The project attempts to develop principles, models and methodologies for the entire product development. Figure 1-2 presents an overview of the project.

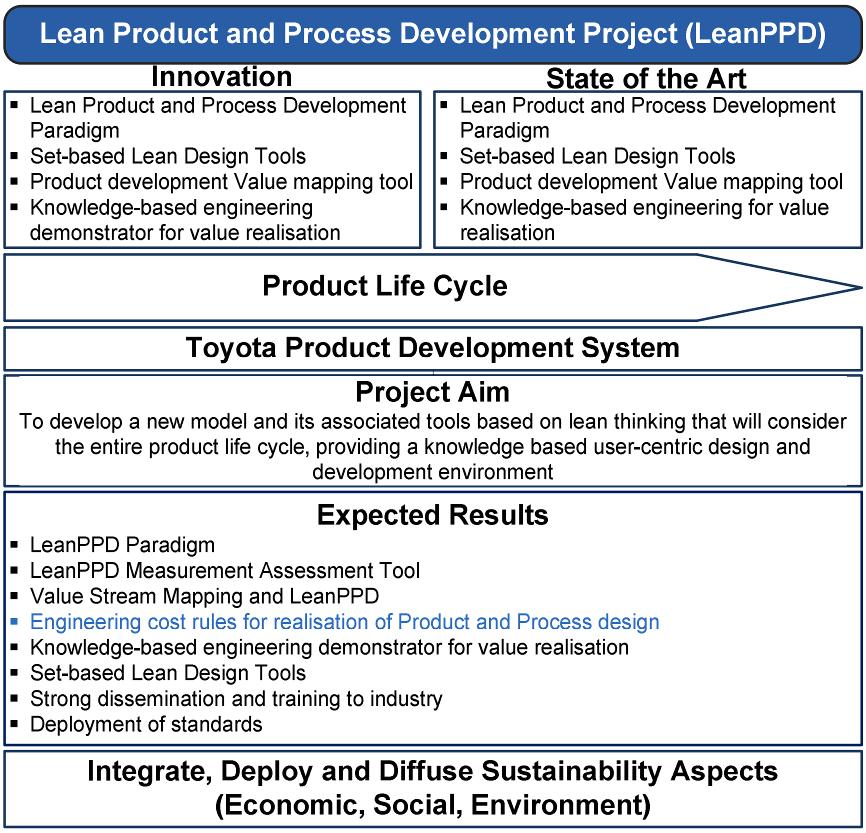

Figure 1-2: Lean product and process development project overview (Al-Ashaab, 2008)

The design stage is considered to be the backbone of product development, since 70% of cost is committed at the design stage (Shehab and Abdalla, 2001). The decision and actions of designers affect the whole product development; therefore, it becomes absolutely crucial for companies to employ their best product development team members equipped with the best tools and techniques at the design stage. Cost estimation is one of the important activities of the design stage. The majority of future decisions are dependent on timely, precise cost estimates. A number of cost estimation systems have been developed by researchers, some of which are discussed in the literature including those of Bouaziz et al. (2006), Chayoukhi et al. (2009), Cicconi et al. (2010), Masmoudi et al. (2007), Quintana and Ciurana (2011) and Shehab and Abdalla (2002b). These systems focus on providing manufacturing cost estimations for designers. The majority of these systems were developed to support designers; however, these systems have a number of limitations and therefore cannot be employed directly for lean product and process development. Some of the limitations are as follows:

The development team has to keep the balance between cost, time and functionality. However, there is diversity in the nature of working between top management and designers. Top management focuses on reducing the product development cost while retaining acceptable functionality, whereas the designers dedicate their efforts to enhance product functionality with little cost consideration. This difference in work preference hinders product performance and raises the difficulties of providing true values to customers. In addition, cost estimation in the majority of companies is the responsibility of cost estimators only; therefore, the designers do not take responsibility for cost estimation. In fact, designers consider cost estimation to be an additional task which hinders them from their routine tasks. Moreover, the information collection requirement from downstream manufacturing processes for cost estimation is a tedious task that is mostly side-stepped by designers. These factors clearly indicate that designers merely apply a cost estimation system in their daily jobs. Therefore, there is need to develop a designer interactive cost estimation system to improve its effectiveness in product design and development.

A number of cost estimation systems (discussed in Chapter 2) emphasise providing a decision support for the selection of alternative design options; however, the majority of these systems focus on cost-based decisions, whereas other important factors such as manufacturing time and product quality are mostly ignored by these systems. It is worth stating that in a dynamic environment, where the customer demands and needs are constantly changing, companies also need to capture and channel customer requirements into their cost estimation process.

Mistakes in product development or ambiguous assumptions lead to rework and higher product development cost. Although a number of cost estimation systems stress identifying the manufacturability of product before estimation, these systems do not, however, focus on eliminating the design mistakes.

This research aims to develop a cost modelling system to support lean product and process development. In the light of the above explained limitations, previously developed cost modelling systems do not fulfil the European industries' requirements which are motivated to adapt the lean product and process development. Therefore, there is a need to develop a new cost estimation system which addresses the above limitations. It is expected that the proposed cost estimation system will provide a new direction for designers, cost estimators, top management and product development team members, and will support them to utilise the cost estimation system in their daily life with the least hassle. The research motivation and research scope explained in the next sections show the importance of this research.

1.2 Research Motivation

Lean thinking consideration in product development has taken on enormous significance. It was initiated with lean manufacturing, followed by lean enterprise and is now lean product development. This demonstrates the importance of lean thinking. A number of authors have worked on lean product development such as Kennedy et al. (2008), Mascitelli (2004), Morgan and Liker (2006), Sobek and Liker (1998), Sobek et al. (1999), Ward (2007) and Ward et al. (1995). However, their concern was typically the development of lean principles.

Companies face problems employing these principles in their product development processes. Therefore, the European Union (EU) initiated the LeanPPD project with a €7 million investment, which aims to convert lean principles into tools and techniques that are easy to adopt by the product development companies.

Since 70% cost is committed at the design phase, and designers do not feel the effectiveness of previous developed cost modelling systems, there is, therefore, a need for a good solution for designers that may help them to employ cost estimation in their routine jobs.

Another reason for conducting this research is the difference between the cost estimators and designers. The cost estimators focus on cost estimation and cost reduction opportunities; whereas, the designers emphasise to enhance the product functionalities with least consideration on cost. The intention of this research is to bridge the gap between these different groups of thoughts and to bring them to the same platform.

1.3 Research Scope

This research is an integral part of the LeanPPD EU-FP7 project which estimates the manufacturing cost of a product along with associate values during design phase. The developed system has the capability of estimating the cost of product design and process development.

The outcome of this research will be used by European industries involved in the LeanPPD project to improve their product development and cost estimation process. In addition, since the cost estimations of manufacturing processes are embedded into the system, the companies having these manufacturing processes can therefore use the system directly, with any necessary adjustments according to their manufacturing capabilities. However, since the system uses the feature-based cost estimation along with the rule-based system, it is therefore restricted to those companies looking for incremental innovation or really new innovation.

With respect to the product development phases, the developed system can be used for the estimation of manufacturing costs in the design phase, specifically in the conceptual and detailed design phases. The cost modelling system can also be used to develop cost quotations.

The developed cost modelling system to support lean product and process development has the ability to provide estimates related to product cost and associated values concurrently. Therefore, it enables the designers to use the cost estimation system effectively in their daily jobs. In addition, the system helps to eliminate mistakes during the design stage, and to incorporate the 'customer voice' during a critical decision making stage. All those companies desiring to take advantage of the lean paradigm can use this cost estimation system to improve their product development process. In particular, the developed system has enormous scope for companies that face challenges in their design stage.

1.4 Aim and Objectives

The aim of this research is to develop a cost modelling system to support lean product design and development. The system will introduce additional capability of cost estimation within the design stage which will enable designers to assess the design and provide decision support at an early product development stage.

The main objectives of the research are to:

1. Identify and analyse cost estimation as well as lean product and process development best practices through an extensive literature review and industrial field study.
2. Determine the lean product and process development enablers which will be incorporated into the cost estimation system.
3. Develop a cost modelling system to support lean product and process development.
4. Validate the cost modelling system through a set of industrial case studies and experts' opinion.

1.5 Thesis Structure

This study presents a detailed discussion related to research introduction, literature review, research methodology, current industrial practices, development of a cost modelling system, validation, discussion and conclusion, and contribution to knowledge. Accordingly, the thesis is divided into seven chapters. An illustration of the thesis chapters is shown in Figure 1-3. The contents of each chapter are given below.

Chapter 1 outlines the fundamental research issue. Research background, motivation, scope, and aim and objectives of this study are clearly mentioned in this chapter.

Chapter 2 presents a critical review of the fields of lean product and process development, and product manufacturing cost estimation for lean product and process development. The literature review helps to identify the possible application of cost estimation for lean product and process development. In addition, the previously developed product cost estimation systems and models have been evaluated against three lean product and process development enablers. Thereafter, the research gap analysis is presented.

In Chapter 3, the research methodology adopted and justification for that adoption is provided.

Current product development and cost estimation practices in European industrial sector are presented in chapter 4. These practices have been captured after analyses of semi-structured interviews and a case study analysis. The methodology to conduct the study and analyses of results are also provided in this chapter.

Chapter 5 explains the developed cost modelling system to support lean product and process development. The architecture of the developed system, system components, system modules, system scenario, and cost model for joining and machining processes are described in detail.

The developed system validation is described in chapter 6. The system is validated through two case studies one from each of the automotive and petroleum industries. In addition experts in the fields of cost estimation, lean product and process development experts, and industrial experts validated the system on the basis of questionnaire submitted to them.

Chapter 7 presents the results and findings after validation of the cost modelling system. This chapter shows how the research findings answer the aims and objectives of the research. In addition, the novelty of the developed system, the impact of three lean product and process development enablers and contributions to knowledge are explained. Finally the limitations of the research and suggestions for future work are pointed out.

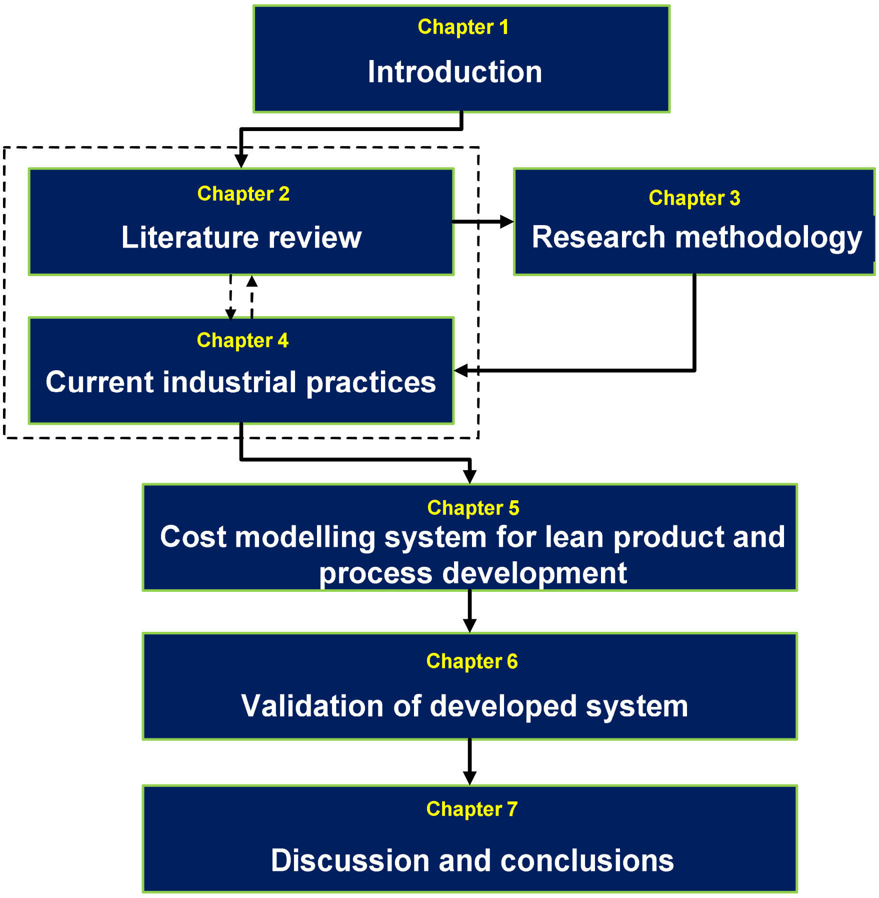

Figure 1-3: Structure of the thesis

1.6 Summary

This chapter aimed to outline the fundamental research issues. To accomplish this aim, the research background has been first introduced. A quick review of the lean journey has been provided initially, followed by an overview of the LeanPPD EU-FP7 project. Finally the problems associated with the previously developed cost estimation systems have been highlighted. The research motivation and research scope are also discussed. Accordingly, the research aim, objectives, and an overview of the thesis structure have also been given. This had to be outlined prior to the commencement of the next chapter which will present an analysis of the literature review.

In the following Chapter, the author presents the literature review and research gap analysis in the area of cost estimation for lean product and process development.

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CHAPTER 2

2 LITERATURE REVIEW

2.1 Introduction

The current socio-technical effects of global competition have forced companies to develop more competitive product development strategies in order to deliver more innovative products that meet customer expectations in a shorter lead time, at less cost, with high quality, and having a quick response to market changes. Since 70% of the product cost is committed in the design phase (Shehab and Abdalla, 2001), the product development team considers this phase critically and puts special measures in place to avoid mistakes or unforeseen circumstances that could hinder the successful manufacture of products. One of the current measures used by industry is to equip designers with cost estimation capabilities which allow for manufacturing cost estimation during the design phase. However, most of the research works on manufacturing cost estimation do not take into consideration lean product and process development principles.

A literature review presented in this chapter combines the research in product manufacturing cost estimation, and lean product and process development. The chapter structure is illustrated in Figure 2-1.

2.2 Product Development

Product development is the process required to bring a new and innovative product into the market by performing a set of activities including market opportunity analysis, design, production, sale and delivery of the product (Ulrich and Eppinger, 2008). Bringing new product into the market is a challenging task. Only one out of four projects enters the market and in the US, 46% of the companies fail to yield an adequate return on investment despite the resources allocated to them. Moreover, one out of three products around the globe fail despite proper research and planning (Homa, 2012). This alarming situation needs serious action to be taken by companies. The survival rate of companies would be enhanced by applying the structured product development approach, bringing innovative products into market, and by improving customer satisfaction (Griffin and Page, 1996).

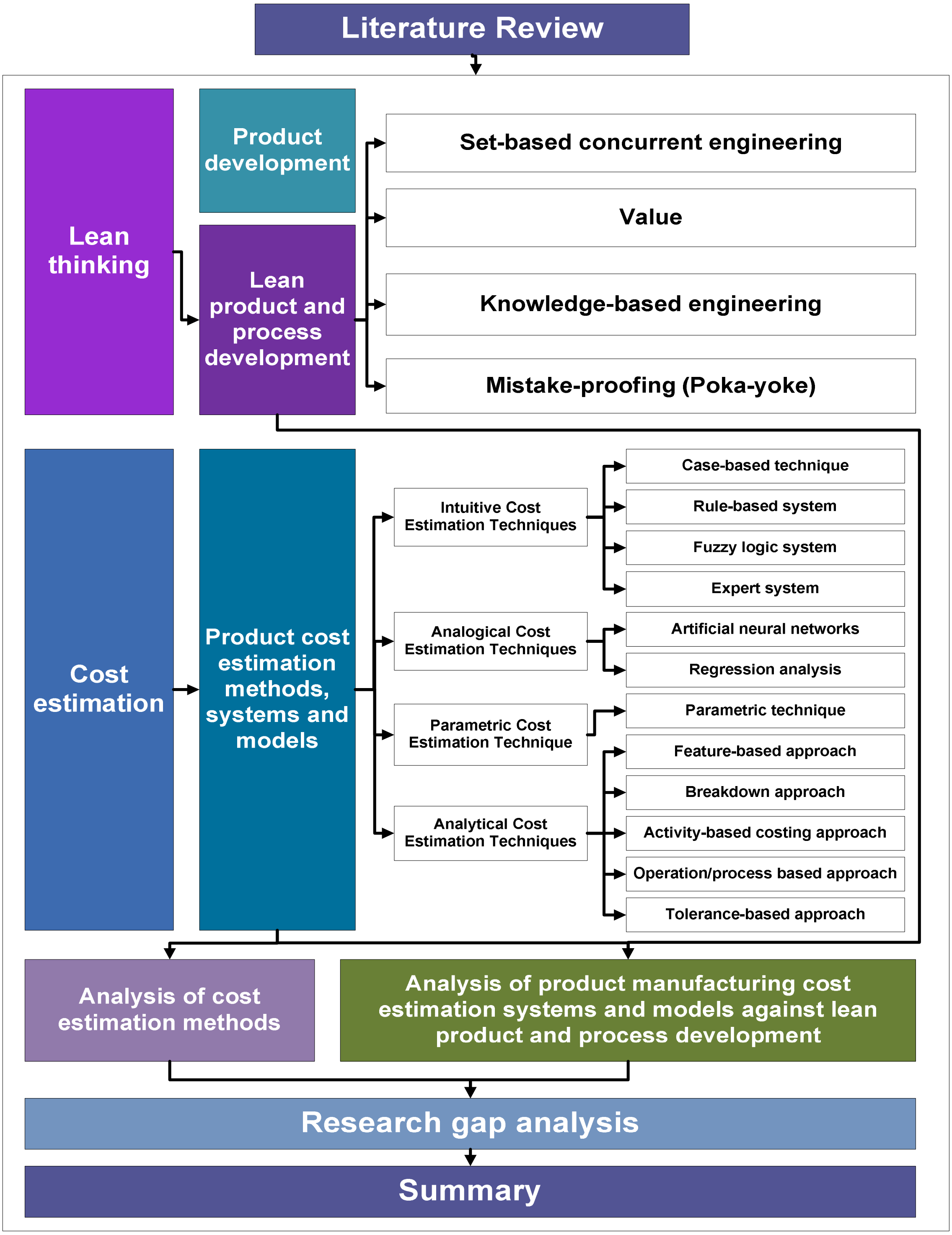

Figure 2-1: The structure of Chapter 2

There are a number of product development approaches. Figure 2-2 presents the well-known product development process proposed by Ulrich and Eppinger (2008). It includes six activities: (i) Planning, (ii) Concept development, (iii) System level design, (iv) Detailed design, (v) Testing and refinement, and (vi) Production ramp-up. The process is generally a sequential process; however, the sub-activities within each activity can be parallel or concurrent. After each activity, a review process is performed to assess and approve the activity.

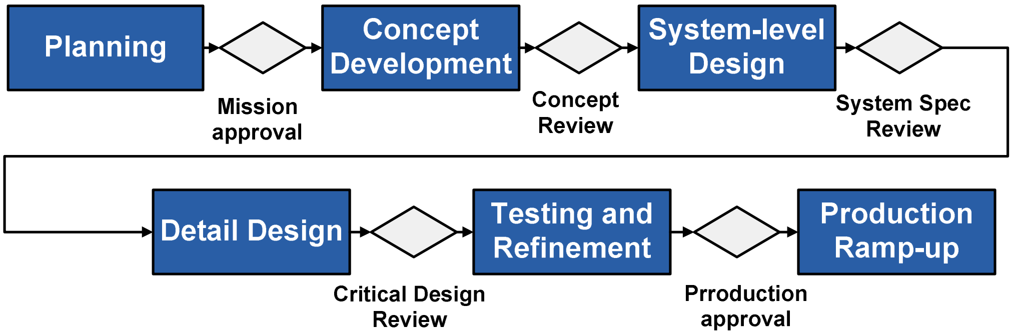

Figure 2-2: Generic product development process
(Ulrich and Eppinger, 2008)

Another product development process identified in literature is the stage-gate process model, which can be recognised as a conceptual and operational model employed to move the new product from idea generation until product launch (Cooper, 1990). A standard stage-gate process model has been illustrated in Figure 2-3, which includes stages and gates. Each stage is designed to reduce the uncertainties and risks. In addition, the activities within the stages are parallel among different functional groups. At the end of each stage, the Go/Kill gates are provided to evaluate and decide whether to move to the next stage (Cooper, 2008). The stage-gate process model is widely applicable in organisations. Roberts (2001) claims that 74% of North American firms, 59% of Japanese firms and 56% of European firms employ the stage-gate product development process.

The development funnel is also a product development process which aims to bring the ideas into a reality by converging the ideas into a product that meets the customer requirements (Wheelwright and Clark, 1992) as explained by (Harkonen, 2009). Figure 2-4 describes a simple development funnel product development process. In this process, wide ranges of alternative ideas are evaluated on the requirements, and narrowed down to a single solution. The challenging parts of the development funnel are: (i) the investigation where large ideas are investigated, (ii) narrowing down the ideas into a single product and (iii) meeting the objectives (Harkonen, 2009).

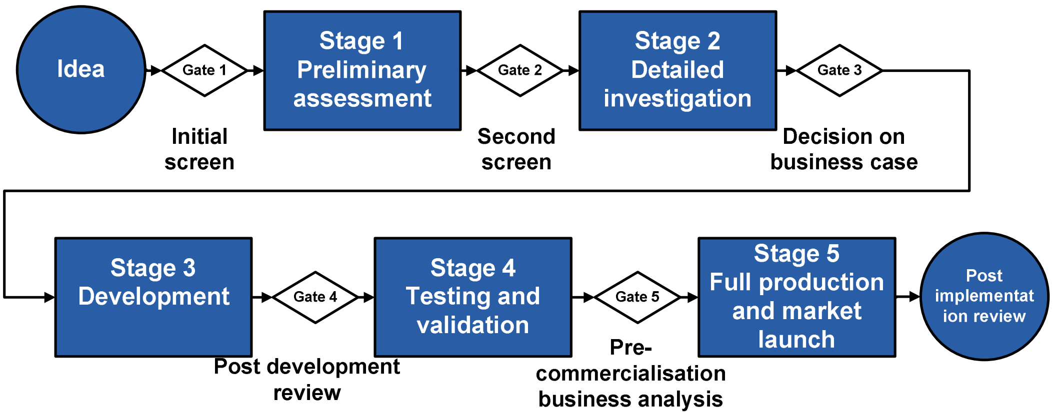

Figure 2-3: stage-gate process model
(Cooper, 1990)

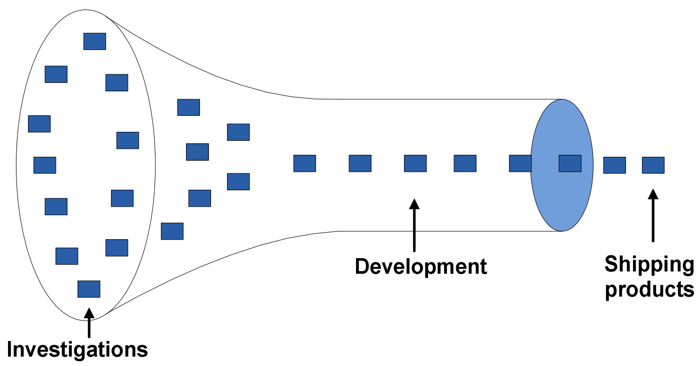

Figure 2-4: Development funnel
(Wheelwright and Clark, 1992 as explained by Harkonen, 2009)

To improve product value, reduce product lead time and bring innovation, lean product development is widely applicable in the industry. Figure 2-5 provides a simplified lean product and process development model. In this process, decisions are delayed until all the necessary information is available to the product development team. Higher customer focus, product development team proficiency and cross-functional orientation are the main reasons for lean product development success (Harkonen, 2009).

Although lean product and process development is not as structured approach as stage-gate or generic product development, the tremendous progress achieved by the implementation of lean thinking in the manufacturing stage has encouraged companies to investigate the advantages of lean thinking in their entire product development. This research investigates the effects of ‘lean’ in the product development design phase. Section 2.3 explains the progress of lean product and process development.

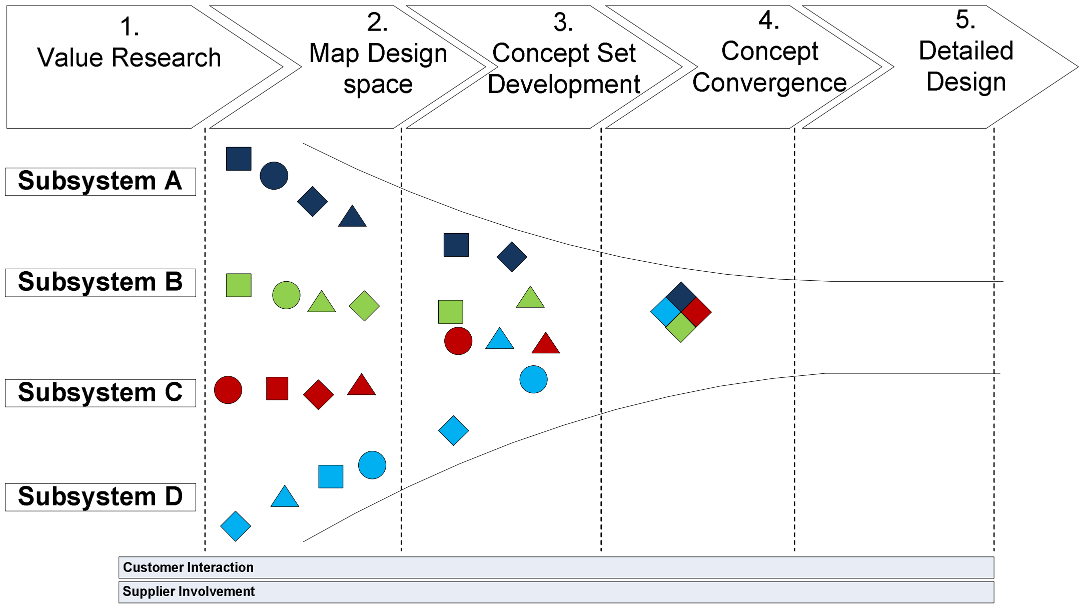

Figure 2-5: Lean product and process development model (Khan et al., 2011a)

2.3 Lean Product and Process Development

Lean product and process development is a systematic approach to the development of products and their associated production processes in a knowledge-based continuous improvement environment, which focuses on the creation of value, and results in the reduction of waste. This is achieved through enhancing a stream of activities, so that decisions are made based on acquired knowledge (Wasim et al., 2012). To identify the importance of lean product and process development, it is essential to be aware of the history of lean thinking. Therefore, a brief history is provided in the following section.

2.3.1 Lean thinking

Lean is the mostly applicable philosophy around the globe. However, the lean concept is not static in fact the definition is drifting with the passage of time. Initially lean was a philosophy of reducing all wastes; the new enhanced view, however, is value creation along with waste reduction (Baines et al., 2006). Before World War II, Ford's production system was mostly applicable in America and Europe; however, after the war, Japan developed the new principles named as lean or lean thinking and applied them in their Toyota company which became the number one automotive company in Japan (Naruse, 1991). Although lean was expanded and upgraded from the Ford production system, lean received world recognition after the great success of Toyota in Japan. America and European companies followed lean principles and developed the tools and techniques for their industries (Hines et al., 2004). After the adaption of lean tools and techniques in America and Europe, Toyota's journey of success continued until it became the number one automobile manufacturer in North America in 2006 (Shah and Ward, 2007). Keeping in view such a huge progress and industrial application, no one can deny the importance of lean, that is why Taichi Ohno, the executive director of Toyota in Japan, said these historic words, "I am sure that if Henry Ford I, once the king of carmakers, were alive, he would create the same system as the Toyota System" (Naruse, 1991).

There is no doubt that the term 'lean thinking' has gained widespread attraction. The journey of lean thinking is illustrated in Table 2-1. Because of its tremendous success, organisations are applying lean thinking to their product development for different purposes. It can be seen from Figure 1-1 (Chapter 1) that lean has entered into the third arena. Lean Manufacturing, the first arena of lean thinking was developed for the shop floor and aimed to enhance value and reduce waste (Womack and Jones, 2003). It is suitable for the shop floor workforce. Five principles of lean thinking, i.e. identify value, identify value stream, flow, pull, and perfection, are the basics pillars of lean manufacturing. Just in time (JIT), Kanban, total quality management (TQM), material requirement planning (MRP) are the major tools applicable for this phase. After the successful implementation of lean thinking at the shop floor level, efforts were initiated to develop lean tools and models for enterprise, which resulted in Lean Enterprise (Al-Ashaab et al., 2010). However, the major problems associated with Lean Enterprise are that only the aerospace industry is concerned with it, and the project members are the only ones who know the project information (Al-Ashaab et al., 2010). After realising the problems associated with Lean Enterprise, European manufacturing companies initiated the third stage of lean thinking in 2008 and named it Lean Product and Process Development (LeanPPD). The project is funded by the EU (LeanPPD, 2009) and aims to develop a new model for European companies which goes beyond lean manufacturing to ensure the transformation of enterprise into a lean environment (Al-Ashaab et al., 2010).

Table 2-1: The journey of lean thinking (Hines et al., 2004)

	1980-1990 Awareness	1990-mid 1990 Quality	Mid 1990-2000 Quality, cost and delivery	2000+ Value system
Literature theme	Dissemination of shop floor practices	Best practice movement, bench marking leading to emulation	Value stream thinking, lean enterprise, collaboration in the supply chain	Capability at the system level
Focus	JIT techniques, cost	Cost, training and promotion, TQM, process reengineering	Cost, process-based to support flow	Value and cost, tactical and strategic, integrated to supply chain
Key business process	Manufacturing shop floor only	Manufacturing and materials management	Order fulfilment	Integrated processes, order fulfilment and new product development
Industry sector	Automotive – vehicle assembly	Automotive – vehicle and component assembly	Manufacturing in general – often focused on repetitive manufacturing	High and low volume manufacturing, extension into service sectors

Lean product and process development is now considered to be the new arena towards the journey of lean thinking. Ward et al. (1995) can be considered to be the first team of researchers who identified Toyota's Product Development (PD) process in the design context. The term 'set-based concurrent engineering' was explained in detail by them. Sobek et al. (1999) further explored set-based concurrent engineering and explained its process, principles and suitable tools, such as checklists, trade-off curves, and matrix for communicating alternatives. Morgan and Liker (2006) identified 13 key principles of lean product development process, which were afterwards grouped into people, processes and technology. Today, researchers and practitioners are striving to develop models, tools and methodologies for lean product development (Al-Ashaab et al., 2010; Kennedy et al., 2008; Morgan and Liker, 2006; Sobek and Liker, 1998; Sobek et al., 1999; Ward, 2007). Progress in this research area still evolves and much more effort is urgently needed for developing a more holistic best practice in lean product development.

It is worth noting that lean is applicable both by its principles and production tools. It may be called as lean at a strategic level (to understand value) and lean tools at an operational level, such as JIT, Kanban, MRPI & II, ERP (to eliminate waste) (Hines et al., 2004). There is a difference in lean application between western companies and their competitors in Japan. The western world focuses on the tools and techniques evolved over the years, whereas, the Japanese focuses on lean principles and apply them directly (Baines et al., 2006). Therefore these principles have a great implementation potential in the presence or absence of tools and techniques. In addition, they can be applied in a series of structured business processes (Haque, 2003). Therefore it is necessary to focus on these principles in detail for the in-depth development of lean tools, techniques and models.

Since this research is concerned with the development of lean for European companies, the main emphasis is, therefore, on the identification of lean tools, techniques and models, rather than lean principles for product development.

Lean product and process development encompasses a number of enablers or building blocks (Al-Ashaab et al., 2010; Khan et al., 2011c); however, this research mainly focuses on set-based concurrent engineering, value, knowledge-based engineering and poka-yoke (mistake-proofing). The reason for this attention is that these enablers have a high potential to develop a cost estimation application. The sections below explain these enablers in detail.

2.3.2 Set-based concurrent engineering

Set-based concurrent engineering is the process of considering a set of possible solutions and gradually narrowing them to converge on a final solution. Starting with a wide range of sets and the gradual elimination of weaker solutions, helps to identify the best solution (Sobek et al., 1999).

Set-based concurrent engineering is the process of exploring alternative ideas by considering a set of design spaces instead of a single design solution (Morgan and Liker, 2006; Sobek et al., 1999; Ward, 2007). With this method, designers communicate explicitly to develop sets of design solutions on the basis of their preferences. As the design progresses, they eliminate the inferior sets of design to narrow down the design space and finally reach the single acceptable solution (Khan et al., 2011a; Ward, 2007). Set-based concurrent engineering includes a number of tools, namely checklists, trade-off curves and matrices for communicating alternatives. Checklists are employed to reduce the conflict and mistakes among functional teams, trade-off curves are used to support design optimisation through visualisation, and matrices for communicating alternatives are applicable to sort out alternative designs through conversations with all stakeholders (Sobek et al., 1999).

Set-based concurrent engineering is also coupled with a number of advantages. For example: it helps to identify more design solutions; reduces communication requirement with suppliers; eliminates back tracking or rework, and work delays; improves concurrency in functional departments, time to market, and design quality; increases the trust in working relationships; and facilitates the availability of a library of backup solutions for meeting changes in design (Al-Ashaab et al., 2009; Madhavan et al., 2008; Nahm and Ishikawa 2006a, 2006b; Sobek et al., 1999; Ward, 2007; Ward et al., 1995). Set-based concurrent engineering differs from point-based concurrent engineering which is mostly applied in US industries. Table 2-2 explains the differences between these two techniques (Kao, 2006; Nahm and Ishikawa, 2005, 2006a, 2006b; Sobek et al., 1999).

Point-based concurrent engineering	Set-based concurrent engineering
In point-based concurrent engineering, the designer chooses one of the design solutions within the solution space, modifies the solution until it meets the design objectives.	In set-based concurrent engineering, the designer identifies sets of possible design solutions and reaches the final solution by eliminating the weaker solutions.
Very effective if first selected solution is precise. Otherwise, iterations to refine the solution can be time-consuming and may lead to suboptimal design.	Gradually narrows down to a single solution and reduces the iteration time.
The development team generates a single solution at each product development stage and throws it to the downstream product development stage without consultation. The feedback is provided to upstream product development stage when problems arise. This feedback may lead to increase in cost and delay in product development.	The development team at each product development stage selects the single feasible solution with the consultation of all the stakeholders.
Decisions are made by development team members at each product development stage. Any decision made by one team member at one product development stage may be invalidated by team members at the next stage.	Functional teams communicate about sets of solutions and regions of the design space, therefore, decisions are made within the design space. In addition, functional teams employ checklists to minimise conflict.
A major problem in point-based concurrent engineering is observed when engineers work concurrently in different groups. Each change in design requires rework. The design team simply freezes the design when the team runs out of time. This may lead to responsibilities issues as well.	No such issue arises in set-based concurrent engineering
In point-based concurrent engineering, development teams start work concurrently. The chances are that the best idea proposed by the upstream development team does not provide clear inspiration to the downstream development team. The downstream development team starts work concurrently with high risk of changes in design, thereby seriously damaging the concurrent engineering philosophy.	Excellent communication among functional teams enhances the concept of concurrent engineering.

Table 2-2: Differences between set-based concurrent engineering and point-based concurrent engineering

There is no clear process to adapt set-based concurrent engineering in real practice. Researchers develop their own processes (Inoue et al., 2010; Kao, 2006; Khan et al., 2011a; Nahm and Ishikawa, 2005, 2006b) to implement the set-based concurrent engineering concept on the basis of principles proposed by Sobek et al. (1999). Table 2-3 represents a review of previously developed set-based concurrent engineering processes.

Table 2-3: A review of previously developed set-based concurrent engineering processes

Inoue et al., 2010; Nahm and Ishikawa, 2005, 2006b	Kao, 2006	Khan et al., 2011a
1. Represent the possible sets of alternatives. 2. Identify the feasible common space of alternative solution. 3. Narrow down the design solution by eliminating the inferior or unacceptable design subset.	1. Generate design alternatives. 2. Evaluate the design alternatives. 3. Prioritise the design alternatives.	1. Identify customer and company value. 2. Map design space to identify the feasible region. 3. Develop a number of innovative concepts and communicate with other team members to understand constraints. 4. Converge to final concept by keeping focus on lean production, conceptual robustness and process planning for manufacturing. 5. Once the final concept is selected; release the final specification, manufacturing tolerances and full system definition.

Nahm and Ishikawa (2006a) presented a set-based parametric design (SBPD) approach to manipulate geometric and non-geometric information in conceptual design development. The approach combines the set-based design (SBD) practice with a parametric modelling technique. A preference set-based design (PSD) and design information solid (DIS) model are the parts of the developed system which tackle the uncertainties and lack of information at the early product development stage. Although the developed 3D-CAD system is employed to explore many design possibilities, the method to identify the designer/customer preferences and the solution narrowing down mechanism was not provided in detail. To overcome this shortcoming, a space-based design methodology was proposed by Nahm and Ishikawa (2006b). The methodology consists of three methods: (1) a space representation method to define the possible design region, (2) a space mapping method to identify the performance space, and (3) a space narrowing method to eliminate weak solutions. In the first method, the designers are allowed to specify the varying degrees of desirability of both the initial design space and required performance space on the basis of their preferences. Performance space is calculated through decomposed fuzzy arithmetic with the extended interval arithmetic in the space mapping method. Finally the design of experiment (DOE) is integrated with a preference and robustness index in a set narrowing method. The design of the experiment is used to decompose the initial design space, whereas the preference and robustness index is employed to find a feasible design subspace by identifying the highest degree of preference and robustness. Inoue et al. (2010) improved the previous work of Nahm and Ishikawa, (2006a, 2006b) by combining finite element analysis (FEA) software with a 3D-CAD system. The system helps to explore better design solutions.

Kao (2006) proposed a set-based concurrent engineering design for a logistics framework that includes three stages: generation, evaluation and prioritization of design alternatives. The key focus at the generation stage is technical requirements identification, such as quality and manufacturability. Computer-aided design (CAD) and computer-aided production planning (CAPP) are utilised for product design and production planning. The evaluation stage includes the assessment of time and cost. Petri nets and activity-based costing were employed to estimate the logistics time and cost. In stage 3, trade-offs are made between the logistics time and cost to determine the best design alternative. For trade-offs, the technique for order preference by similarity to ideal solution (TOPSIS) was employed to offset unfavourable value in one attribute by favourable values in other attributes.

To eliminate the inferior solution, Malak et al. (2009) combined the set-based design with multi-attribute utility theory. Multi-attribute utility theory is a pure mathematical framework to define and evaluate trade-offs on multiple decision criteria. The developed approach involves the elimination of concepts that are dominated by others, and refining the remaining concepts to enable more complete eliminations.

Khan et al. (2011a) proposed the set-based concurrent engineering process for lean product and process development. The process is composed of several key phases namely (1) value research, (2) map design space, (3) concept set development, (4) concept convergence, and (5) detailed design. Although a structured process was proposed by Khan et al. (2011a), concept convergence still needs attention.

A number of researchers have employed the set-based concurrent engineering process; however, there is no clear information to define performance variables (i.e. set of designs), or a method to narrow down feasible regions for the selection of the final design. There is a need to focus on this area of research.

2.3.3 Value

Today, product-based competition has been shifted to value-based product development (Horn and Salvendy, 2006). Therefore, the term ‘customer satisfaction’ has gained worldwide attention (Cater and Cater, 2009). No company can survive without providing value to customers (Horn and Salvendy, 2006). Highly profit-oriented firms spend an enormous amount of time with their customers in discussing their value and future requirements (Flint et al., 2010). The definition of lean has also drifted from waste reduction to value creation (Baines et al., 2006). After recognising the importance of value in lean product development, Morgan and Liker (2006) placed value as the primary objective of lean product and process development and stressed defining value at the early stage of product development. Baines et al. (2006) and Haque and James-Moore (2004) also recommended defining value precisely for successful product development and waste reduction; therefore it is mandatory to define value. Womack and Jones (2003) defined product value in terms of both customer and producer. From a customer perspective, value is a good and/or service which satisfies customer requirements within a specific price and time; whereas from a producer perspective, value may be defined to reach from where they are (initial product state) to where they want to be safely with the least hassle at a reasonable price. Customer value is a function of trade-off between benefits achieved and sacrifices made (Olaru et al., 2008); where benefits include product quality, services received and relationships developed; and sacrifices include financial sacrifices such as direct acquisition and operational costs. Value, in terms of customer perceived value, is the product's benefits received by customers and their willingness to pay (Aurum and Wohlin, 2007).

Khan et al. (2011b) categorised product development value into product value and process value; where product value relates to a specific product under development and process value is associated with the process of developing the specific product. Browning (2000) defined product value as the ratio of benefits to cost. Moreover, it is function of performance, affordability and availability. Aurum and Wohlin (2007) explained product value as the market value that is influenced by quality attributes. Pawar et al. (2009) described product value that provides maximum output while keeping the ownership with producer. Baines et al. (2006) emphasised the need to define process value precisely, because product development differs from production operations. TQM, six sigma and customer relationship management are the main elements of process value (Horn and Salvendy, 2006). Supporting creativity and creating a continuous improvement learning environment enhances process value. Flint et al. (2010) emphasised developing skills to create collaborative relationships with customers, especially lead-users, to identify customer change value.

At Toyota, the customer defined value process is initiated by the chief engineer. The chief engineer defines value through market analysis and develops a plan to actually achieve the defined value (Morgan and Liker, 2006). Therefore, for a successful lean product and process development, it is compulsory to define value precisely at the start of the product development process.

2.3.4 Knowledge-based engineering

In-order to survive and grow faster than their competitors, the lean product development team places emphasis on creating a knowledge-based continuous improvement environment (Morgan and Liker, 2006).

Knowledge is mainly classified into three types (Amadori, 2012): tacit, implicit and explicit. Tacit knowledge is the type of knowledge that a person has but can't express it or does not necessarily know that he/she possesses it. Explicit is the type of knowledge that is well documented and organised. Implicit knowledge on the other hand is a specific type of knowledge that is half way between tacit and explicit, i.e. the knowledge which is known to be tacit but has the ability to transform into explicit through some sort of mining and translation process.

The concept of knowledge-based engineering has been shifted from transfer approach to knowledge modelling approach (Studer et al., 1998); i.e. initially, knowledge-based engineering was considered as the process of transferring human knowledge into a form that is ready to use; however, now it has been transformed into dedicated software development with specific problem solving capability. Therefore, it can be said that knowledge-based engineering is the use of advanced, dedicated software tools to capture (acquire) and reuse product and process engineering knowledge (Curran et al., 2009; Skarka, 2007; Stokes, 2001).

The main objectives of knowledge-based engineering are automating the design tasks, supporting multidisciplinary conceptual design, solving the specific problems and massive savings in time and cost of product development (Cooper et al., 1999; Curran et al., 2009; Studer et al., 1998). Knowledge-based engineering can be used for radical innovative tasks; however, it is more suitable for incremental innovative products (Skarka, 2007).

MOKA: a Methodology and tools Oriented to Knowledge-based engineering Application is the most recognised knowledge-based engineering methodology. This methodology is based on six knowledge life cycle stages: (1) Identify:

identify the required knowledge, (2) Justify: acquire the management approval before proceeding further, (3) Capture: collect the various pieces of knowledge required, (4) Formalize: analyse the captured knowledge and represent it in a consistent, structured way, (5) Package: translate the acquired knowledge into a form suitable for the knowledge-based engineering (KBE) system, test it, and remove the errors, and (6) Activate: deliver the packaged system to all potential users (Oldham et al., 1998)). The methodology is widely applied within the automotive and aeronautical industry. MOKA is available in UML (Unified Modelling Language) and MML (MOKA Modelling Language). KNOMAD: Knowledge Nurture for Optimal Multidisciplinary Analysis and Design is a methodology developed to utilise, develop and evaluate multidisciplinary knowledge with knowledge-based engineering framework. The methodology is based on six knowledge life cycle stages: (1) Knowledge capture: identify the objectives and knowledge sources, capture the explicit and tacit knowledge, and document it for use in the subsequent stage; (2) Normalisation: check the quality of knowledge captured and standardise it for ease of use; (3) Organisation: provide a structure knowledge to stakeholders from various disciplines for access and retrieval of necessary knowledge; (4) Modelling: model product and process knowledge; (5) Analysis: analyse the report files of product and process models in detail; optimise the models with respect to design objectives; (6) Delivery: first validate the solution with respect to requirement, and finally distribute the validated optimised solution to stakeholders for necessary action. KNOMAD is considered to be a better solution than MOKA because it performs multidisciplinary modelling and analysis. In addition, data normalisation supports the provision of quality confirmed data.

It can be seen from the above explained knowledge-based engineering methodologies that a knowledge life cycle is a key component; therefore, it is essential to be familiar with the knowledge life cycle. A knowledge life cycle is described as "a process that produces knowledge with a conceptual framework that provides a cognitive map of the processes" (Maksimovic et al., 2011). Knowledge life cycle includes a number of stages to develop a knowledge-based engineering application. Table 2-4 illustrates the different stages of the knowledge life cycle.

Table 2-4: stages of knowledge life cycle
(Maksimovic et al., 2011)

	KLCs in KM				KLCs in KBE	
KLCs	McElroy (2003)	Jashapara (2004)	Buckowitz and Williams (1999)	Dalkir (2005)	Rodriguez and Al-Ashaab (2007)	Stokes (2001) MOKA
Stages	Individual and group learning	Discovering Knowledge	Get	Capture and/or Creation	Identify	Identify
	Knowledge claim formulation	Generating Knowledge	Use	Sharing and Dissemination	Capture and Standardise	Justify
	Information acquisition	Evaluating Knowledge	Learn	Acquisition and Application	Represent	Capture
	Knowledge validation	Sharing Knowledge	Contribute		Implement	Formalize
	Knowledge integration	Leveraging Knowledge	Assess		Use	Package
			Build and Sustain			Activate
			Divest			

Key: KLC = Knowledge Life Cycle, KM = Knowledge Management, KBE= Knowledge-Based Engineering, MOKA = Methodology and tools Oriented to Knowledge-based engineering Application

One of the limitations of the current knowledge life cycles is that they do not support dynamic knowledge capture. In other words, previously developed knowledge life cycles do not facilitate users in capturing the data of a newly developed product for utilisation in the future. To tackle this problem, a novel knowledge life cycle for lean product and process development was proposed by Maksimovic (2011) that includes seven stages: (1) identification, (2) previous projects and domain knowledge capture, (3) representation, (4) sharing, (5) knowledge-based engineering, (6) dynamic use and provision, and (7) dynamic capturing. The users in stage six are allowed to use the dynamic knowledge for decision making. Design templates, checklists, trade-off curves and A3 problem solving templates are proposed for this dynamic use of knowledge. In stage seven, new knowledge can be created through new simulation, prototyping and testing of the product, and then stored in a database for future use.

2.3.5 Mistake-proofing (Poka-yoke)

Mistake-proofing (poka-yoke) is the term mainly applied in lean manufacturing to eliminate error. The ambition of mistake-proofing is to avoid the passing of defective product downstream and to eliminate the risk that undetected defects end up in the customer's hand (Kremer and Fabrizio, 2005). Jamaludin (2008) defined mistake-proofing as a device or practice that aims to prevent the error causing the defects. Whereas Mital et al. (2008) characterised mistake-proofing as a concept to correct the problem as close to the source as possible.

Mistake-proofing contains a number of advantages, i.e. reduces the redesign, rework and repair requirements; removes the necessity for inspections; minimises the defect rates; reduces the workstation inventory; minimises lengthy documentation (Beauregard et al., 1997; Chase and Stewart, 1995; Hinckley, 2001). Mistakes can be avoided by adopting one or more of the following principles: (1) eliminate the possibility of error by redesigning the product or process, (2) replace the existing manufacturing process by a more reliable process to improve consistency, (3) prevent the product or process so that it is impossible for mistakes to occur, (4) reduce the complexity in product or process so that it is easier to perform the work, (5) detect the error before further processing, and (6) mitigate the errors to minimise their effects (Mital et al., 2008). Different mistake-proofing processes have been developed by researchers. Table 2-5 explains the steps of these processes in detail.

Table 2-5: Mistake-proofing processes

Beauregard et al. (1997)	Chase & Stewart (1995)	Hinckley (2001)
1. Define the purpose of mistake-proofing 2. Outline the desired outcome 3. Adopt the best method for the mistake-proofing situation	1. Identify problem 2. Priorities problems 3. Find root cause 4. Create solutions 5. Measure the results	1. Identify and select problem 2. Analyse the problem 3. Generate potential solutions 4. Compare, select and plan solutions 5. Implement solutions 6. Evaluate and standardise solution

In product and process development, the ideal position for mistake-proofing is the design phase because 70% of the cost is committed in that phase. However, once the product has been designed and the process has been selected, only prevention, facilitation, detection and mitigation can be employed to reduce the errors (Mital et al., 2008). Feng and Zhang (1999) developed a method to evaluate the manufacturability and manufacturing cost at the early design stage. They employed manufacturing process selection criteria as product material, quality, form and geometric tolerances. The cost estimation systems developed by Gayretli and Abdalla (1999), Shehab and Abdalla (2002a), and Mauchand et al. (2008) facilitate the removal of mistakes during the suitable manufacturing process selection. The knowledge-based design advisory system proposed by Dai et al. (2010) supports designers in checking geometrical features, process capability, tolerance quality, tools and machine capabilities.

Mistakes also occur during the process parameter selection in the downstream manufacturing process. Therefore there is a need to consider this fact for a successful mistake-proof product development.

2.4 Cost Estimation

In today’s competitive global market, companies’ survival is entirely dependent on delivering innovative product in a shorter lead time, at less cost, of high quality, and with a quick response to market changes and customer satisfaction. Cost is the most significant factor in the entire product development process. If the company fails to provide a meaningful and reliable cost estimate, then there are significantly higher chances that the company would be behind schedule with higher product development costs (Roy, 2003). Therefore it is absolutely essential that the product development cost must be understood at the beginning of product development. In this section, the cost estimation definitions and objectives have been highlighted.

There are numerous definitions for cost estimation. For example, the Association for Advancement of Cost Engineering (AACE) defines cost estimation as “the determination of quantity and the predicting or forecasting, within a defined scope, of the cost required to construct and equip a facility, to manufacture goods, or to furnish a service" (AACE, 1990). Shehab and Abdalla (2001) explain cost estimation as a methodology that forecasts the cost related to activities before their physically execution. Aderoba (1997) relates cost estimation as being a prediction of product cost before its manufacturing. H'mida et al. (2006) identify manufacturing cost estimation as the art of predicting the cost to make a given product or batch of products. The definitions of cost estimation are shown in Table 2-6. The researcher will adapt the cost estimation as a methodology that forecasts the manufacturing cost of product before manufacture, i.e. at the product development design stage.

Table 2-6: Definitions of cost estimation

Author, Year	Cost estimation definition
AACE 1990	"The determination of quantity and the predicting or forecasting, within a defined scope, of the cost required to construct and equip a facility, to manufacture goods, or to furnish a service."
Aderoba, 1997	Prediction of product cost before its manufacturing.
Shehab and Abdalla, 2001	Cost estimation is a methodology that forecasts the cost related to activities before their physical execution.
H'mida et al., 2006	Manufacturing cost estimation is the art of predicting the cost to make a given product or batch of products.
Tammineni et al., 2009	Cost estimation is the process of forecasting the product cost prior to execution of any product development stages.

It is also essential to distinguish the difference between cost accounting, cost engineering and cost estimation. Cost accounting is a financial term widely used to measure product cost after the execution of an activity/project; whereas, "Cost engineering is concerned with cost estimation, cost control, business planning and management science, including problems of project management, planning, scheduling, profitability analysis of engineering projects and processes" (Roy, 2003 page 1). It can be concluded from the above explained definitions that cost accounting identifies the actual consumption of resources, cost estimation utilises cost accounting and other information to predict the future cost, whereas cost engineering employs cost estimation and other activities to manage profitable business.

Cost estimation is a vast field and its objectives vary from company to company. Companies employ cost estimation to execute a number of functions, such as (1) cost management, (2) budgeting/long term financial planning, (3) suppliers' quotations assurance or quotations development in order to negotiate with suppliers, (4) decision making, (5) evaluation of product design alternatives in the design phase, (6) manufacturing cost control, and (7) development of production efficiency standards (Ben-Arieh, 2000; García-Crespo et al., 2011; Roy, 2003).

2.5 Cost Estimation Methods

A reliable estimate depends on the selection of suitable method. A number of cost estimation methods have been identified by researchers. It is the responsibility of the estimator to select a suitable method prior to the commencement of the estimation process. In the following sections, different cost estimation methods have been explained. To select a suitable estimation method, a comparison of these cost methods has been done with respect to accuracy and cost estimation lead time. In addition, the possible use of these cost estimation methods have been identified at different stages of product development and at different degrees of innovation. To compare the cost estimation against different degrees of innovation, three innovation types have been identified through the literature review: incremental innovation (where the firm makes few changes to an already developed product); really new innovation (the product is either new to the firm or a new market is allocated); and radical innovation (the technology is new to the firm as well as new to customers) (Garcia and Calantone, 2002; Micheal et al., 2003; Salavou, 2004).

Cost estimation methods have evolved over the last four decades. There is no agreed classification of cost estimation methods, as different authors have proposed dissimilar categories of cost estimation methods. Shehab and Abdalla

(2001) classified four cost estimation methods as intuitive, parametric, analogical and analytical. Roy (2003) categorised five cost estimation methods as traditional, parametric, feature-based, neural networks and case-based reasoning. Tammineni et al. (2009) proposed four methods of cost estimation: analogy-based, parametric, feature-based and bottom-up. One of the most comprehensive and widely acceptable classifications has been provided by Niazi et al. (2006), as they listed twelve cost estimation methods and categorised them into qualitative and quantitative methods, as shown in Figure 2-6. Since our main focus is the development of a cost modelling system to support lean product and process development, in this section a comprehensive literature review is conducted to find out the previously developed manufacturing cost estimation systems and models, which estimate the manufacturing cost of product in the design phase. Special attention was given to exploring the research work that focuses on assisting the development team towards cost estimation and cost reduction opportunities in the early design stage. Detailed descriptions of these cost estimation methods, previously developed cost estimation systems and models are explained in the following section.

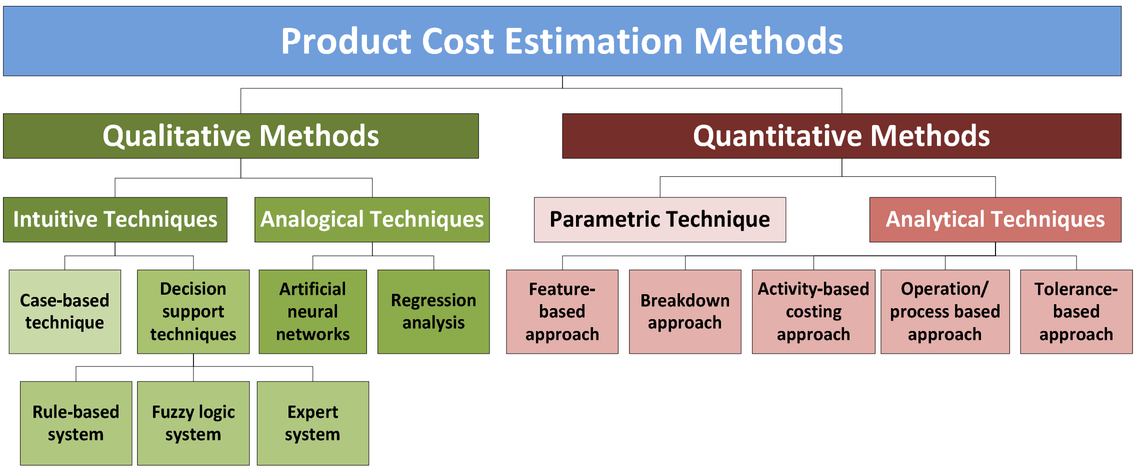

Figure 2-6: Classification of cost estimation methods
(Adapted from Niazi et al., 2006)

2.5.1 Intuitive cost estimation techniques

Intuitive cost estimation techniques are associated with estimating cost on the basis of past experience utilisation (Duverlie and Castelain, 1999; García-Crespo et al., 2011; Niazi et al., 2006). In these techniques, knowledge is stored in the form of rules, decision trees, judgements etc., at the specific location in databases, which may be used in the later stages for the cost estimation of new products (Niazi et al., 2006). Although these techniques are used for rapid cost approximation and do not necessarily follow a systematic process, they are, however, used extensively and sufficiently accurately in certain circumstances (Zaihirain et al., 2009). These techniques include case-based techniques and decision support techniques.

2.5.1.1 Case-based technique

Case-based technique, widely known as case-based reasoning (CBR), is the cost estimation method associated with the utilisation of the results of precedence cases to identify the solution for new problems (Duverlie and Castelain, 1999; García-Crespo et al., 2011; Niazi et al., 2006; Roy, 2003; Wang and Meng, 2010). The case-based technique is categorised as an artificial intelligence technique (Roy, 2003), because it stores and reuses historical data in a structured way to identify the cost of an unknown problem. The process of case-based technique includes: (1) define the characteristics of new case (problem), (2) select the similar case from the historical data with the help of similarity measure, (3) adopt the precedence case directly or modify to adapt, (4) test the case to evaluate the solution, and (5) record the case in the database for future utilisation (Duverlie and Castelain, 1999).

The case-based technique is applied to develop a rough estimate quickly and easily (Karadgi et al., 2009; Niazi et al., 2006). Precision levels depend on the similarity of precedence cases. A large number of previous cases are required to develop a reliable estimate (Roy, 2003). Reuse of precedence cases minimises previously committed errors and enhances organisational learning (Duverlie and Castelain, 1999; Roy, 2003). The case-based technique is useful at the product concept development stage for a quick and reliable estimate

(Niazi et al., 2006); however, this technique is not suitable for radical innovative products, since the data for precedence cases are not available (Roy, 2003).

A cost estimation system using case-based reasoning (CBR) and a knowledge-based engineering approach has been developed by Karadgi et al. (2009). The system is applicable for estimating the cost of deep drawn sheet metal components. A case-based reasoning system retrieves the process plan of most similar complex components, whereas a knowledge-based system revises, reuses and retains the process plan. The cost is estimated using the revised or retrieved process plan. The system is developed in the Drools toolkit, which is a behavioural modelling approach to combine business rules and process (Drools, 2012). To retrieve the process plan of similar components in the casting process, the case-based reasoning technique was employed by Chougule and Ravi (2006). The developed system facilitates cost estimation in the early product development design stage.

A hybrid cost estimation system, by combining case-based reasoning (CBR) with fuzzy logic and rule-based reasoning (RBR) techniques, was proposed by Chan (2005). The system assists its users to identify the electroplating coating weight quickly and accurately at the product development planning and design stage. In the developed system, a case-based reasoning technique has been employed to identify similar cases. In the case of failure, rule-based reasoning (RBR) and fuzzy logic integrate with case-based reasoning techniques to sort out similar cases. The fuzzy logic sub-system converts the numerical variables into linguistic variables in order to reduce uncertainties in similar case identification; whereas rule-based reasoning sub-systems use the selection rules to identify the nearest match case. Wang and Meng (2010) integrated case-based reasoning with activity-based techniques to estimate the cost of steel components. The proposed system supports make or buy decisions in the early product development planning phase. Case-based reasoning and neural networks were joined by Wang et al. (2003) to estimate the cost of injection moulding components. The developed system is applicable in the early product development design and planning phase. The system includes case representation, case indexing, case retrieval, case adaptation and case learning. Neural network method supports to retrieve the similar case. If the similarity between new and previous cases is higher, the system is adopted directly. However, if the similarity is lower, the system requires making minor changes before implementation. The new case is also stored in the database on the basis of similarity criteria.

2.5.1.2 Decision support techniques

Decision support techniques are associated with estimating the cost to make better judgements by using the stored knowledge of experts (Niazi et al., 2006). These techniques are further classified into rule-based system, fuzzy logic system and expert system, as explained below.

Rule-based system

A rule-based system is a cost estimation method associated with the estimation of process time and cost of feasible manufacturing processes based on design and/or manufacturing constraints along with rules (Niazi et al., 2006). In this method, rules are developed to accomplish different requirements. Djassemi (2008), Er and Dias (2000) and Mauchand et al. (2008) developed rules to select the manufacturing process. Shehab and Abdalla (2002b) proposed the fuzzy logic rules to estimate the machining time. Masel et al. (2010) developed the rules to estimate the geometry and volume of forging die. Researchers also developed the rules to compare the estimated cost with target cost (Gayretli and Abdalla, 1999; Shehab and Abdalla, 2001, 2002b).

Rule-based systems are applicable in the early design phase to estimate the product cost. This method is exceedingly supportive to optimise the cost; however, the process of optimisation is time-consuming since large numbers of rules are required (Niazi et al., 2006); therefore, this method is not suitable for radical innovative products.

To facilitate inexperienced designers in the estimation of the manufacturing cost of products at the design stage, Shehab and Abdalla (2001) developed a knowledge-based system. This system employs a rule-based system, fuzzy logic system and analytical techniques. Rules related to the manufacturing process and machine selection help to identify the feasible machining process. The system not only recommends the most economical product assembly choice but also supports the selection of material and manufacturing processes based on design requirements.

The knowledge-based system developed by Gayretli and Abdalla (1999) helps designers to identify the manufacturing cost of product within the design stage. The system employs a rule-based technique, along with a feature-based approach. Proposed rules facilitate manufacturing process identification and optimisation. Masel et al. (2010) proposed a rule-based system to estimate the cost of forging die required to manufacture jet engine parts. The die design rules were employed to estimate the geometry and volume of forging die in the conceptual design stage. The rules include the identification of filling, expanding, plug formation, pulling and filleting requirements.

To identify the cost of an appropriate casting process, Er and Dias (2000) employed the rule-based system. Fourteen casting processes were evaluated on the basis of material, product geometric features, casting accuracy, production volume and overall comparative cost. Mauchand et al. (2008) extended the work of Er and Dias (2000) and focused on generalising the manufacturing processes instead of being restricted to casting processes only. Esawi and Ashby (2003) and Djassemi (2008) also developed rules to identify suitable manufacturing processes followed by manufacturing cost estimations. Although these methods provide the information for all the suitable manufacturing processes, the cost estimates are, however, exceedingly rough.

Fuzzy logic system

The fuzzy logic system is a cost estimation method associated with uncertainty handling during the product development cost estimation (Shehab and Abdalla, 2001). Fuzzy production rules are mainly similar to traditional production rules with one difference that linguistic expression is used in fuzzy rules and truth values are assigned (Shehab and Abdalla, 2002b; Shehab, 2001). The process of the fuzzy logic includes three steps: i.e. fuzzification of inputs, fuzzy inference based on a defined set of rules, and defuzzification of the indirect fuzzy values. Jahan-Shahi et al. (2001) applied the fuzzy logic system to reduce the uncertainty of non-processing variables; whereas, Shehab and Abdalla (2001; 2002b; 2002a) applied the method to reduce the uncertainty of machining time.

Fuzzy logic systems are employed in the early design phase to reduce estimation uncertainty. This methodology is helpful in generating reliable results; however, the cost estimation of complex features is a tedious task (Niazi et al., 2006). This method is suitable for really new and radical innovative products.

A model to estimate the cost and time of flat plate processing using multi-valued sets has been developed by Jahan-Shahi et al. (2001). The uncertainty model includes four non-processing variables such as operator conditions, nature of work, environmental conditions, and management and organisational conditions. A Monte Carlo simulation was employed to analyse the uncertainty. The results indicate that an uncertainty model can be applied in different operator–work–environment–organisation conditions to generate more reliable results. Shehab and Abdalla (2001) employed the fuzzy logic technique to handle uncertainty in machining time estimation. The fuzzy logic system, integrated with case-based reasoning and rule-based reasoning, was used by Chan (2005) to estimate the electroplating coating weight and ultimately the cost. Fuzzy logic and rule-based reasoning (RBR) were employed to sort out a similar case and to reduce uncertainties in similar case identification.

Expert system

The expert system is a cost estimation method associated with the storing of cost knowledge in a database and reusing it on request to develop quicker, reliable, and precise estimates (Niazi et al., 2006). The expert system focuses mainly on theoretical knowledge of text books rather than depending on practical knowledge. These systems help to identify the machining condition, manufacturability, manufacturing time and cost of product in the design phase (Arezoo et al., 2000; Chan, 2003; Djassemi, 2008; Er and Dias, 2000; Mauchand et al., 2008).

Expert systems are employed in the early design phase to develop quicker and reliable estimates; however, a complex programming is required for accurate estimates (Niazi et al., 2006).

An expert computer aided cutting tool selection system to select the cutting tool and cutting conditions (feed, speed and depth of cut) for simple turning operations has been proposed by Arezoo et al. (2000). The system helps to identify the manufacturing time and cost of product in the design phase. Djassemi (2008), Er and Dias (2000), Esawi and Ashby (2003) and Mauchand et al. (2008), also developed expert systems to identify the most suitable manufacturing process. An expert system developed by Chan (2003) supports the designer in identifying the manufacturability of a product.

2.5.2 Analogical Cost Estimation Techniques

Analogical cost estimation techniques are associated with the identification of product cost on the basis of the cost of previously developed, similar products (Duverlie and Castelain, 1999; García-Crespo et al., 2011; Niazi et al., 2006). The effectiveness of these techniques is highly dependent on the availability of past data (Zaihirain et al., 2009). These techniques include artificial neural networks and regression analysis.

2.5.2.1 Artificial neural networks

Artificial neural networks utilise the principle of artificial intelligence and the human brain, in which the knowledge of previous similar products is stored in the system, and a mechanism is developed to make the system independent such that it makes decisions that cannot be defined in clearly mathematical terms and generates the output for unseen conditions (Cavalieri et al., 2004; Roy, 2003; Shehab, 2001). The artificial neural network process is performed in two stages, i.e. the preparatory stage and the production stage (Chen and Chen, 2002). In the preparatory stage, a neural network is constructed and trained with respect to existing products and their historical cost data. In the production stage, the new product is identified, the network is applied to the product and the cost of product is then estimated. The artificial neural network function is identical to the human brain because the information is coded to network in the form of an electric pulse, and the system generates the results associated with inputs that have never been seen by the system (Cavalieri et al., 2004). The multilayer perceptron is a specific type of artificial neural network, which contains multilayers, namely input layer, hidden layers, and output layer (Cavalieri et al., 2004; Wang et al., 2000).

Artificial neural networks can be applied in any phase of product development to estimate the product cost. This method is simple, consistent and accurate, and can be applied to deal with uncertain conditions and nonlinearity issues; however, it is completely data dependent, requires high costs to develop the neural network, and development time is slow because of the trial and error process (Chou and Tai, 2010; Ciurana et al., 2008; Niazi et al., 2006). Since the method involves artificial intelligence, it is, therefore, highly suitable for really innovative and radical innovative products.

An artificial neural network and multiple regression analysis were integrated by Ciurana et al. (2008) to estimate the cost of vertical high speed machining centres. The model was proposed for manufacturers' as well as for buyers' decision making. Twenty networks were designed on a MATLAB Neural Network Toolbox using the back propagation algorithm. The results explained that correlation obtained by the multilayer artificial neural network model was better than multiple regression analysis. Rimašauskas and Bargelis (2010) presented a model for estimating the manufacturing cost of sheet metalworking using an artificial neural network. The network input layer is formed of part thickness, number of design features, material, and perimeter of the contour being cut. The results showed that estimates generated by the neural network were fairly accurate as compared to the parametric model. A back propagation network was combined with a feature-based model to estimate the cost of plastic injection components (Wang, 2007). The input layer consists of volume, material, product net weight, material density, surface area, number of cavities, projection area, product length, width and height. The results indicate that the system is effective to generate an estimate of products at the early development stage.

Cao et al. (2010) developed a multi-parameter cost-tolerance model using a fuzzy neural network (FNN). Tolerance and cost influence coefficients were used as inputs and manufacturing cost as an output. A total of 40 input and output pairs were generated. Thirty pairs were generated for network training; whereas, 10 pairs were developed for network performance testing. The model is helpful to reduce the errors in tolerance design.

2.5.2.2 Regression analysis

In regression analysis, historical cost data are used to establish a relationship between the product costs of the previous design cases, variables are selected for a new product, and the relationship is used to forecast the cost of a new product (Niazi et al., 2006). Ciurana et al. (2008) devised two regression analysis methods: forward selection and backward elimination. In the former, an independent variable with the biggest contribution is included in each step. In the latter, independent variables with the lowest contribution to the prediction power of the model are eliminated in each step.

Regression analysis can be applied in the product development design phase to estimate the product cost. The method is simple; however it has limitations in resolving linearity issues (Niazi et al., 2006). Since the regression analysis is highly dependent on historical data, it has limitations in its employment for radical innovative products.

Ciurana et al. (2008) developed a cost estimation model to estimate the cost of vertical high speed machining centres using multiple regression analysis and artificial neural networks. The model supports decision making for manufacturers as well as buyers. Four variables, namely work area, positioning accuracy, spindle speed, and power, were considered in developing the multiple regression analysis model for buyers, whereas, three variables, namely weight, spindle speed, and number of axes, were used to develop the model for manufacturers. The model was tested using Microsoft Excel. Regression analysis and artificial neural network, and support vector regression, were employed by Liu et al. (2009) to estimate the product life cycle cost.

2.5.3 Parametric Cost Estimation Technique

The parametric cost estimation technique is associated with the estimation of product cost using certain products' parameters or characteristics and developing a relationship with cost (Duverlie and Castelain, 1999; Qian and Ben-Arieh, 2008; Roy, 2003). Parameters identified for cost estimation do not necessarily describe the product completely (García-Crespo et al., 2011). Examples of parameters include volume, weight, number of inputs-outputs (Duverlie and Castelain, 1999; Qian and Ben-Arieh, 2008; Roy, 2003;). The relationship developed between parameters and cost is known as the cost estimation relationship (CER) (Roy, 2003). There are three different types of parametric methods, namely the method of scales, statistical models and cost estimation formulae (CEF) (Duverlie and Castelain, 1999; Qian and Ben-Arieh, 2008). In the method of scales, the estimator identifies the most significant parameter and develops a cost to parameter ratio. In statistical models, the product's historical information is collected using statistical techniques and finally a relation is developed from the information to estimate the cost, whereas in cost estimation formulae, a mathematical relationship is developed to connect cost with parameters.

The parametric technique is helpful to estimate the cost during the design stage when product structure and manufacturing processes are not recognised and without the use of a process plan (Niazi et al., 2006; Qian and Ben-Arieh, 2008). The method is simple, easy to implement even when the product is not completely defined. It predicts the cost excellently when procedures are followed, meaningful and accurate data are collected, and assumptions are documented clearly. Moreover, large numbers of parameters are required and a complex mathematical relationship needs to be developed for precise estimation (Duverlie and Castelain, 1999; García-Crespo et al., 2011; Roy, 2003). Since parametric cost estimation does not entirely depend on whole product information, it can, therefore, be applied for radical innovative product, however only rough estimates are expected.

Parametric, analytical and case-based reasoning techniques were integrated by Chougule and Ravi (2006) to estimate the manufacturing cost of the casting process at the product development design stage. The developed web-enabled system facilitates cost estimation in the early product development design stage. The tooling cost increases with part complexity; therefore, the authors employed the parametric technique to identify the tooling cost. The authors also proposed analytical equations to estimate the material, labour, energy and overhead costs.

A cost estimation model that integrates activity-based costing (ABC) with parametric costing was developed by Qian and Ben-Arieh (2008) to estimate the cost of machining rotational parts. Their model is applicable in the design and development phase for web-based cost estimation and for supplier selection. The authors presented three linear parametric models: one using activity cost drivers, a second considering batch size and the third for machining time. The results indicate that the proposed model is more accurate than traditional cost estimation methods.

Masmoudi et al. (2007) presented a computer assisted method for the welding operation. Cost of product features and final assembly is estimated by parametric and analytical methods. The system is developed in a Microsoft access database, and allows the user to make decisions after comparing alternative designs and welding processes. Chayoukhi et al. (2009) improved the work of Masmoudi et al. (2007) to generate more accurate estimates.

2.5.4 Analytical Cost Estimation Techniques

Analytical cost estimation techniques are associated with the estimation of product cost by decomposing the product into its elementary units, analysing the cost of each unit and finally the summation of all units cost (García-Crespo et al., 2011; Niazi et al., 2006). These techniques provide accurate estimates as each unit is analysed in detail; however, the process is time-consuming and hard to estimate without detailed information. Analytical techniques are classified into feature-based approach, breakdown approach, activity-based costing approach, operation/process based approach, and tolerance based approach, as explained in the following section.

2.5.4.1 Feature-based approach

The feature-based cost estimation approach is associated with estimation of product cost by identifying product's features and correlating the cost with each feature (García-Crespo et al., 2011; Niazi et al., 2006; Qian and Ben-Arieh, 2008). Feature-based cost estimation is a widely applicable method; however, there is no consensus of specific feature definition among organisations (Roy, 2003; Souchoroukov, 2004). For example the wing is a feature of an aircraft, which contains many parts, and each part contains many lower levels of feature. Niazi et al. (2006) explained two types of features: design related and process related. Product material and geometric details are examples of design related features, whereas specific manufacturing processes, such as machining, injection moulding and casting are process related features. Roy (2003) pointed out six types of features: geometric (length, width, depth), attribute (tolerance, density, mass), physical (hole, pocket, core), process (drill, welding, machining), assembly (interconnect, align, engage), and activity (design engineering, structural analysis). The process of the feature-based cost estimation approach for simple machining processes includes: (1) decompose the part/assembly model into a subpart/subassembly level; (2) identify all features for each subpart/subassembly; (3) identify the machining process for each feature; (4) estimate the machining time and cost of each feature; and (5) estimate the machining time and cost of all features associated with each part/assembly (Bouaziz et al., 2006).

The feature-based cost estimation approach is helpful to estimate the cost during the design stage. Cost visualisation is easy as features with higher cost can be identified; however, the cost of complex features is difficult to estimate (Niazi et al., 2006). Since in a feature-based cost estimation approach, the estimator requires detailed product information, this estimation process is, therefore, feasible for incremental innovative products rather than radical innovative products.

The feature-based cost estimation approach was employed by Gupta et al. (1994) to evaluate alternative process plans for designers. The model also supports the process planners in selecting the appropriate process plan based on machine tools availability. The designers at the upstream location receive support for manufacturability and optimise the design by balancing the quality against efficient manufacturing. However, the system has restrictions in that it is suitable for alternative process plans identification and machining problems reduction only.

Ou-Yang and Lin (1997) developed a feature-based manufacturing cost estimation model for inexperienced designers having little knowledge of the manufacturing process. The system guides the designers to identify the product machining cost in the conceptual design phase. The system helps designers to evaluate alternative design options on the basis of manufacturing cost. During the estimation process, designers build the model based on features and specify its roughness. The system first examines the manufacturability of features, followed by manufacturing time and finally manufacturing cost of the model.

To estimate the machining cost of product in the design phase, Shehab and Abdalla (2001) used the feature-based approach, rule-based system, and fuzzy logic system. The system estimates the cost of each product feature and recommends the most economical assembly process. The system was further improved (Shehab and Abdalla, 2002b) for injection moulding components. Bouaziz et al. (2006) developed a system for designers to estimate the cost of die manufacturing. The main objectives were (1) to decrease the time of estimation, and (2) to improve the quality of the estimate by removing uncertainties. The system is supportive for estimating the cost of complex machining features during the concept development phase.

A cost estimation system for welding joints within the design phase was proposed by Chayoukhi et al. (2009). Their system employs a semi analytical approach to estimate the cost, and is supportive for identification of the most economical design. The cost estimation algorithm includes: (1) decompose the product into sub assemblies; (2) model each sub assembly by preparation features and welding features; (3) for each feature, associate the several suitable manufacturing processes; (4) associate the cost with each manufacturing process.

2.5.4.2 Breakdown approach

The breakdown approach is associated with the summation of all the costs incurred during the product development cycle, such as material costs and overheads (García-Crespo et al., 2011; Niazi et al., 2006). The accuracy of estimation increases with increasing the breakdown cost components. For example, Chan (2003) break the cost down into material cost, processing cost, tooling cost, and factory overheads, Chougule and Ravi (2006) break the cost down into direct and indirect material cost, labour cost, energy cost, and tooling; (2003), whereas Klansek and Kravanja (2006) break the cost down into a more detailed level of 18 components.

The breakdown approach can be applied at the design stage to estimate the product cost. However, time is consumed in gathering the detailed information for the breakdown approach (Niazi et al., 2006). For radical innovative products, detailed information is not available; therefore, the breakdown approach is not a suitable approach for these products.

A knowledge-based expert system for product designers to assess the manufacturability of product designs was proposed by Chan (2003). The developed system helps designers to develop designs that satisfy the requirements by comparing alternative options. Chan breaks down the cost into material cost, processing cost, tooling cost, and factory overheads. From the developed system, Chan also identified that direct processing costs varied consistently around 0.75 to 0.8 times the estimates made by companies. The cost of composite and steel structures was estimated by Klansek and Kravanja (2006) using the breakdown approach. The major cost drivers include material cost, power consumption cost and labour cost. Each cost driver was further divided into six, six and twelve sub cost drivers respectively; therefore, the system helps to estimate the cost accurately.

2.5.4.3 Activity-based costing approach

Activity-based costing (ABC) is associated with the estimation of cost by identifying the number of activities required to develop a product and the cost associated with each activity (Ben-Arieh, 2000; García-Crespo et al., 2011; Niazi et al., 2006; Qian and Ben-Arieh, 2008; Yongqian et al., 2010). The ABC works on the principle that cost objects utilise activities and activities consume resources (Yongqian et al., 2010). Lere (2000) categorised ABC as unit level activities, batch level activities, and product-level activities. Implementation of ABC is a simple seven steps procedure, i.e. identify activities; identify cost centres; analyse indirect costs and calculate their cost-drivers rates; assign resources to each cost centre and determine cost centre driver rates; analyse each activity and find the total cost for each activity; define activity drivers for each activity and find activity cost-driver rate; and finally estimate the cost of new parts via activity cost-drivers spent (Ben-Arieh, 2000).

The ABC approach is helpful in estimating cost during the design stage. It provides accurate and traceable cost information; therefore, designers may identify high cost consumption activities and improve the product design before manufacturing. The shortcoming of this approach is that comprehensive information related to production activities is required which is a time-consuming job (Ben-Arieh, 2000; Niazi et al., 2006; Qian and Ben-Arieh, 2008; Yongqian et al., 2010). ABC is suitable for incremental innovative products only.

Özbayrak et al. (2004) compared the push and pull manufacturing systems using ABC. The manufacturing systems were compared by using the SIMAN simulation system. The results show that a pull type manufacturing system consumes less cost for small batch sizes than a push type manufacturing system, provided that the system has no breakdowns. However, if there are delays in the system, such as equipment failure, regular interruption etc., in that case the push type manufacturing system has superiority over the pull type.

A web-based cost estimation system using an activity-based cost estimating approach was developed by Qian and Ben-Arieh (2008). The system has the capability to provide process-planning, estimate machining time and cost, and select an appropriate supplier. With the developed system, designers and suppliers can communicate with each other quickly and easily, thus reducing both lead time and procurement cost. Maropoulos et al. (2003) proposed aggregate process modelling that operates on the principle of alternative processes and resources parameters selection automatically for the feature-based design, ultimately measuring the manufacturability of the product. Multi-criteria (quality cost and delivery, QCD) were employed for design optimization. Hence, the designer receives the information related to quality, cost, time and manufacturability of product.

2.5.4.4 Operation/process-based approach

The operation/process-based approach is associated with the identification of operations required to develop the product and associating the cost with all operational and non-operational times (Niazi et al., 2006). Operational times contain actual processing time, whereas non-operational times include setup time and waiting time etc. (Niazi et al., 2006; García-Crespo et al., 2011). Operational time depends on the type of manufacturing process employed. For example the operational times of composite components' manufacturing process incorporate layup time, tool closing, cure cycle, cutting time, part removal time, part finish time, hot fly forming, tool cleaning, inspection time, marking time and packaging time (Curran et al., 2008).

The operation/process-based approach is an extension of ABC and other analytical methods. Since, other analytical methods are incapable of considering the effect of change in material, design architectures or manufacturing processes, the operation/process-based approach is, therefore, a suitable method for analysing the alternative manufacturing process (Fuchs et al., 2008); however, time is consumed in gathering the detailed information (Niazi et al., 2006). Since a detailed level of information is required in the operation/process-based approach, this approach is also not considered to be a suitable estimation approach for radical innovative products.

The cost of aerospace composite parts and assembly structures using SEER-DFM was estimated by Curran et al. (2008). Layup time, tool closing, cure cycle, cutting time, part removal time, part finish time, hot fly forming, tool cleaning, inspection time, marking time and packaging time were used to estimate the cost of composite components manufacturing; the main objective was to create an opportunity for cost reduction so that the company can challenge their suppliers and negotiate with them. The results indicate that the developed system has excellent capability to support decision making and to compress time for cost reduction. Choi et al. (2007) developed a knowledge-based engineering system to estimate the weight and manufacturing cost of a composite structure at the conceptual stage of a design using CAD geometry and process-based techniques. The authors employed a theoretical model developed by Gutowski et al. (1994) to estimate the manufacturing time of the composite structure.

2.5.4.5 Tolerance-based approach

A tolerance-based cost estimation approach is associated with the estimation of product cost by keeping tolerance as a function of cost (Cao et al., 2010; Dimitrellou et al., 2008; Niazi et al., 2006). The tolerance-based approach considers the principle that tighter tolerances are always coupled with elevated manufacturing costs (Cao et al., 2010; Dimitrellou et al., 2008).

Tolerance-based cost estimation is helpful in estimating the product tolerance and associated cost during the design stage; however, time is consumed in gathering detailed information (Niazi et al., 2006); therefore, this approach is suitable for incremental innovative products only.

A multi-parameter cost-tolerance model using a fuzzy neural network (FNN) was proposed by Cao et al. (2010) to reduce the errors in tolerance design. Tolerance and a cost influence coefficient were used as inputs and manufacturing cost as output. Cost-tolerance data were generated for four machining features, namely planer, cylindrical, hole and locating features. The results indicate that cost increases with tighter tolerance and higher cost influence coefficient. Dimitrellou et al. (2008) developed an optimum cost-tolerance transfer system. Their system was based on the fact that the majority of machine shops do not produce, formulate and store cost-tolerance information. In order to mitigate the effects, process planners have to employ their own judgement and knowledge. This approach is time-consuming and can be dangerous when a part has a large number of tolerances. The developed system contains two modules, namely the database module and transfer module, for storing and transferring the tolerance knowledge respectively. The system was implemented on the gear segment. The results indicate that the system is helpful to overcome the cost optimum tolerance problem.

2.6 Analysis of Cost Estimation Methods

It can be seen from the above literature that there are a number of cost estimation methods. However, it should be noted that no single cost estimation method is applicable during the whole product development stage (Souchoroukov, 2004), because of the particular data type requirement for each cost estimation method. In addition, only a rough estimation is possible at the early product development stage, because of the availability of a limited amount of data and incomplete product information; however, in the later product development stage, higher estimation precision can be accomplished by using large amounts of data and detailed product information. Table 2-7 summarises the potential application of each cost estimation method at the different product development stages.

The precision level and cost estimation lead time against the type of data available for all cost estimation methods are also presented in Figure2-7 and Figure 2-8 respectively. These figures are based on the fact that detailed cost estimation methods require high lead times. In addition, the provision of supplementary information and product data improves the precision of estimates.

Table 2-7: Use of cost estimation methods at different stages of product development

Cost estimation \ Product Development stages	1. Planning	2. Concept Development	3. System-level Design	4. Detail Design	5. Testing and Refinement	6. Production Ramp-up
Case-based technique	✓	✓	✓	x	x	x
Rule-based system	✓	✓	✓	x	x	x
Fuzzy logic system	✓	✓	✓	x	x	x
Expert system	✓	✓	✓	x	x	x
Artificial neural networks	✓	✓	✓	x	x	x
Regression analysis	✓	✓	✓	x	x	x
Parametric technique	✓	✓	✓	x	x	x
Feature-based approach	x	✓	✓	✓	✓	✓
Breakdown approach	x	X	x	✓	✓	✓
Activity-based costing approach	x	X	✓	✓	✓	✓
Operation/process-based approach	x	X	x	✓	✓	✓
Tolerance-based approach	x	X	x	✓	✓	✓

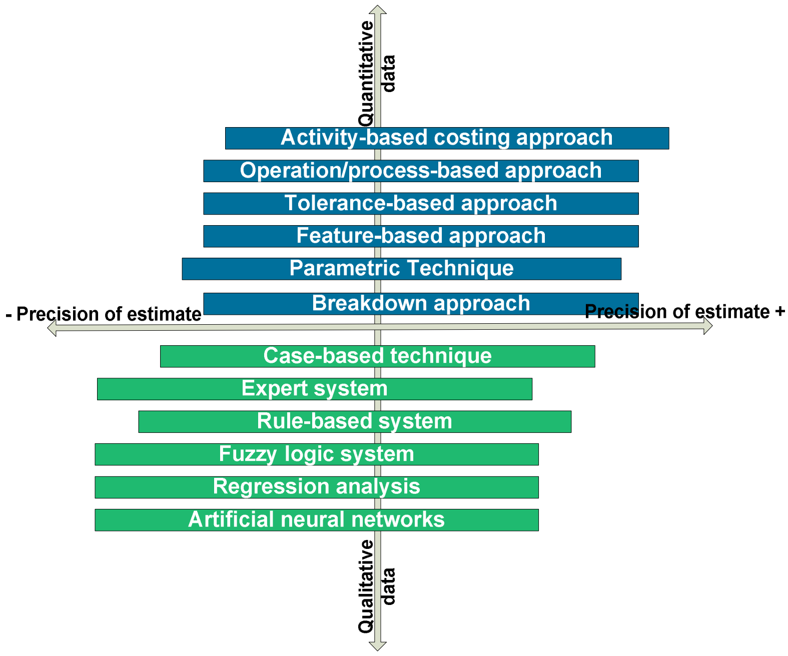

Figure 2-7: Precision Vs Type of data available

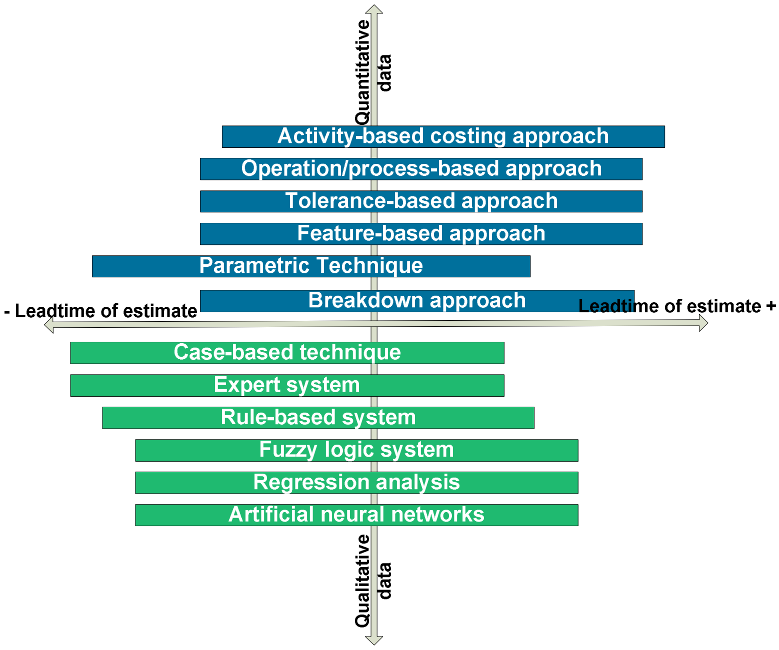

Figure 2-8: Lead times Vs Type of data available

Product innovation can be incremental, really new or radical (Garcia and Calantone, 2002). Incremental innovation is the type of innovation where the firms make minor changes in their previously developed product and then launch it into the market. Radical innovation is the type of innovation where the firm develops an entirely new product for new customers with entirely new technology. Really new innovation is located in between incremental and radical innovation, where either the product is new for the customer or the technology is new for the company (Garcia and Calantone, 2002; Micheal et al., 2003; Salavou, 2004). Since this research focus is the design stage, it is, therefore, necessary to identify the prospective application of these cost estimation methods with respect to a product's degree of innovation. For this purpose, Figure 2-9 has been developed. Since quantitative cost estimation methods require a detailed amount of data, these methods are, therefore, suitable for incremental innovative products only. Qualitative methods on the other hand, have more tendencies to apply to radical innovative products and really new innovative products, because they require descriptive data more than quantitative data. Only one quantitative cost estimation method, i.e. the parametric technique, is applicable for radical innovative products, because it does not require the complete product information.

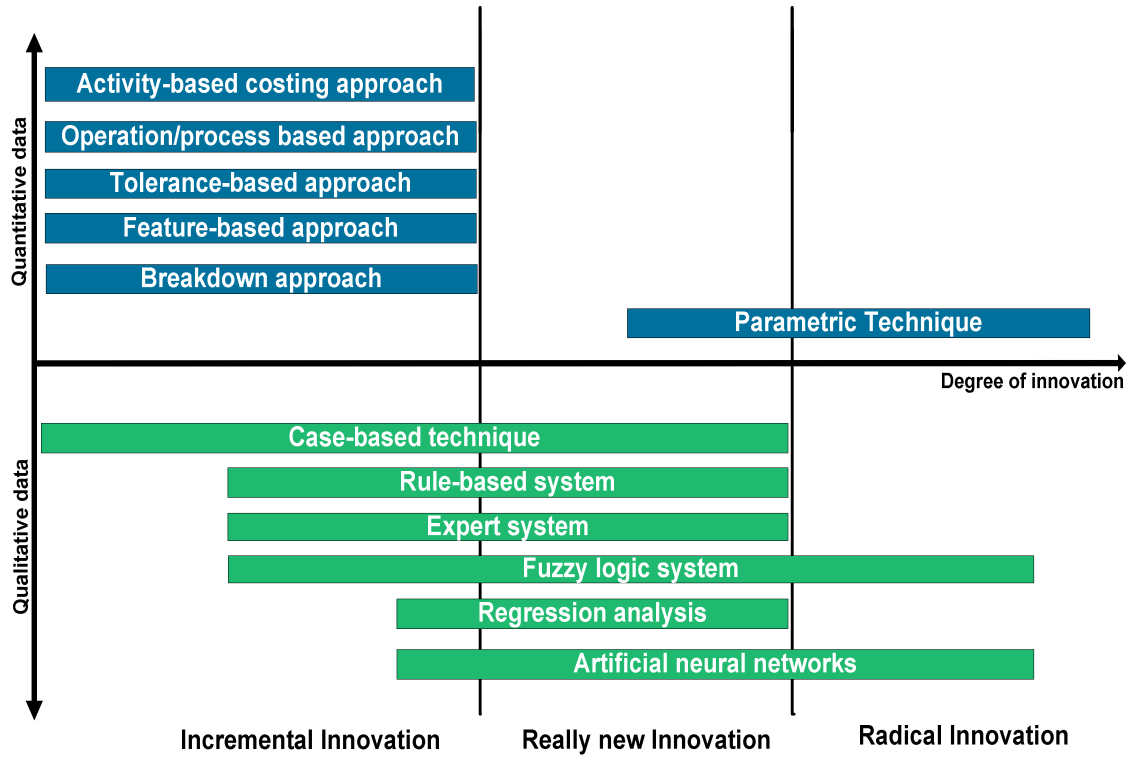

Figure 2-9: Degree of innovation Vs Type of data available

2.7 Analysis of Product Manufacturing Cost Estimation Systems and Models against Lean Product and Process Development

In this section, previously developed systems and models have been evaluated against three lean product and process development enablers: set-based concurrent engineering, knowledge-based engineering and poka-yoke. Since the first step of set-based concurrent engineering process is the identification of customer and company value, value and set-based concurrent engineering have therefore been merged as a single enabler in this research. In addition, it is worthy of note that poka-yoke has been evaluated with only one objective, i.e. mistakes elimination at product manufacturability identification. Two other objectives of poka-yoke, i.e. mistakes elimination at product design and mistakes elimination at process parameters, have not been evaluated, because if the cost estimation process is compared against these three poka-yoke objectives, then no single cost estimation system fulfils the criteria of mistake-proofing. The above mentioned poka-yoke objectives have been explained in chapter 5, section 5.4.2.

It can be seen that in the area of product manufacturing cost estimation in the design phase, a number of cost systems and models have been developed for various applications. Table 2-8 represents the cost estimation systems and models widely available in the literature.

Table 2-8: Product manufacturing cost estimation systems and models

Cost estimation method	Authors	Manufacturing process	Knowledge-based engineering	Poka-yoke	Set-based concurrent engineering
Case-based technique	Wang et al. (2003)	Injection moulding components	Did not explain properly	No	No
	Chan (2005)	Electroplating	No	No	No
	Chougule and Ravi (2006)	Casting	No	No	No
	Karadgi et al. (2009)	Deep drawn sheet metal components	Yes	No	No
	Wang and Meng (2010)	Steel Components (Rolling, forging etc)	No	No	No
Rule-based system	Gayretli and Abdalla (1999)	Machining	Yes	Manufacturing processes selection	No
	Er and Dias (2000)	Casting	Yes	No	No
	Esawi and Ashby (2003)	General purpose	Yes	Yes	No
	Shehab and Abdalla (2001, 2002a and 2002b)	Machining and injection moulding	Yes	Mistakes reduction during machining process identification	No
	Mauchand et al. (2008)	General purpose	Yes	Manufactura-bility identification	No
	Djassemi (2008)	General purpose	Yes	Yes	No
	Masel et al. (2010)	Forging	No	No	No
Fuzzy logic system	Jahan-Shahi et al. (2001)	Flat plate processing (profiling, drilling and marking)	No	No	No
	Shehab and Abdalla (2001, 2002a and 2002b)	Machining and injection moulding	Yes	Mistakes reduction during machining process identification	No

	Chan (2005)	Electroplating	No	No	No
Expert system	Arezoo et al. (2000)	Simple turning	Yes	Tool selection, feed speed and depth of cut	No
	Er and Dias (2000)	Casting	Yes	No	No
	Esawi and Ashby (2003)	General purpose	Yes	Yes	No
	Mauchand et al. (2008)	General purpose	Yes	Manufactura-bility identification	No
	Djassemi (2008)	General purpose	Yes	Yes	No
Artificial neural networks	Wang (2007)	Plastic injection moulding	Yes	No	No
	Ciurana et al. (2008)	Machining	No	No	No
	Rimašauskas and Bargelis (2010)	Sheet metal work	No	No	No
	Cao et al. (2010)	Machining	No	Errors in tolerance design	No
Regression analysis	Ciurana et al. (2008)	Machining	No	No	No
	Liu et al. (2009)	Life cycle cost	No	No	No
Parametric cost estimation technique	Chougule and Ravi (2006)	Casting	No	No	No
	Masmoudi et al. (2007)	Welding	Yes	No	No
	Qian and Ben-Arieh (2008)	Machining	Yes	No	No
	Chayoukhi et al. (2009)	Welding	Yes	No	No
Feature-based approach	Gupta et al. (1994)	Machining	Did not explain	Manufactura-bility identification	Trade-off among alternative process plans
	Ou-Yang and Lin (1997)	Machining	Yes	Manufactura-bility identification	No
	Shehab and Abdalla (2001, 2002a and 2002b)	Machining and injection moulding	Yes	Mistakes reduction during machining process identification	No
	Bouaziz et al. (2006)	Machining	Yes	Manufacturing process selection through criteria proposed by user	No

	Chayoukhi et al. (2009)	Welding	Yes	No	Yes
Breakdown approach	Chan (2003)	Machining	Yes	Manufactura-bility	No
	Klansek and Kravanja (2006)	Composite and steel structure	No	No	No
Activity-based costing approach	Maropoulos et al. (2003)	Machining	Yes	Product manufactura-bility	No
	Özbayrak et al. (2004)	Machining	No	No	No
	Qian and Ben-Arieh (2008)	Machining	Yes	No	No
Operation/process-based approach	Choi et al. (2007)	Composite part	Yes	No	No
	Curran et al. (2008)	Composite part	No	No	No
Tolerance-based approach	Dimitrellou et al. (2008)	Machining	Yes	Errors in tolerance	No
	Cao et al. (2010)	Machining	No	Errors in tolerance design	No

It can be seen from Table 2-8 that previously developed systems and models are applicable for a large number of manufacturing processes. Figure 2-10 represents these cost estimation models and systems with respect to the applicable manufacturing processes. It is clear from Figure 2-10 that although the systems and models are applicable in the design stage, no individual cost estimation process is suitable for a specific manufacturing process. In fact, the researchers employed different cost estimation methods on the basis of product innovation, the degree of information available, the required accuracy level, and the available time to develop the estimate. Therefore, it can be concluded that the selection of a particular cost estimation method does not entirely depend on the particular manufacturing process. In fact, other factors such as degree of innovation, precision of estimate and estimation time are also required to be considered.

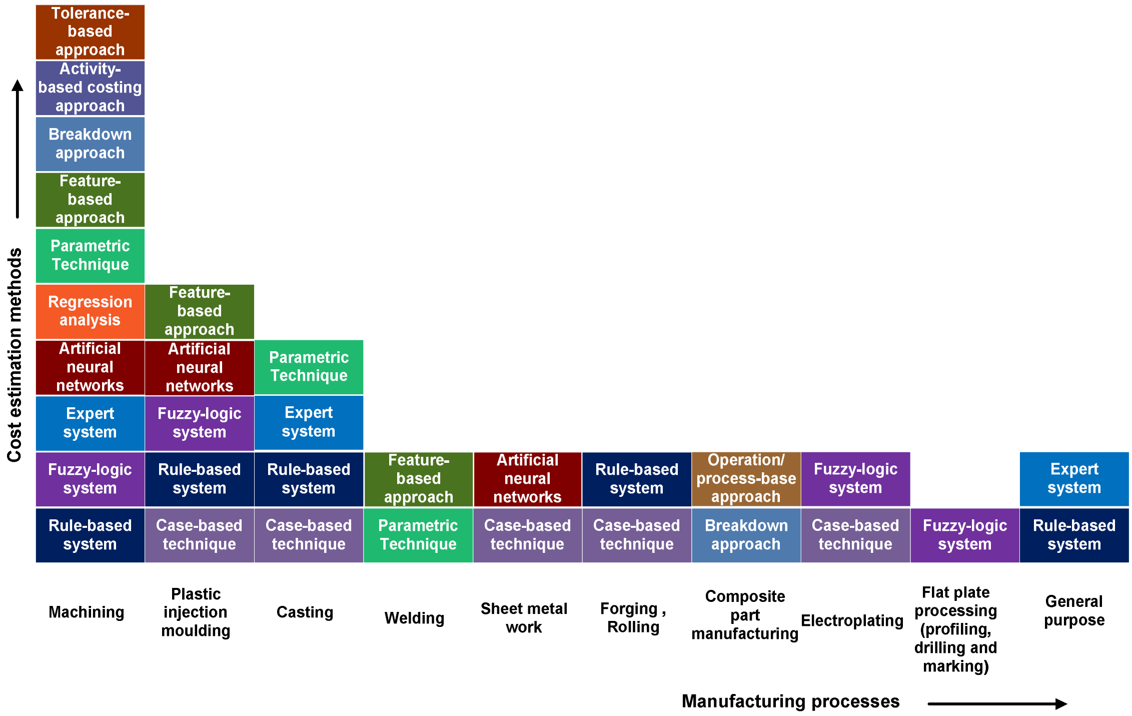

Figure 2-10: Product manufacturing cost estimation systems and models applicable for different manufacturing processes

It can also be identified from Table 2-8 that little effort was made in the cost modelling for lean product and process development. To confirm this statement, previously developed product manufacturing cost estimation systems and models were evaluated against three lean product and process development enablers. The comparison is available in Figures 2-11 – 2-13. It can be seen that previously developed cost estimation systems incorporate knowledge-based engineering at 53%, poka-yoke at 44% and set-based concurrent engineering at only 3%. The main reason for the higher percentage is that knowledge-based engineering is not a new concept. In fact researchers have been striving to develop a knowledge-based system since the last decade. However, there is a need to be aware of the difference between a knowledge-based system and knowledge-based engineering. A knowledge-based system employs knowledge management methodology and techniques to capture, store and reuse the knowledge from various sources in order to fulfil the business objectives (Curran et al., 2009); knowledge-based engineering, however, is the use of advanced dedicated software tools to capture (acquire) and reuse product and process engineering knowledge (Curran et al., 2009;

Skarka, 2007; Stokes, 2001). CAD integration is compulsory in knowledge-based engineering (Cooper et al., 1999). The key explanation for the higher value of poka-yoke (44%) is that in this comparison, poka-yoke has been compared with only one objective, i.e. mistakes elimination at product manufacturability identification. Two other objectives of poka-yoke, i.e. mistakes elimination at product design and mistakes elimination at process parameters, have not been evaluated. If the cost estimation process is compared against these three poka-yoke objectives, then this number will descend to zero.

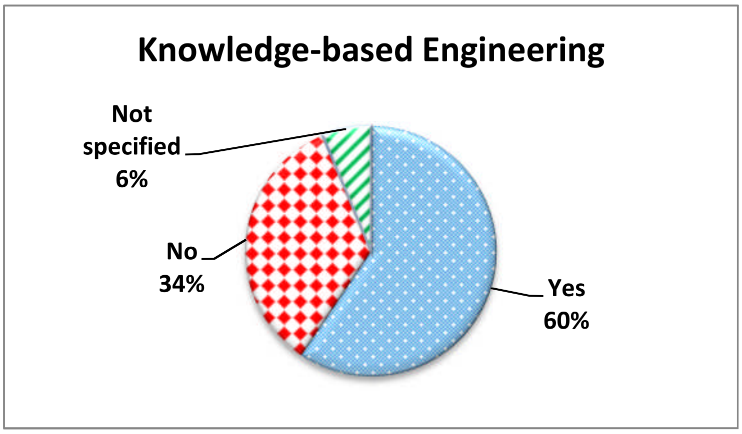

Figure 2-11: The application of knowledge-based engineering in product manufacturing cost estimation systems and models

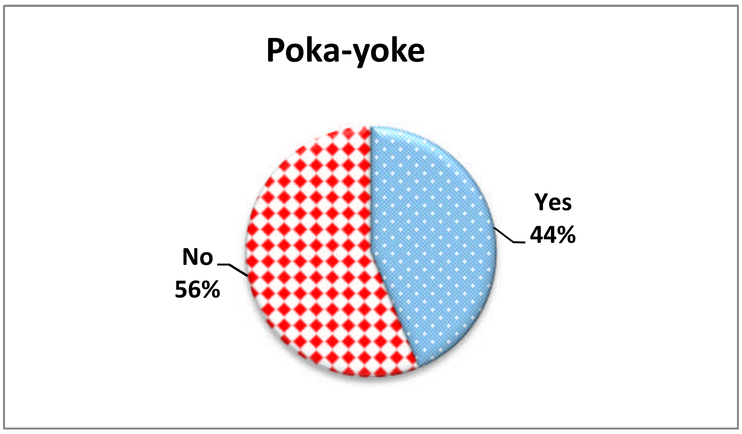

Figure 2-12: The application of poka-yoke in product manufacturing cost estimation systems and models

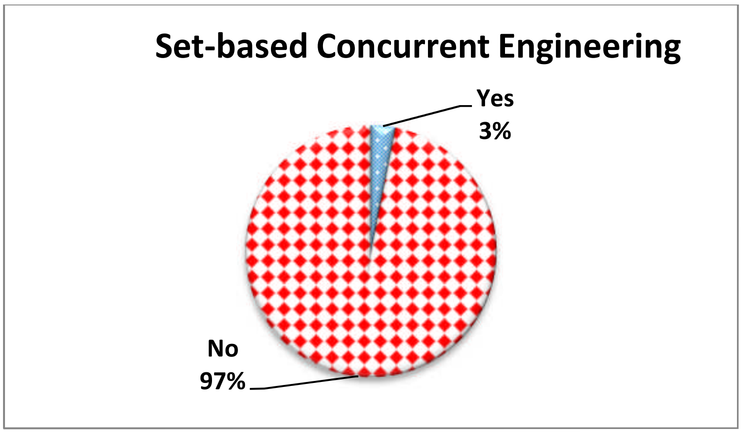

Figure 2-13: The application of set-based concurrent engineering in product manufacturing cost estimation systems and models

2.8 Research Gap Analysis

This section demonstrates the findings from the research gap analysis for the key areas of focus for the literature covered in this thesis. The analysis was conducted by considering research requirements that were recognised through industry interaction and from the observed trends in the literature.

The main research gaps that were identified for the analysis of product manufacturing cost estimation systems and models against lean product and process development include:

1. Cost is an important decision making element for lean product and process development. The literature clearly identifies that little effort has been made to develop a cost model that take into consideration lean product and process development enablers such as knowledge-based engineering, set-based engineering and poka-yoke (mistake-proofing).
2. Previously developed cost estimation systems provide limited decision making support to development team members. There is a need to enhance the capability of these systems.

When considering the lean product and process development, the following gap has been identified.

1. A number of researchers employed set-based concurrent engineering; however, there is no clear information to define

performance variables (i.e. set of designs), and methods to narrow down feasible regions in order to select the final design.

2. The value identification process at the start of the product development is mostly ignored by companies. Therefore, there is a need to identify value with respect to the customer as well as with respect to the manufacturer.
3. Dynamic knowledge capture and reuse is entirely ignored by previous researchers. Therefore, there is need to consider this factor for knowledge-based engineering.
4. There is a need to consider all possible mistake-proofing elements for a successful product development.

2.9 Summary

This chapter has analysed the previous work in the area of product development, lean product development and cost estimation to provide a better understanding of cost estimation practices for lean product and process development. It initially identifies the different structured product development processes widely applicable in the industry. After that a brief history of the lean journey has been highlighted, followed by a discussion of the work in the area of lean product and process development. Four lean product development enablers have been explained in detail.

Different cost estimation methods, and cost estimation systems and models developed have been discussed. An analysis of cost estimation methods has been provided. After that the analysis of product manufacturing cost estimation systems and models against lean product and process development has been outlined to present the research gap in the area of cost estimation for lean product and process development. Finally, a number of research gaps revealed through the literature review have been summarised.

The following chapter describes the research methodology, explaining the different research strategies considered in this research.

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CHAPTER 3

3 RESEARCH METHODOLOGY

3.1 Introduction

The aim of this chapter is to explain how the research was designed and the research methodology followed. The justification of research methodology selected and rationale of their selection has been provided in detail.

3.2 Research Method Selection and Justification

A summary of the selected research approach which has been adopted by the researcher is shown in Figure 3-1. The rationale of their selection is explained in the sections below.

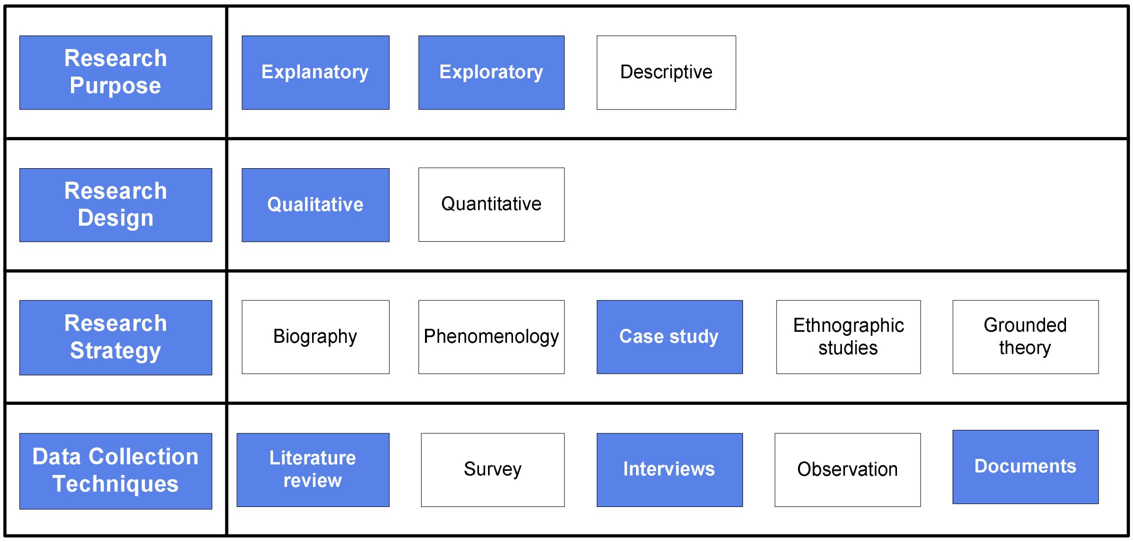

Figure 3-1: Research approaches selection

3.2.1 The rationale of explanatory and exploratory approaches as the research purpose

Taking into account the aim, objectives and context of this research, a combination of exploratory and explanatory is the most appropriate approach for its overall purpose. Since the cost estimation for lean product and process development has not been researched enough, exploratory is, therefore, dominant at the initial stage of the research, whereas explanatory becomes more relevant at the later research stage where the author is clarifying the cost modelling system.

3.2.2 The rationale of the qualitative approach

A number of reasons directed the author to the adoption of a qualitative approach in this study. Firstly, the overall topic calls for further exploration, in order to meet the research objectives.

Secondly, since the study attempts to identify the suitable lean product and process development enablers, the capability of qualitative data to provide wider and richer description is a motivation to select a qualitative approach.

Finally, although lean thinking has been exercised for more than three decades, this concept is new in the design context. The European industry appears to be unaware of the tools and techniques of lean in the design phase, therefore a qualitative approach was selected to investigate the insight more clearly.

3.2.3 The rationale of the case study method

The first rationale behind the selection of the case study is that cost estimation for lean product and process development is a relatively new phenomenon, and there is no strong theoretical background for this research. The case study approach is generally appropriate for this type of problem in which the research and theory are at their early development stage.

Secondly, the case study approach is suitable to capture the knowledge of experts and developing the theories from it. Since the European industries are looking to go beyond lean thinking, it was necessary to first identify the insight of current practices from product development team members.

Finally, since the dominant purpose of this research is exploratory, a qualitative research approach has, therefore, been applied. Semi-structured interviews were conducted to identify industrial cost estimation practices in the context of lean product and process development.

3.3 Research Methodology Adopted

After identifying and justifying the adopted research purpose, research design, and research approach, this section discusses the research methodology process which involves the use of a literature review, industrial interviews and case studies. The research process is composed of three phases, which are systematically represented in Figure 3-2.

Phase 1: Understanding context and current practices

The first phase is related to gaining a contextual understanding, research protocol development and capturing the current practices on lean product and process development, and providing cost estimation for lean product and process development in European industries. An extensive literature review on the issue of product development process, lean thinking, lean product and process development, and cost estimation for lean product and process development has been performed. In the area of cost estimation, the main intentions were the identification of cost estimation objectives, different cost estimation methods, and the variety of cost estimation models and systems to support manufacturing cost estimation in the design phase.

In the area of lean product and process development, the major targets were the identification of lean product and process development enablers. The cost estimation training, interaction with cost experts in SCAF (society of cost analysis and forecasting) workshop, and lean product and process development group meetings allowed the researcher to gain a better understanding of the context.

In order to identify the industrial current practices, a questionnaire was developed by means of preliminary knowledge gap analysis and brainstorming. The industrial field study was carried out with eleven different European industries including aerospace, automotive, telecommunication, medical and domestic appliances.

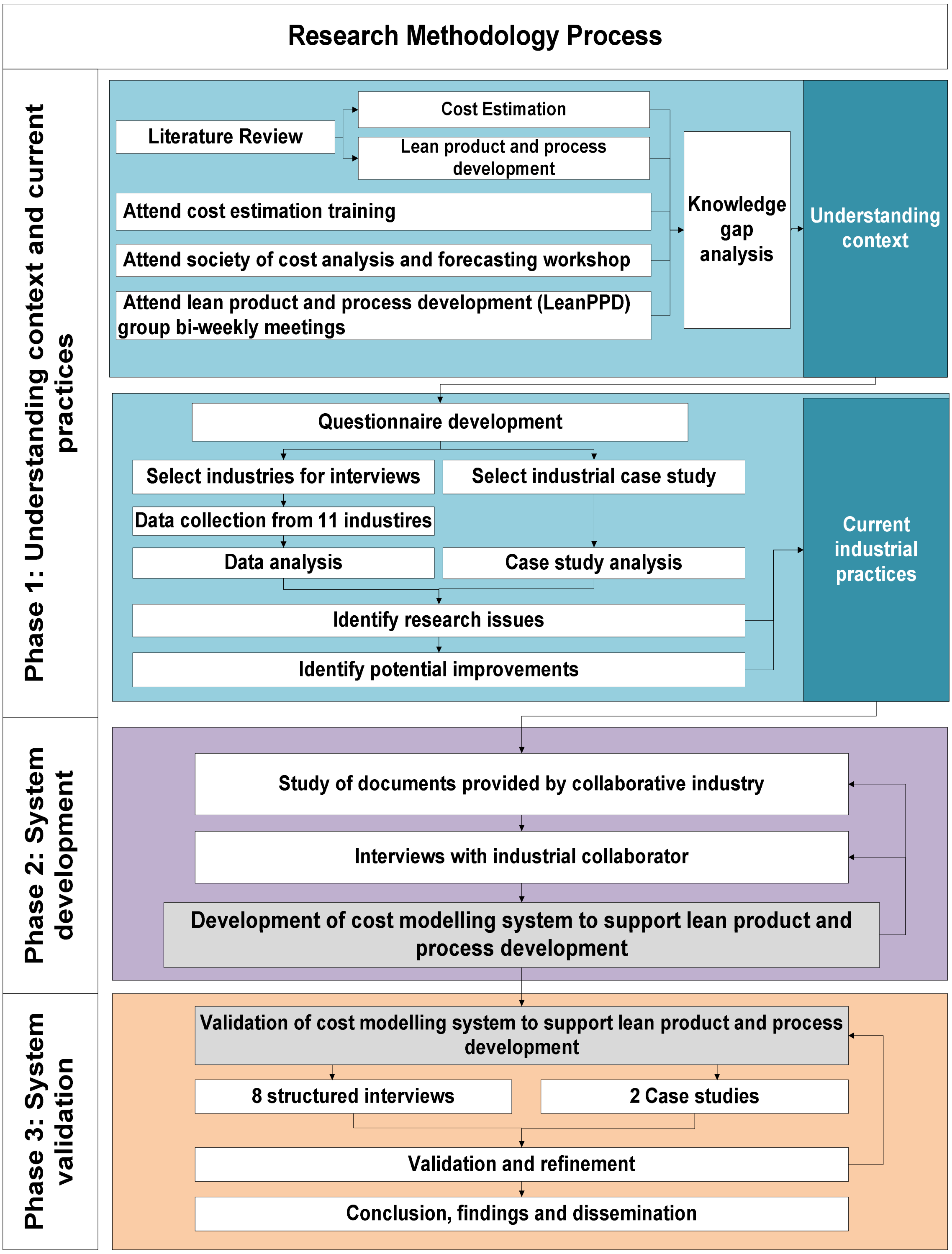

Figure 3-2: Research methodology adopted

A total number of 43 face-to-face interviews via semi-structured questionnaires were carried out with product designers, cost estimators, product development team leaders, logistics managers and manufacturing engineers. In addition, a case study with one of the industrial partners was also carried out. Analysis of the interviews and the case study allowed recognition of the current issues, potential improvement areas, and the role of cost estimation for lean product and process development.

Phase 2: System development

This phase of the research is focused on the development of a cost modelling system to support lean product and process development. In phase 1, it was identified that the European industry lacks lean thinking in their design phase. It was further recognised that three lean product and process development enablers have a potential to be used in the cost modelling system.

In phase 2, an effort was made to discover how the cost modelling system can be developed for the above identified lean product and process development enablers. The interviews and feedback meetings with one of the industrial collaborators helped to explore this question. The company provided a document in order to study their product development process, and the regular meetings with the industrial collaborator helped to develop the cost modelling system in the context of lean product and process development.

Phase 3: System validation

The third phase is concerned with the validation of the system, which was done by means of qualitative assessment. The validation was performed in two stages. In first stage, the system was validated through two case studies. The objectives of the case studies validation were the avoidance of bias, and reliability issues. One case study was linked with the automotive industry, the other with the petroleum industry. In second stage eight interviews were conducted with cost estimation experts, lean experts and industrial representatives. The system was demonstrated to the experts and their feedback was captured using a structured questionnaire. Any additional feedback was transcribed. The aims of the interviews were to assess the validity and generalisability of the developed system. An iterative process was followed whereby modification to the system was made based on the feedback received. The results of the interviews and case studies are presented in chapter 6.

3.4 Summary

This chapter outlines the research methodology that has been implemented to ensure that its design is appropriate to provide the answer to the research questions and attain its aim and objectives. It initially summarises the research overview which consists of the research purpose, research design, research strategy and data collection techniques. Three research purposes have been outlined and their characteristics have been provided. Also, a summary of different research designs (qualitative and quantitative) used to capture the knowledge was included.

Within the qualitative research context, the chapter explains a range of research strategies: biography, phenomenology, case study, ethnography and grounded theory. Finally five data collection techniques: literature review, survey, interviews, observation and documents have been explained.

The chapter also presents the rationale for selecting a suitable research strategy. Finally the adopted research methodology was explained, where each of three stages were covered including "Understanding context and current practices", "System development", and "System validation". An emphasis on explaining the steps in the research has been presented.

The following chapter describes the current cost estimation and product development industrial practices in the European product development companies. It also presents the views of product development team members about the development of a cost modelling system to support lean product and process development.

CHAPTER 4

4 CURRENT INDUSTRIAL PRACTICES

4.1 Introduction

In the previous chapter, the research methodology was presented. The case study along with semi-structured interviews were chosen to be the most appropriate to fulfil the thesis aim and objectives. In this chapter, the author discusses the current industrial practice identification with the use of semi-structured interviews and case study analyses, as illustrated in Figure 4-1.

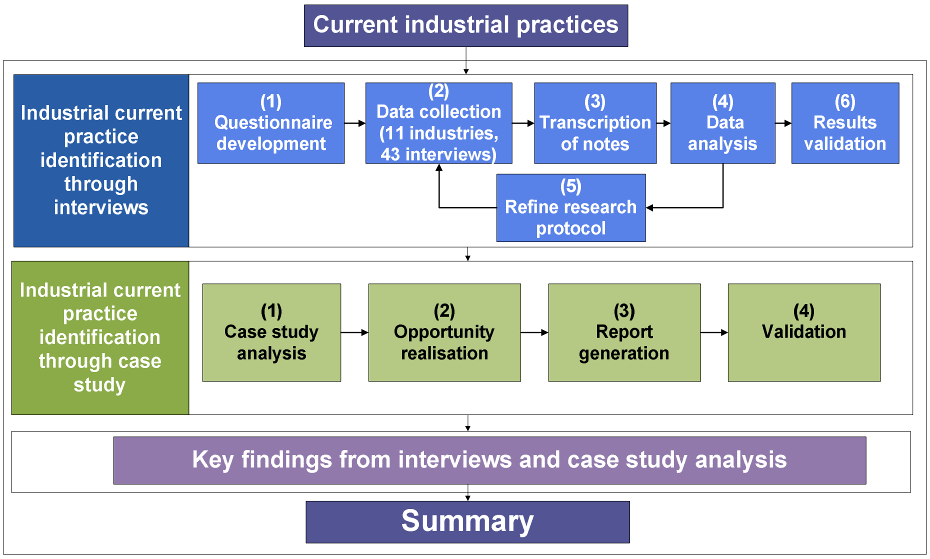

Figure 4-1: Outline of Chapter 4

4.2 Detailed Research Methodology

The research methodology followed to identify current industrial practices is based on the sequence of steps as illustrated in Figure 4-2. Step 1 involved the development of a semi-structured questionnaire based on the research objective, preliminary knowledge gap analysis, and brainstorming session carried out in collaboration with three other PhD researchers within the LeanPPD project. Since the purpose of this research is exploratory, it was, therefore, decided to use a semi-structured questionnaire because it includes open questions, which are important to gain an overall understanding of current practices in the European industrial sector. Before the team sent the questionnaire out to be completed, it was reviewed initially by the collaborating companies involved in the LeanPPD project. The questionnaire was improved accordingly, as and where necessary, until an adequate and unambiguous version was produced.

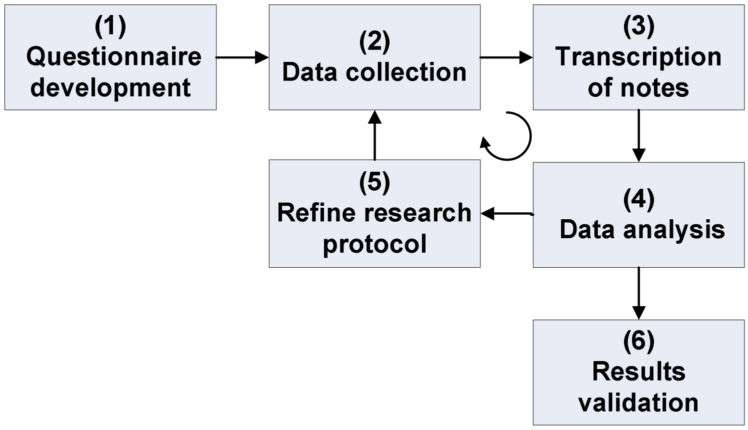

Figure 4-2: Research methodology to identify current industrial practices

Since only five European companies were involved in the project, which represents a very small sample, it was decided to approach companies outside the consortium. Twenty-five companies were contacted by phone or by email in order to introduce them to the theme of the project and to ask them to complete the questionnaire. A special measure was taken to contact only those companies that have product design and development facilities. Eleven companies out of twenty-five responded positively and face-to-face interviews were conducted accordingly. Table 4-1 lists the companies involved in the field study.

The field study questionnaire was divided into five sections as follow:

1. Product development process
2. Product design
3. Knowledge-based engineering and environment
4. Cost estimation, and

5. Additional questions related to challenges and key issues

Table 4-1: List of the companies involved in the field study

BAE Systems - BVT surface fleet, United Kingdom
BAE Systems, United Kingdom
Bosch, United Kingdom
Eaton Electrical, United Kingdom
Indesit, Italy
Metsec Plc, United Kingdom
Rolls-Royce, United Kingdom
Sitech Sp. So. o., Poland
Thermofisher Scientific, United Kingdom
Visteon Engineering Services Ltd, United Kingdom
VolksWagen A.G. Germany

The reason for dividing the questionnaire into sections is because four researchers including the author are working on a lean product and process development (LeanPPD) project. Therefore, each researcher was responsible for developing one section. The author developed cost estimation section as a whole. In addition, some questions were embedded in sections 2, 3 and 5 to keep the continuity of the questionnaire. The series of interviews was conducted together with other research members of the LeanPPD project.

A total of 43 interviews were accomplished with professionals of well-known European industries, including aerospace, automotive, telecommunication, medical equipment and home appliances (See Figure 4-2, step 2). The professionals selected for interviews were product designers, cost estimators, product development team leaders, logistics managers and manufacturing engineers. Table 4-2 represents a sample of the experts involved in this study. The coordinator of each industry was requested to identify the participants randomly, based on different experience levels ranging from 1 year to 29 years in managing projects. As a result, it is believed that the participants were a true representation of each industry. The questionnaire used during the interviews is provided in Appendix A. The interviews had an average length of 2 to 2.5 hours.

During the first 20 minutes, the researcher presented the aim, objectives and purpose of the interview. Afterwards, 1 to 1.5 hours were spent on the questionnaire (Appendix A), and the rest of the time was spent on capturing the industrial understanding and future focus for product development in the context of lean product and process development and cost estimation for lean product and process development. The responses were noted (step 3, Figure 4-2) and analysed (step 4). At the end of each interview, the results were analysed, and the research protocol was refined and applied to the succeeding interviews (step 5). Finally all the analysis of all interviews was returned to the representative of each industry collaborating in the interviews (step 6, Figure 4-2). The purpose of this activity was to generalise and validate the results.

Table 4-2: Sample of experts interviewed

Current Role	Years of Experience
Company A	
Head of product design & development	18
Product design and development manager	13+
Stamping design engineer	7
CAED designer (Team Leader)	9
Designer	12
Logistics manager	12
Logistics planner (for new projects)	5
Company B	
Manager	29
Systems engineer manager	16
Software validation senior engineer	19
Hardware validation engineer	12

4.2.1 Questionnaire key issues

Cost estimation for lean product and process development questions were structured to address the key issues identified from the literature review. Figure 4-3 explains these issues in detail.

Figure 4-3: Key issues discussed in questionnaire

The questionnaire key issues include:

1. Cost estimation as an aid for decision making
   - What is the role of cost estimation in product development?
   - During concept selection, which criteria do companies consider in reaching a final solution?
   - Which tools/techniques have companies formally implemented and utilised as an aid during the design of the product?
2. Cost estimation responsibility during product development
   - Who is responsible for cost estimation in product design?
3. Cost knowledge utilisation in industry
   - What methods do companies mostly apply for cost estimation?
   - What sources do companies apply to store cost data?
4. Challenges in product development
   - Challenges related to product development

4.2.2 Interviews analysis and results

The questionnaire was developed based on research objectives, the knowledge gap identified from the literature, and brainstorming sessions carried out with three other PhD researchers. The rationale of each question is explained below. It is worth noting that the interviews results are mostly presented in the form of graphs. The key reason for these graphs is that validation of the analysis was done by industrial experts who stressed that generation of the results should be in the form of graphs for their ease of understanding and quick reviews.

4.2.2.1 Cost estimation as an aid for decision making

Rationale: Cost estimation is the backbone of successful product development. Set-based concurrent engineering requires design criteria to identify the best solution. For that reason, it is critical to identify the role of cost estimation, its importance in decision making, and the different tools and techniques that companies apply to aid decision making during product design in industry. Therefore, the three questions raised here are as follows:

1. What is the role of cost estimation in product development?

- ➢ During concept selection which criteria do companies consider in reaching a final solution?
- ➢ Which tools/techniques have companies formally implemented and utilised as an aid during the design of the product?

All the above questions and their answers are explained in detail below.

Question: What is the role of cost estimation in product development?

Result: Cost estimation in lean product development stimulates decision making which ultimately leads to a reduction in the overall product development cost and the elimination of waste. However, in practice, the product development team members utilise the cost estimation for different purposes. The majority of the interviewees (74%) use cost estimation to target and reduce the overall cost; 63% of interviewees use cost estimation to compare the cost of alternative products or components; 46% utilise cost estimation to support decision making; and 26% of the candidates acquire additional information from the cost estimation process (Figure 4-4). Examples of additional information include: to provide cost estimation to target customers, to reduce uncertainty, and to meet product cost. From the results, it can be seen that cost is mostly not considered for decision making. Although the majority of interviewees employ cost estimation to reduce the cost and to compare product alternatives, the decision making element is limited. This practice conflicts with lean thinking, which needs to improve for future products.

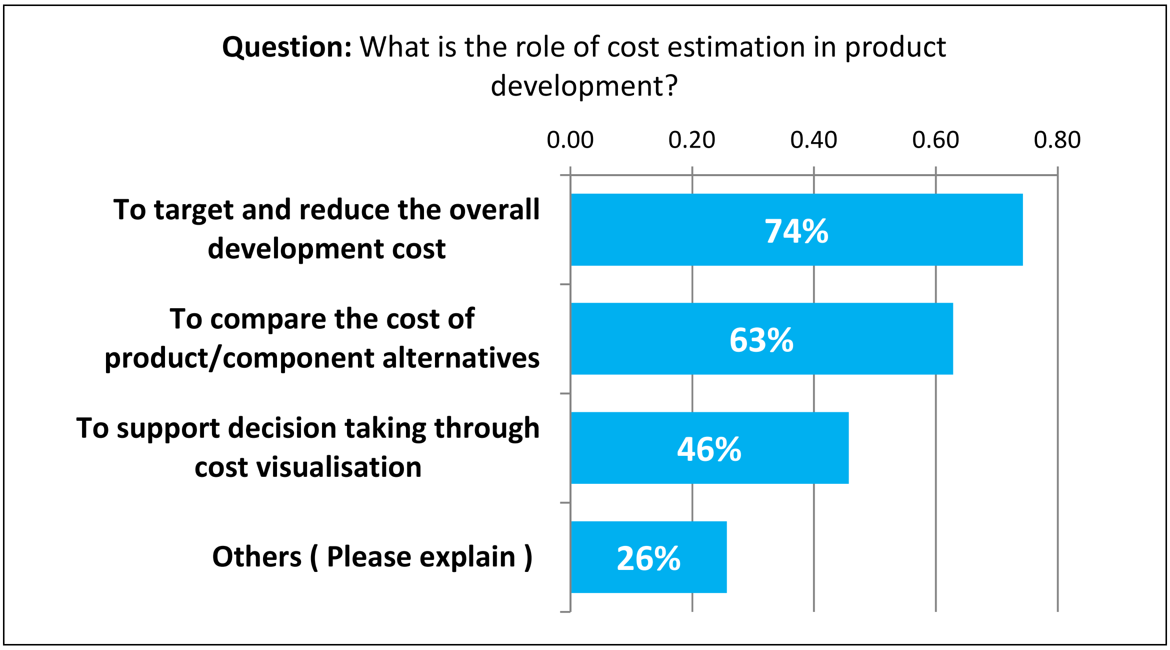

Figure 4-4: Role of cost estimation in product development

Question: During concept selection which of the following criteria do you consider in reaching a final solution?

Result: Set-based concurrent engineering requires a number of design characteristics for decision making. Candidates consider product functions, performance, safety, cost and reliability as important criteria for concept selection. Their ratings are 100%, 96%, 95%, 94%, and 93% respectively (Figure 4-5). In comparison, product featurability, enhanced capability, ergonomics, customisation, and sustainability are rated quite low i.e. 55%, 65%, 67%, 67%, and 70% respectively. The results strengthen our hypothesis that cost is always considered as a crucial criterion during product development.

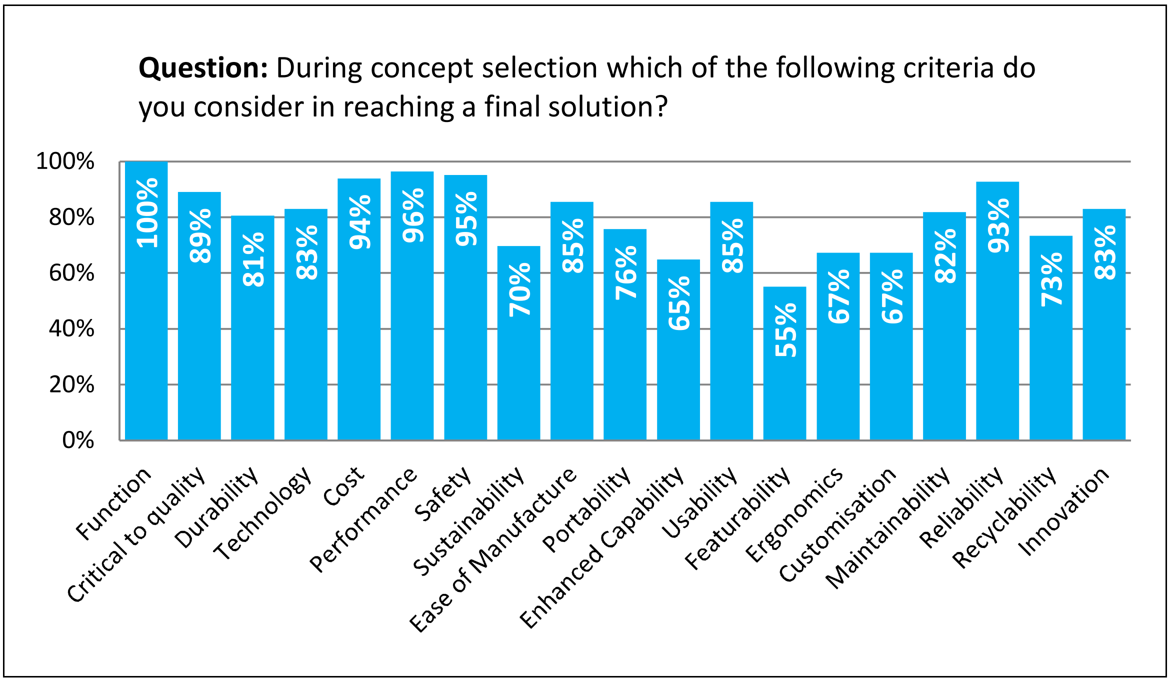

Figure 4-5: Criteria for concept selection

Question: Which of the following tools/techniques have you formally implemented and utilised as an aid during the design of the product?

Result: DFMA (Design for manufacture and assembly), design for reliability, design to cost, and design for maintainability tools have been developed and considered mostly as an aid during product design (Figure 4-6). However, it can be seen from the results that design to cost is not an effective tool because its effectiveness is only 65%. This demonstrates the deficiency in terms of an effective design to cost tool. Therefore, there is a need to focus on this tool for a successful product development.

4.2.2.2 Cost estimation responsibility during product development

Rationale: The chief engineer serves as the system integrator who develops a strong vision for the product and "seek(s) out the right people and resources at the right time" (Morgan and Liker, 2006). The Chief engineer is responsible for estimating the resources required for each stage of development. The chief engineer can request additional resources when necessary as is typical closer to project milestones (Morgan and Liker, 2006). Therefore, the following question arises here:

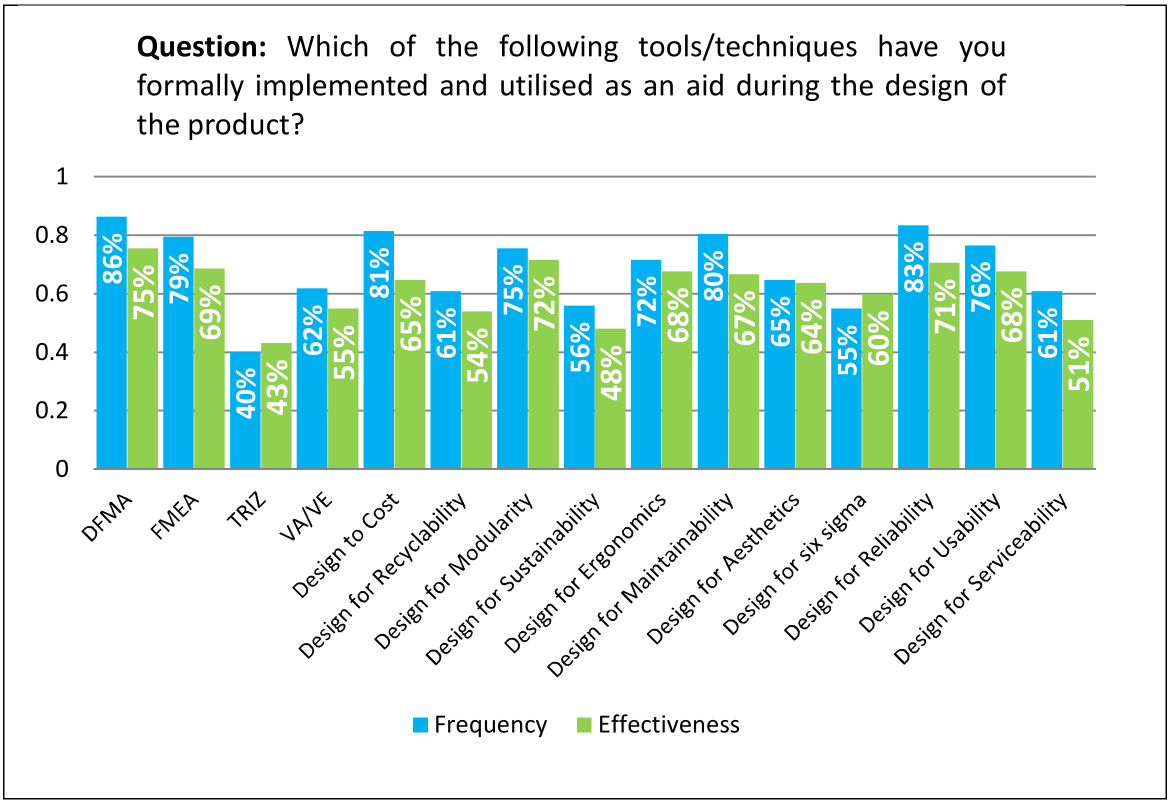

Figure 4-6: Tools/techniques used to aid product design

Question: Who is responsible for cost estimation in product design?

Result: It can be seen from Figure 4-7 that cost estimation responsibility is not clear. Interviewees suggested that multiple departments were responsible for cost estimation. Therefore, it is necessary to place responsibility with the chief engineer for effective product development. In addition, designers are required to coordinate with chief engineer to meet the cost targets.

4.2.2.3 Cost knowledge utilisation in industry

Rationale: Knowledge-based engineering is an important tool of lean product and process development. Knowledge-based engineering emphasises locating and retrieving the knowledge in an efficient way so that product development engineers may use it at the right time (Morgan and Liker, 2006). In terms of current industrial practice identification, the following issues can arise here:

- ➢ What methods do companies mostly apply for cost estimation?

➢ What source do companies apply to store cost data?

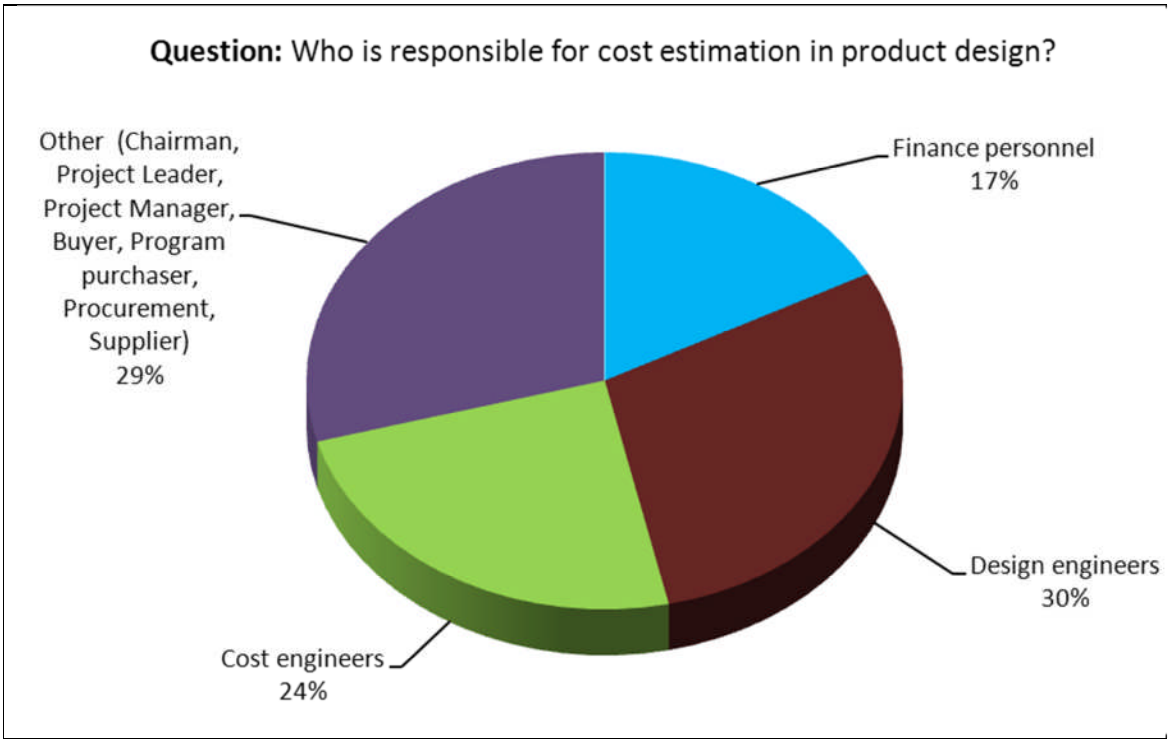

Figure 4-7: Responsibility for cost estimation

The following section explains the results of the above-mentioned questions.

Question: What methods do you use to analyse the cost of design?

Result: It can be seen from Figure 4-8 that companies use a variety of cost estimation methods, depending on their innovation type. Case-based reasoning techniques, analogical methods and activity/feature-based methods are mostly applied by companies as their percentage of use is 61%, 54% and 48% respectively. In addition, companies rely mostly on in-house developed software rather than depending on commercial software.

Question: How and which of the following data are stored at your company for a specific product during the entire product life cycle?

Result: Once the data of previous projects is captured, they are stored in some specific format for future use. It can be seen from Figure 4-9 that most of the companies do not use a precise method of storing cost data: 17% store the cost data in paper form, which is difficult to retrieve quickly; 29% store cost data in a shared drive, which is also difficult to retrieve quickly. However, 33% and 21% of the companies store cost data in a PDM database and ERP system respectively, which can retrieve the data quickly and easily.

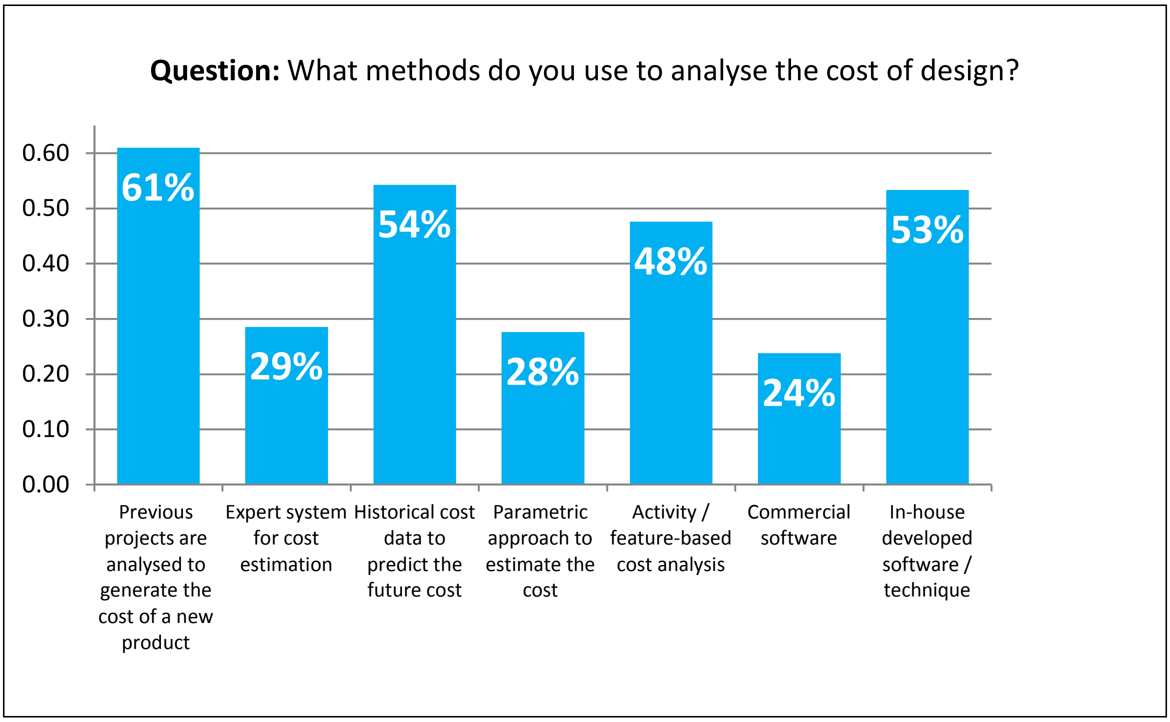

Figure 4-8: Cost estimation methods widely applicable in industry

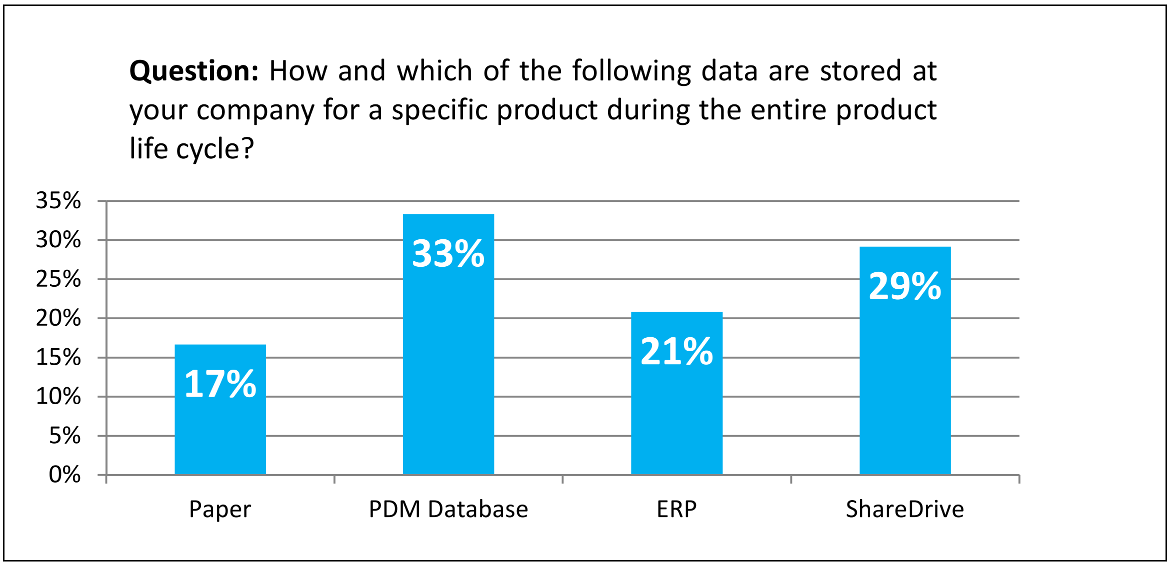

Figure 4-9: Source of cost data storage

4.2.2.4 Challenges related to product and process development

Rationale: Product development teams always face challenges in their development process. In order to resolve these challenges in future, it is necessary to identify them at an early stage. Therefore the main aim of this question is to quantify the major challenges faced by the development team as under:

- ➢ What are the main challenges that you face in terms of developing a product?

The following section explains the results of above-mentioned question.

Question: What are the main challenges that you face in product development?

Result: 73% of the candidates suggest that they normally face cost overruns during product development (see Figure 4-10).

4.2.3 Industrial understanding and future focus of lean product development

Since a considerable time in each interview was spent identifying the industrial understanding and perception about lean product and process development, the researcher also put effort into exploring the experts' views about the possible lean enablers to develop a successful cost modelling system to support lean product and process development. In this section, analysis of the open ended questionnaire is explained.

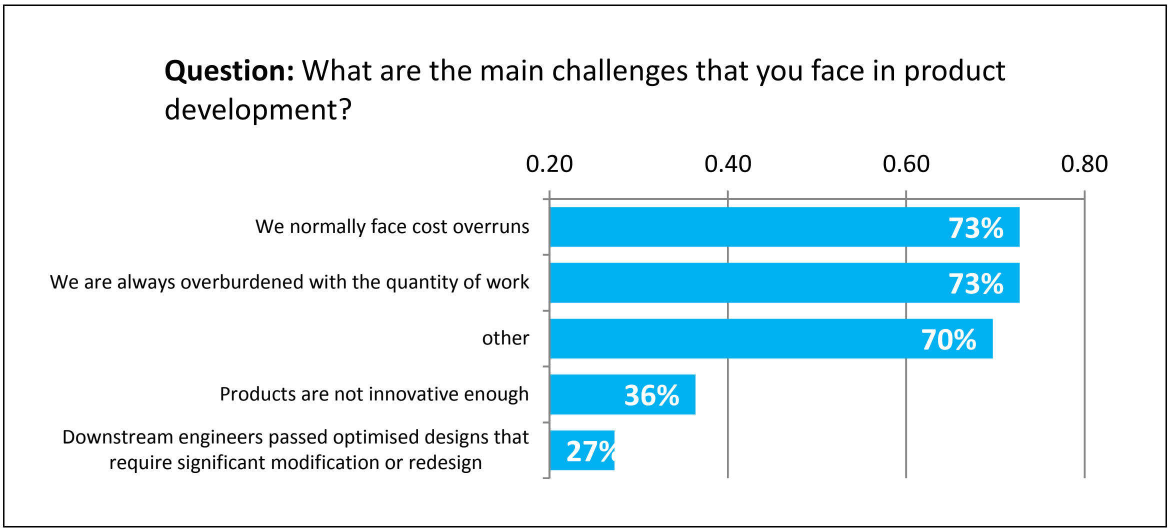

Figure 4-10: Challenges related to cost

1. What is your idea of lean in design; do you consider it useful in your product design and development?

The industry has different views on the lean issue. For example, one of the interviewees explained that lean is a philosophy which aims to improve the people in terms of performance and to sell the business. Another interviewee replied that lean in design is hard to digest; people (designers) are scared of it. Some of the respondents did not like to relate the term lean to Toyota or Japan, whereas, others did not care about it. For example, one of the interviewees commented “who cares about naming it as lean, the real requirement is to progress the business”. In terms of lean’s usefulness in product design and development, the respondents said that they have really seen an improvement in their product by applying lean, however, lean tool such as value stream mapping is needed to avoid because it restricts the productivity of designers.

2. In future, what is your ambition towards LeanPPD, (1) lean principles or (2) lean tools?

In manufacturing, lean operates at two levels, i.e. lean principles and lean tools. In LeanPPD, lean principles were proposed by Morgan and Liker (2006), whereas LeanPPD tools are not used in common practice. In response to the above-mentioned question, the interviewees were clearly divided into two groups. The respondents in favour of principles provided a couple of good comments. For example, a manager explained that “lean is not about applying the tools, but it is to change the mindset of people and culture”. A project manager highlighted that the “A3 template is a LeanPPD tool which helps to solve the problems, but it does not change the environment”. A product design and development manager added that “we are already applying a number of lean tools, but we are looking to change the culture and thinking of people; this change is possible only if we apply lean principles”. Another project manager explained that when a company is the initiator of lean, then tools are good; however, when the company has a well-established product development process, then the tools do not necessarily serve their purpose.

In comparison, a number of respondents advocated the development of lean tools and techniques. For example, a design engineer responded that "although it is true that culture drives behaviour and behaviour drives performance, we can't provide all these things without tools". A product development manager responded that "the essence of set-based concurrent engineering is its principle; but we don't apply all the principles; instead we take case studies and apply bits of principles, which do not solve the problems." In summarising, the interviewees favoured both LeanPPD tools and principles. Although some of the respondents advocated refining the previously developed LeanPPD principle, the majority of the interviewee supported the development of tools specifically for lean initiators.

3. LeanPPD is composed of a number of enablers; which enablers do you propose for developing a cost modelling system to support lean product and process development?

To develop a cost modelling system to support lean product and process development, the majority of respondents proposed set-based concurrent engineering, knowledge-based engineering and poka-yoke. The respondents highlighted that knowledge is in the mind of people, which needs to be captured and utilised for product improvement. The respondents also stressed that trade-off curves need to dig further to progress their businesses.

4.3 Case Study

One case study was also conducted during the industrial current practices identification phase. The aim of the case study was to identify the industrial cost estimation practice and to realise the potential improvement opportunities in terms of lean product and process development. The research methodology used to analyse the case study followed the activities expressed in Figure 4-11.

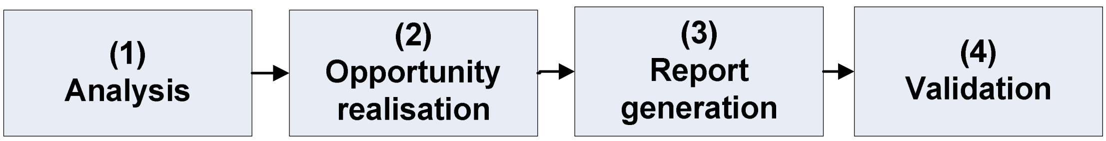

Figure 4-11: Research methodology to analyse case study

The case study is related to a car seat manufacturing company. The company is a first tier supplier, and develops and manufactures the steel structure of vehicles. An example of the car seat steel structure is provided in Figure 4-12. The company has its development and manufacturing facilities in Europe, India and China.

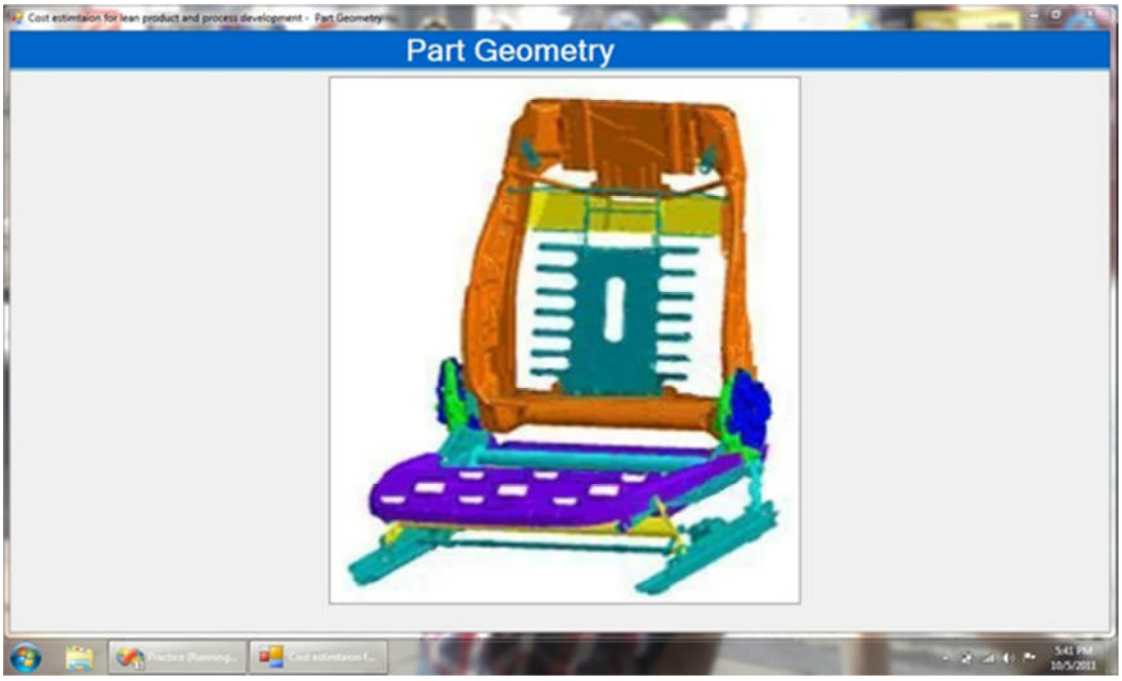

Figure 4-12: Structure of a seat

During the interaction with this case study, the emphasis was on identification of the cost estimation process. The participant selected for interview has a wide experience of product development. He is an active member of LeanPPD team, and deeply involved in developing lean tools for his company. Therefore his suggestions were noted carefully to identify improvement areas and to develop a precise cost modelling system. The research methodology used to analyse this case study includes four activities: analysis, opportunity realisation, report generation and validation, as presented in Figure 4-11. The analysis phase (activity 1, Figure 4-11) is concerned with case study analysis to identify current cost estimation practice. Activity 2 (i.e. opportunity realisation) is associated with potential improvement opportunities identification. The report generation (activity 3) is concerned with the development of the report; and finally, the validation (activity 4) is associated with the validation of the developed report by the concerned industry.

During the analysis phase, it was identified that the company mostly applies the experts' judgement to estimate the manufacturing cost of product in the design phase. Whenever, the company identifies a new opportunity, a new design is proposed by the product design team. The design team initially develops a conceptual design which includes a mixture of the newly proposed design along with the old design. On average, a new design includes 75% to 85% of components from a previously developed design. Once the conceptual design is developed, a quotation is generated accordingly through a quotation expert team. The team includes a financial advisor, a product design representative, a marketing personnel member and a representative from the manufacturing department. Since the new design includes 75% to 85% of the previous design, the quotation expert team does not, therefore, develop the quotation from scratch. The design representative initially informs about the newly proposed and the old design percentages. The financial person informs about the cost of previously developed product, whereas the manufacturing expert generates the process plan of the newly proposed components. The cost of newly proposed components is estimated and added to the old components cost. The profit margin is also added, and finally the quotation is developed. Finally, the marketing person compares it with expected competitors' cost before it is sent to the customer.

Since the aim of activity 2 (Figure 4-11) was to identify the potential improvement area, the case study was, therefore, further investigated. It was identified that the company does not apply lean enablers in their true spirit. Set-based concurrent engineering, knowledge-based engineering and mistake-proofing were identified as potential improvement areas. In addition, the discussions with participants helped to realise the possible use of the above explained enablers (See Chapter 5). At the end, the cost estimation process and potential improvement areas were reported and sent to the participating company for validation.

4.4 Key Findings from Interviews and Case Study Analysis

In this section the key findings from the industrial field study and case study analysis are explained in detail as follows:

1. The role of cost estimation in lean product development is not fully understood. The product development team mostly characterises cost estimation to target and reduce the overall development cost. However, it is not considered frequently as a tool for decision making. Therefore, there is a need to realise this fact for successful lean product development.
2. Development teams employ functions, performance, safety, cost and reliability as major criteria to identify the design space in set-based concurrent engineering. These results strengthen our hypothesis that cost is always considered as a critical criterion during product development.
3. DFMA (design for manufacture and assembly), design to cost, design for minimum risk and reliability tools are mostly employed as aids during product design. However, the development team do not consider cost as an effective tool for product development. This needs a critical investigation to resume the effectiveness of cost for successful product development.
4. The technical leader/chief engineer is always responsible for managing the resources. However, the field survey suggests that multiple departments perform cost estimation. Therefore, there is a need to build a consensus on this aspect.
5. Different cost estimation methods are employed, based on the precision of the estimate required. However, the product development team prefers to employ case-based reasoning, analogical and feature/activity-based costing in the design stage. In addition, they prefer to develop cost estimation software in-house rather than being entirely dependent on commercial software.

6. In term of initiatives taken for the cost data storage and utilisation, companies employ different media, such as paper format, PDM database, ERP and shared drive. Although cost data retrieval through PDM database and ERP is easy and quick, paper format and shared drives are not, however, suitable sources for cost data storage and retrieval.
7. Development teams face challenges regarding cost overruns, therefore efforts should be made to minimise these challenges.
8. Lean is considered to be very useful for a successful product development; however, European companies face hurdles to accept the fact that Toyota is the leader in lean product development. Furthermore, since tools such as value stream mapping in manufacturing provide hurdles at the shop floor level, therefore the designers are scared away from these kinds of tools in the design phase. The designers believe that implementation of these tools will restrict innovation. Therefore, there is a need to minimise the designers' concern and to change people's mindsets for a successful product development.
9. To go beyond lean manufacturing, the industry needs to develop lean tools and principles for the whole product development.
10. Set-based concurrent engineering, knowledge-based engineering and mistake-proofing have an enormous potential to be applied in the development of cost modelling system to support lean product and process development.

4.5 Summary

This chapter has presented the current product development and cost estimation practices in the European industrial sector. These practices were captured through semi-structured interviews and case study analysis. This was necessary after the research methodology that has been followed was outlined in the previous chapter.

Semi-structured interviews were conducted with European companies' product development professionals including designers, cost estimators, product development team leaders, logistics managers and manufacturing engineers. The research methodology of interviews, the key research issues discussed in the questionnaire, and interviews analysis and results were described in detail.

A case study analysis was also conducted during the current industrial practices identification phase. The case study was from one of the industrial collaborator participating in the LeanPPD project. The research methodology to analyse the case study was explained in detail. The key findings from interviews and case study analysis were also laid down in this chapter.

The following chapter describes the development of the "Cost modelling system to support lean product and process development" that can be used for the estimation of product manufacturing cost at the product development conceptual and detailed design stages. The proposed cost estimation process, developed system components, system modules, scenario and cost modelling for joining and machining processes are all discussed in the following chapter.

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CHAPTER 5

5 COST MODELLING SYSTEM TO SUPPORT LEAN PRODUCT AND PROCESS DEVELOPMENT

5.1 Introduction

The aim of this chapter is to explain the components and scenario of the developed cost modelling system to support lean product and process development. The system supports three lean product and process development enablers, namely set-based concurrent engineering, knowledge-based engineering, and poka-yoke (mistake-proofing). Two manufacturing processes, namely joining and machining processes, have been considered in this research.

The system provides a number of benefits, as it enables designers to incorporate lean thinking in cost estimation. It also allows for the consideration of downstream manufacturable process information at an early upstream stage of the design and as a result the designer performs the process concurrently and makes decisions quickly. The system provides a number of design values for alternative design concepts to identify the feasible design region. Moreover, the system helps to avoid mistakes during product features design, material and manufacturing process selection, and process parameters identification; hence it guides towards a mistake-proof product development. The chapter outline is illustrated in Figure 5-1.

5.2 Proposed Cost Estimation Process for Lean Product and Process Development

As explained in Chapter 2, a number of initiatives have been taken by several authors to develop methods and systems for estimating the manufacturing cost during the early design stage; however, most of these systems are concerned with cost estimation without considering lean product and process development.

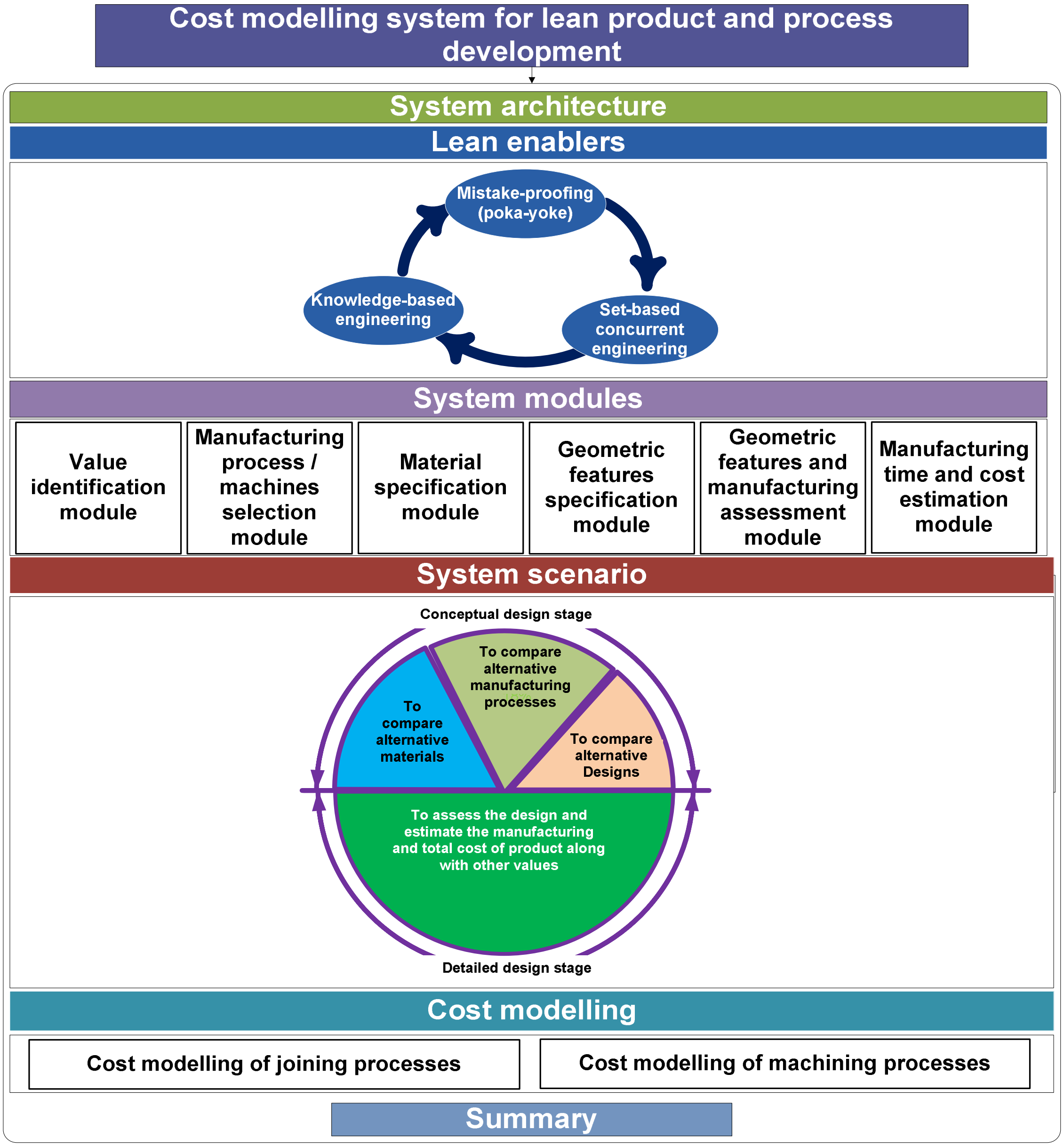


Figure 5-1: Outline of Chapter 5

Although they consider some aspects of lean product and process development enablers, they do not, however, follow the lean thinking. For example, cost in the design phase is evaluated in two different ways, i.e. design for cost and design to cost (Shehab and Abdalla, 2001). In the former, the engineering process is used deliberately to reduce the life cycle cost of product, whereas in the latter, also known as target costing, the design is required to satisfy the targets. Figure 5-2 represents a traditional target costing process or design to cost process. In this costing process, resources, i.e. material, and manufacturing processes are identified and the cost associated with each resource is estimated accordingly. This cost estimation process is perfectly acceptable if the targets are achieved in a single cycle with zero number of revisions. In other words, the traditional target costing process is suitable for experts who are expected to take the right decisions during the selection of alternative options. However, the same estimation process becomes entirely inaccurate for inexperienced product development team members whose non expert decisions intensify a higher number of revisions. In order to overcome this issue, a cost estimation process for lean product and process development has been proposed in the developed system. Figure 5-3 illustrates this proposed cost estimation process. The process is applicable for the conceptual and detailed design stage. In the conceptual design stage, the customer and company values of multiple designs are estimated concurrently instead of a single solution, whereas in the detailed design stage, mistakes are rectified before moving to the production stage. The proposed cost estimation process follows six steps as explained below.

The first step of the estimation process is the specification of customer and company values. The detailed description of value is available in Section 5.4.1. In step 2, the designer inputs the targets associated with each value specified in step 1. Step 3 is the development of alternative designs and the estimation of cost along with associated values. This step is initiated by developing a number of designs in the form of a CAD model, namely part models. For the estimation purpose, each part model is decomposed into assemblies and sub assemblies, followed by the selection of geometric features in each assembly.

After that suitable materials and manufacturing processes are identified, followed by estimating the manufacturing time, cost and all related values associated with each geometric feature. Finally the manufacturing time, cost and all related values of the complete part model are estimated. It is worth noting that only suitable materials and manufacturing processes are selected in this stage. For this purpose, poka-yoke (mistake-proofing) rules have been proposed. A detailed description of poka-yoke (mistake-proofing) is available in Section 5.4.2.

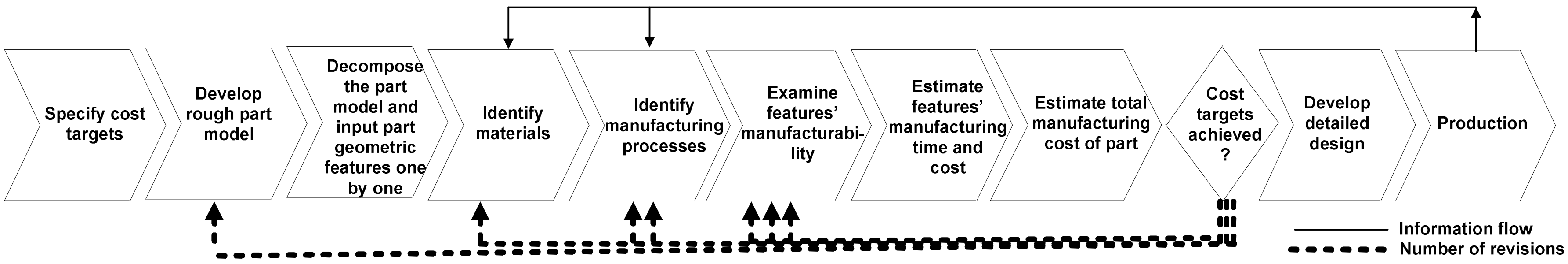


Figure 5-2: Traditional target costing process

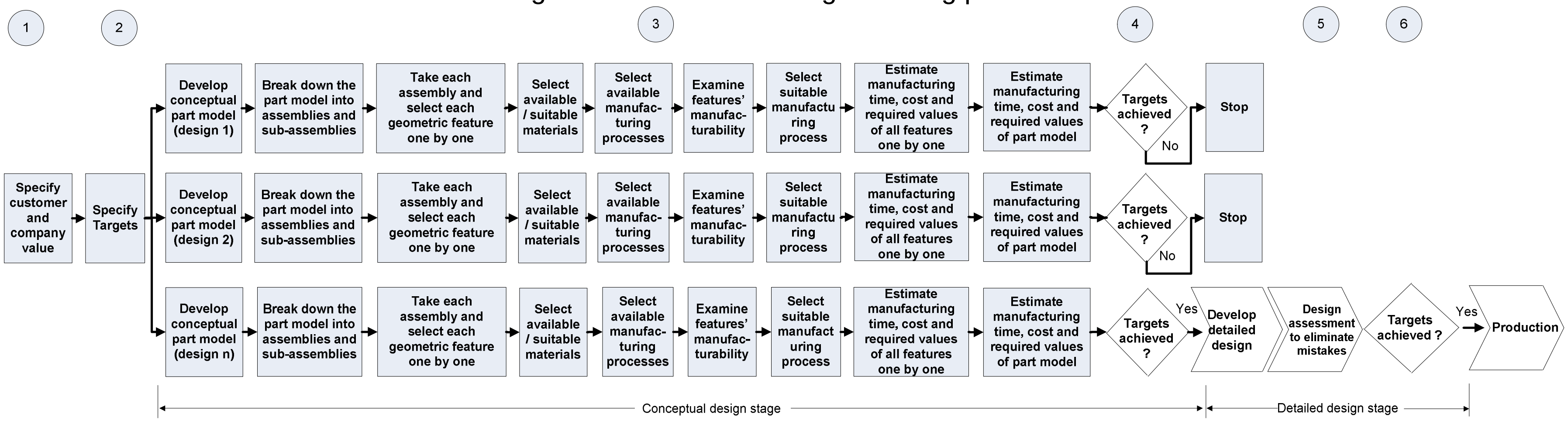


Figure 5-3: Proposed cost estimation process for lean product and process development

Once the manufacturing time, cost and all associated values of multiple designs are estimated, they are narrowed down gradually to identify the final best design option by eliminating the weak solution gradually in step 4 (Figure 5-3). For this purpose, a quantification method has been proposed. The quantification method is explained in detail in Section 5.4.1.

After identifying the best solution, the design is developed further in the detailed design stage. A detailed CAD model is finalised, tolerances are fixed and final testing is also performed in the detailed design stage. Since the detailed design stage involves a large number of activities, more chances of mistakes are present in this stage. To rectify this issue, the detailed design is assessed on the basis of rules proposed in the developed system (step 5, Figure 5-3). In step 6, the values specified in step 1 are estimated to confirm that targets have been achieved successfully.

The proposed cost estimation process for lean product and process development appears to be lengthy and time-consuming, but the absence of revisions makes this process highly suitable for lean product development. In addition, this process reduces the difference between the experienced and inexperienced product development team members. This process has been proposed on the basis of the gap identified in the literature review and industrial field study. The proposed process not only suggests the optimum solution, but also helps to reduce the product cost. In addition, the assessment of design with predefined criteria minimises the number of mistakes and ultimately reduces the rework requirement.

5.3 Development of Cost Modelling System

Three lean product and process development enablers, namely set-based concurrent engineering, poka-yoke (mistake-proofing) and knowledge-based engineering have been embedded into the system. The system provides a number of design values for designers to promote more accurate decisions during the concept generation stage. It enhances the design by reducing design mistakes through predefined assessment criteria. Additionally the system has been developed to allow for the selection of the most adequate materials, alternative manufacturing processes and alternative designs. The overall architecture of the developed system consists of: a set of lean enablers; a CAD solid modelling system; a user interface; and six modules: value identification, manufacturing process/machines selection, material selection, geometric features specification, geometric features and manufacturability assessment, and manufacturing time and cost estimation. In addition, the system includes six separate groups of database: geometric features database, materials database, machine database, geometric features assessment database, manufacturability assessment database, and previous projects cost database, as shown in Figure 5-4. This system application is developed in C# 3.0 within the .NET Framework and Microsoft SQL Server 2008. Detailed descriptions of the system components are outlined in the following sections.

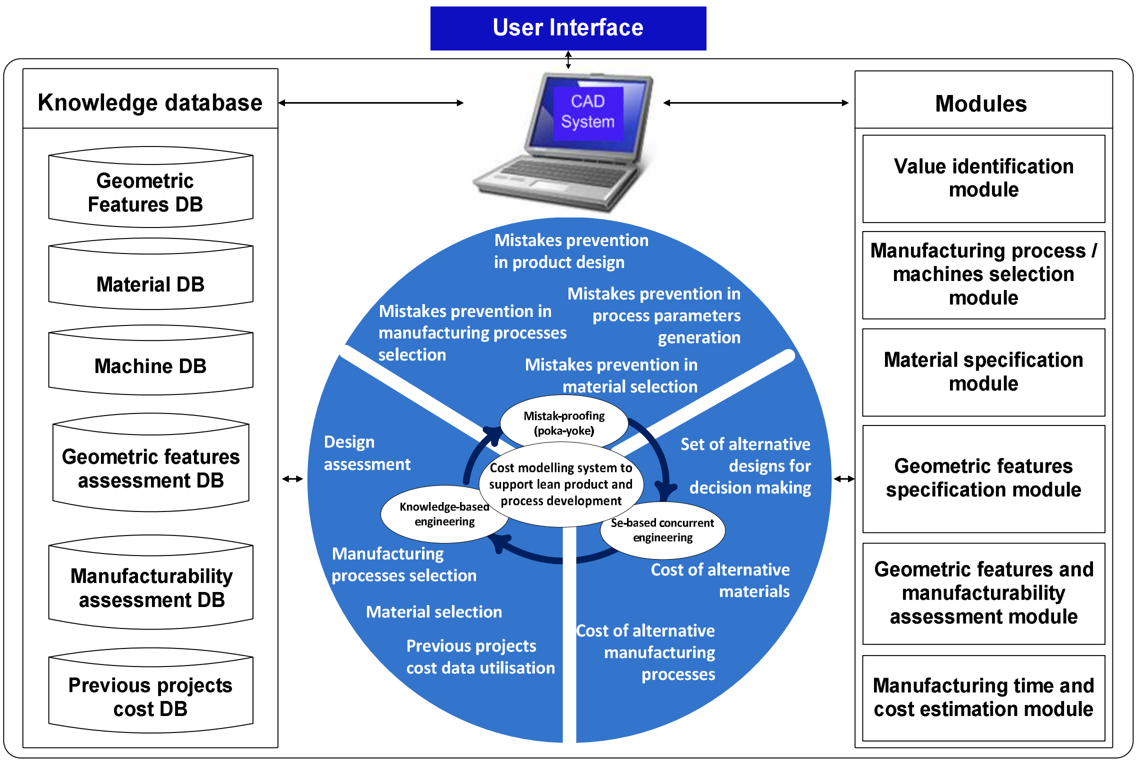


Figure 5-4: Architecture of the developed system

5.4 Lean Enablers

Since the aim of this research is to enable the advantages of lean thinking, and to strengthen the designer's decision taking and mistakes elimination capability, suitable tools and techniques (enablers) were, therefore, identified through a literature review and industrial field study. After a detailed literature review and an interaction with industrial experts, three lean enablers have been identified as suitable for a proposed cost modelling system. These enablers include set-based concurrent engineering, poka-yoke (mistake-proofing) and knowledge-based engineering, as presented in Figure 5-5. The description of each enabler is explained below.

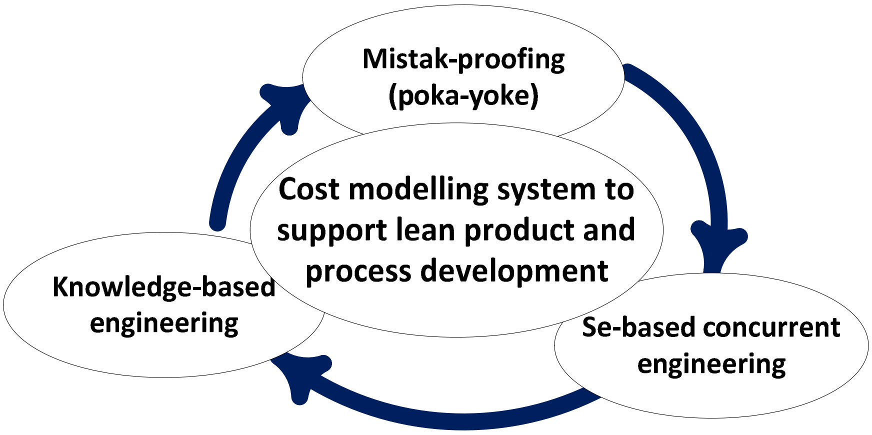


Figure 5-5: Lean enablers proposed for developed cost modelling system

5.4.1 Set-based concurrent engineering

During the development of the system, a systematic set-based concurrent engineering process was taken into consideration. In addition, a method to eliminate weak solution was explored. Figure 5-6 illustrates the process of set-based concurrent engineering.

1. Explore customer and company values and give them preferences

As explained in Chapter 2, value is the backbone of lean product development, therefore it is absolutely important for the development team to define value at the start of the project. Since, the precise value definition is also a critical task in lean product development, the first step of set-based concurrent engineering process is, therefore, value identification. In this step, it is crucial for designers to be aware of customer and company values, along with their preferences. The developed system has the capability to generate estimates for 16 values: product cost, manufacturing time, production volume, product weight, product hardness, thermal conductivity, maximum service temperature, minimum service temperature, tensile strength, yield strength, elongation, density, Young's modulus, friction coefficient, corrosion resistance and surface finish. It is important to know that some of these values could be considered as design parameters or design attributes. To avoid this confusion, the simple rule applied is that the name designates the value, whereas the associated unit designates the value parameter or value attribute. These values were identified after long discussions with industrial experts. Designers are also required to assign a preference from 1 to 9 for each value on the basis of degree of importance. It should be noted that a "Likert scale" has been followed for these preference numbers.

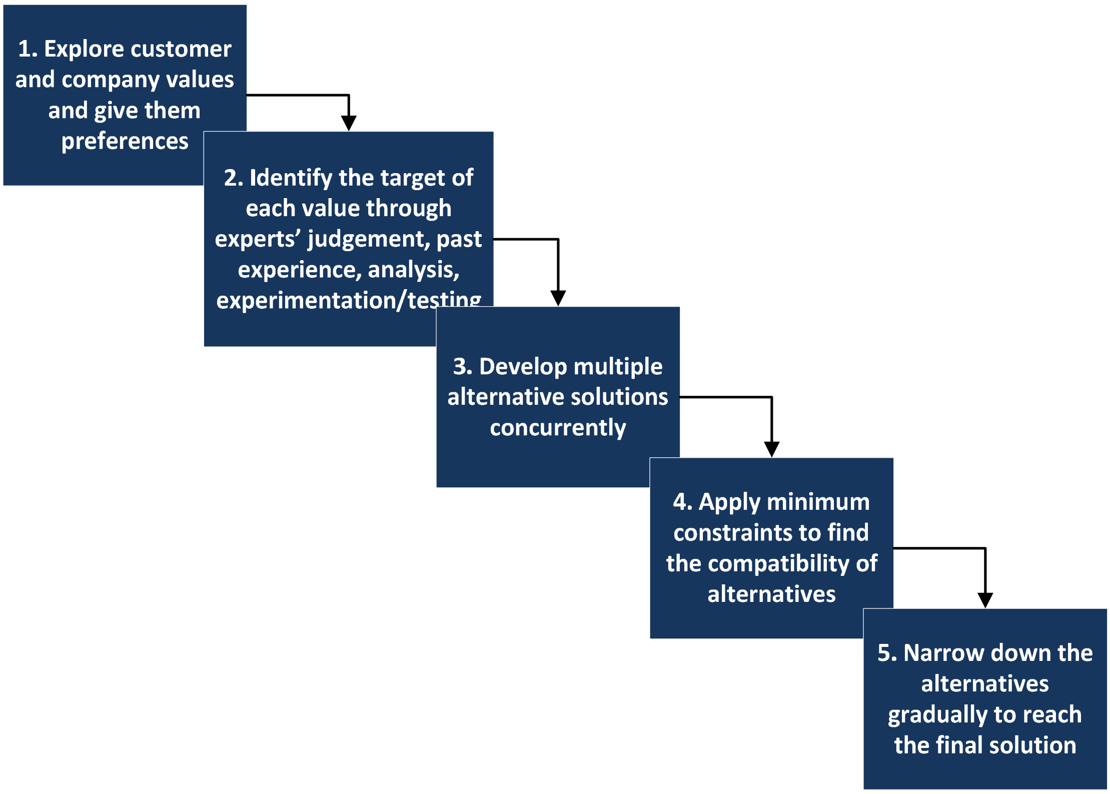


Figure 5-6: Set-based concurrent engineering process for developed cost modelling system

2. Identify the target of each value through experts' judgement, past experience, analysis, experimentation/testing

In this step, the designer is required to input the targets against each value. For example, if the crash strength of the final product is greater than 75 (MPa), then the proposed material is an acceptable option; otherwise, the material will be unacceptable. These targets can be provided by top management or marketing experts. In addition, the company's database may be employed to gather the targets' information.

Four target ranges were set into the system, namely excellent, acceptable, marginal and unacceptable. Each target range is denoted by a special graphical visual and target intermediator (Table 5-1). The target intermediator is simply a conversion number, which has been introduced here to compare targets with estimated results. For example, if the estimated result of crash strength is greater than 75 (MPa), i.e. excellent, then the target intermediator of crash strength will be assigned number 10. Value preferences and target intermediators collectively facilitate the elimination of weak solutions in step 5 (see Figure 5-6). Further examples of target ranges are provided in Chapter 6.

Table 5-1: Target range and associated target intermediator

Targets and graphical visuals	Target range	Target intermediator
Excellent-☺	Defined by designer (See Set-based concurrent engineering process Step 2, Figure 5-6)	10
Acceptable-●	Defined by designer	7
Marginal-▲	Defined by designer	3
Unacceptable-x	Defined by designer	0

3. Develop multiple alternative solutions concurrently

The third step is associated with the development of multiple alternative designs concurrently (see Figure 5-6). These alternatives are designed on the basis of innovation required, values identified in step 1 and company policies. Moreover, designers may utilise their own imagination and brainstorming to develop alternatives. Previous projects' data can also be used as a source of innovation.

4. Apply minimum constraints to find the compatibility of alternatives

Once a conceptual design is developed and the CAD file is generated, the system reads the CAD information to develop the estimates. The estimation procedure has been explained in Section 5.6. The poka-yoke rules have been developed to identify the compatibility of proposed materials and manufacturing processes. To represent the output of multiple solutions, a matrix for communicating alternatives has been employed. Table 5-2 presents an example of the matrix for communicating alternatives.

Table 5-2: Matrix for communicating alternatives

Values \ Designs	Design 1	Design 2	Design 3	Design 4	Design 5
Product weight (Kg)	▲	☺	☺	☺	●
Tensile strength (MPa)	☺	●	▲	☺	▲
Product cost (£)	☺	▲	☺	●	▲
Maximum service temperature(^{o}C)	☺	●	▲	▲	x
Production volume (Units per day)	▲	☺	☺	●	x

Legend: Excellent-☺=10, Acceptable-● = 7, Marginal-▲ = 3, Unacceptable-x = 0

5. Narrow down the alternatives gradually to reach the final solution

The final step of set-based concurrent engineering is the reduction of solution space through the elimination of weak solutions. Set-based concurrent engineering stresses avoiding early decision making and emphasises eliminating the weaker solution. Therefore, only a better set is selected. In the developed system, a quantification method has been proposed to eliminate the weaker solution. In this method, each solution is quantified into a single readable number called the quantification number, as follows; Let n be the total number of values and m be the total number of solutions; P_1, P_2, …, P_n be the customer and company preferences for the values V_1, V_2, …, V_n respectively; T_{m1}, T_{m2},…, T_{mn} be the resultant target intermediator for each value estimate; and Q_1, Q_2,…, Q_m be the quantification numbers against each solution. The following equation (equation 5-1) can be applied to calculate the quantification number.

$$\begin{bmatrix} T11 & T12 & . & . & T1n \\ T21 & T22 & . & . & T2n \\ . & . & . & . & . \\ . & . & . & . & . \\ Tm1 & Tm2 & . & . & Tmn \end{bmatrix} \text{x} \begin{bmatrix} P1 \\ P2 \\ . \\ . \\ Pn \end{bmatrix} = \begin{bmatrix} Q1 \\ Q2 \\ . \\ . \\ Qm \end{bmatrix} \qquad \text{.......................................(5-1)}$$

The solution with the lowest quantification number will be the weakest solution and will be eliminated prior to the remaining solutions. Case studies are presented in Chapter 6 to illustrate the above explained concept.

The proposed methodology will enhance the decision taking capability and reduce errors in the early design stage that may cause wastes in manufacturing and/or the later stages of product development.

In addition to the quantification method, trade-off values have been implemented in the developed system. This is a decision making tool which supports the development team in taking quick decisions.

5.4.2 Poka-yoke (mistake-proofing)

In product design and development, mistakes can occur at the product design stage, at the cost estimation stage, or even at the manufacturing stage where the manufacturer selects suitable process parameters on the basis of design. In the system, poka-yoke has been applied to eliminate three types of error: (1) mistakes elimination in manufacturability identification; (2) mistakes elimination in product design; and (3) mistakes elimination in process parameters selection (see Figure 5-7). It is worthy to state that these errors have been identified through literature gap and industrial field study analyses.

5.4.2.1 Mistakes elimination in manufacturability identification

In order to generate reliable estimates, it is necessary to make the right assumptions. Incorrect assumptions lead to incorrect costs, and ultimately a reduction in market profit and a loss in customer confidence. In the developed system, rules have been developed to identify the following:

1. Materials’ manufacturability
2. Machines’ availability in the manufacturing facility, and

3. Machines' capability to manufacture the component

In the presence of the right rules, only suitable information passes through the system, and ultimately accurate results can be generated. Examples of some rules are explained below.

Figure 5-7: Poka-yoke in the developed system

Materials' manufacturability

If

(The material is low carbon steel) AND

(The manufacturing process is turning) AND

(The required hardness of material is below 100BHN) AND

(The required thermal conductivity of the material is below 50W/mK) AND

(Additional rule)

Then

(The material is manufacturable)

Machines' availability in manufacturing facility

If

(The component material is low carbon steel) AND

(The manufacturing process is drilling) AND

(The size of component is 350mm x 250mm x 100mm) AND

(Additional rule)

Then

(D001 and M005 are suitable machines available in the manufacturing facility)

D001 is a drilling machine and M005 is a CNC milling machine

Machines' capability to manufacture the component

If

(The component material is Low Carbon Steel) AND

(The part feature is a hole) AND

(The diameter of the hole is <= 3mm) AND

(The tolerance of the hole <=0.005mm) AND

(Additional rule)

Then

(M005 available in the manufacturing facility has the capability to process the component)

M005 is a CNC milling machine

5.4.2.2 Mistakes elimination in product design

Designers can execute mistakes during the design of product. Although these mistakes reduce as the experience of the designer increases, there is still the possibility that inexperienced designers generate more mistakes. The probability of mistakes is even higher in the case of a complex or innovative design. For example, in the case of resistance spot welding, the minimum recommended distance between the edge and spot centre is 5.6mm for a sheet thickness of 1.5mm; if the designer does not follow the minimum-dimension requirement, there are chances of no weld at all, poor-quality weld, or distortion of the parts being joined. In order to minimise these mistakes, geometric features assessment rules have been applied in the developed system. These rules assess the CAD design to evaluate if the design has been developed within limits. In the case of the designer avoiding the design limits, the system generates an error message with a suitable value suggestion. The following is an example of the geometric features assessment rule.

If

(The sheet thickness is > 0.5mm) AND

(The sheet thickness is < 0.6mm) AND

(Material is Low Carbon Steel) AND

(Manufacturing process is resistance spot welding) AND

(Spot spacing is <= 10 mm)

Then

(Spot space design is within range; Minimum recommended spot space is 10mm)

5.4.2.3 Mistakes elimination in process parameters selection

Another mistake that commonly occurs in product development is the selection of the right process parameters at the manufacturing stage, i.e. if the designer develops a design within recommended limits and estimates the cost precisely, there are still chances that the manufacturer/process planner will misinterpret critical dimensions and apply incorrect process parameters. For example, in the case of resistance spot welding, the weld current is 8.51 Amp for part thickness of 0.51mm and part material as low carbon steel. If the manufacturer/process planner misinterprets the part thickness, then the wrong parameters will be selected, which may result in a faulty product and high repair cost. To avoid these types of errors, rules have been applied in the developed system. An example of these rules is given below. These rules provide the right process parameters information to manufacturers.

Process parameters generation rule

If

(The component material is low carbon steel) AND

(The part thickness is 0.51 mm) AND

(Machine selected is resistance spot welding) AND

(Additional rule)

Then

(Weld current is 8.51A) AND

(Weld time is 7 cycles) AND

(Hold time is 7 cycles) AND

(Squeeze time is 7 cycles)

5.4.3 Knowledge-based engineering for cost modelling system

In the developed system, the lean knowledge life cycle proposed by Maksimovic et al. (2011) was employed to capture the knowledge and to develop the system. The detail of each knowledge life cycle stage is presented in the section below.

5.4.3.1 Knowledge Identification

The first stage of the knowledge life cycle is knowledge identification. Principally it is an initial planning stage, where the knowledge required for a specific problem is identified. Once the required knowledge is identified, it is captured in the knowledge capture stage. In order to identify the knowledge for this research, a number of interviews with the product development teams were conducted to identify the required knowledge. Since the research is related to the cost estimation process, all the necessary data were, therefore, identified, which include the machines information, materials' capability, product design rules, etc.

5.4.3.2 Previous product and domain knowledge capture

In this stage, the knowledge highlighted in the knowledge identification stage was captured. In the case of resistance spot welding, it was identified that the company was using welding standards to design the product. The designers employ those standards to identify the number of spots, edge distance etc. These rules were captured and processed further to apply in the knowledge-based engineering application. In addition, the machines and material information was collected and stored in the database. In the case of laser welding and machining, it was realised that the companies have no machines available; therefore, the machines information was collected through visits to the manufacturing facilities available in Cranfield University. All the knowledge related to cost estimation was identified from textbooks and previous research work.

5.4.3.3 Knowledge representation

Once the knowledge is captured, it is required to be presented in a form which can easily be transformed into a knowledge-based engineering application. In this research, the knowledge captured in stage 2 was presented in the form of rules. Examples of these rules are presented below.

Material and related properties identification rule

If

(The component required hardness is 75Bhn) AND

(The component density is 2.67 x10^3) AND

(Additional rule)

Then

(Material MAT-AL$$ is selected) AND

(Selected material thermal conductivity is 205 W/mK) AND

(Selected material tensile strength is 76 MPa) AND

(Selected material maximum service temperature is 130°C) AND

(Selected material minimum service temperature is -273°C) AND

(Additional rule)

Where MAT-AL$$ is Aluminium alloys (cast)

Product design rule

If

(The sheet thickness is > 0.8mm) AND

(The sheet thickness is < 1.0mm) AND

(Material is Low Carbon Steel) AND

(Manufacturing process is resistance spot welding) AND

Then

Recommended Spot spacing is = 15 mm

Recommended edge distance is = 4.3mm

Recommended overlap is = 8.6mm

Further examples of these rules have been provided in Section 5.4.2.2. In addition to the rules, machines information was also captured and presented in the form of table. The machines information is available in Section 5.5.2. The captured knowledge was validated through industrial representatives to eliminate mistakes before the system development.

5.4.3.4 Knowledge sharing

The aim of this stage is to share the knowledge with all stakeholders so that they may access the knowledge in order to view it or modify it when changes in the product occur. In the developed system, the captured knowledge was stored in an SQL server and MS visual studio application, where it is easily accessible for all the stakeholders.

5.4.3.5 Knowledge-based engineering

In this stage, the knowledge represented in the form of rules was employed to develop the cost modelling system to support lean product and process development. This system has been developed in Microsoft visual studio which provides the users an integrated environment for the cost estimation of multiple applications. It is an end-to-end and service-oriented application based on the .NET enterprise application server technologies. The system offers full interoperability with Java enterprise and Oracle servers. This application is developed in C# 3.0 within the .NET Framework and Microsoft SQL Server 2008. The user interface design concentrates on building client-side application using Windows Forms. The MS SQL server database is employed to design and build up rules and knowledge. In addition, a CAD-Excel-SQL server interface has been developed for reading CAD data information and transferring it into the SQL server for quick cost estimation. The main reasons for using Microsoft visual studio are the facts that it is easily available for academic research purpose, widely applicable in industry and can integrate easily with PDM system applied in the case study company.

It is worth stating that feature-based cost estimation method has been used in the developed system because this method has high precision of estimates and easy to apply in design stage. However, to overcome the drawback of lengthy estimation time, cost estimation rules have been integrated with the developed system.

5.4.3.6 Dynamic knowledge use and provision

In this step, the cost modelling system was provided to the designers to estimate the cost and to make the right decisions. The case studies have been explained in Chapter 6 to show the use of knowledge.

In addition, the knowledge was provided in the knowledge repository to be used further for new product development. Since the case study company employs almost 80% of a previously developed product, it was, therefore, planned to use the cost knowledge of a previous product along with the cost knowledge of the new product to estimate the total product cost.

5.4.3.7 Dynamic knowledge capturing

Dynamic knowledge capturing is the most critical stage of the lean knowledge life cycle, where the new knowledge is captured dynamically and aligned with previous knowledge, in order to update the system application with new knowledge. Since the system is developed on the basis that a new product consists of 80% of old components with only 20% of innovative components, provision has, therefore, been made in the developed system to utilise the cost of previous products. The previous product cost, along with the new estimate, is stored in a database to be utilised in future product development.

5.5 System Modules

The system is composed of six modules to generate a systematic cost estimation process for lean product and process development. The description of each module is provided in the following sections.

5.5.1 Value identification module

In order to narrow down alternative design solutions, this module provides a list of values for the designer. The designer is required to select the values according to the requirements. In order to map the design space for feasible design space identification, the designer is also obliged to input the preferences and targets of each value in this module. In total, 16 values have been identified and integrated into the system such as product cost and manufacturing time. The list of values has been explained in Section 5.4.1. This list was established from interaction with industry. The system has been structured to generate the results of all 16 values. The values can be populated according to requirement.

The value identification module facilitates the set-based concurrent engineering concept, where the designers communicate explicitly to develop sets of design solutions on the basis of their preferences. These sets help the designers to make the right decisions by eliminating weaker solutions.

5.5.2 Manufacturing process/machines selection module

After the identification of values, designers provide manufacturing process information. This is an important element of the system, because sometimes more than one manufacturing process can be suited to a specific part/assembly, e.g. friction welding, electron beam welding, furnace brazing or diffusion brazing. Therefore designers have to select the precise manufacturing process within the acceptable cost boundary. This module is linked to the machine database, which not only helps to identify the manufacturing process(es) capability in the downstream manufacturing facility, but also facilitates in locating the most suitable machine(s).

The manufacturing process/machines selection module supports two lean product and process development enablers, namely knowledge-based engineering, and mistake-proofing. Rules have been developed to identify the suitable manufacturing processes and designate particular machines available on the manufacturing shop floor. All the machines' information is stored in the machine database (see Table 5-3).

Table 5-3: An example of the machine database

Machine name	Machine ID	Machine Efficiency (%)	Power of machine (KWh)	Maximum travel in X axis	Maximum travel in Y axis	Maximum travel in Z axis
Milling Machine	D001	90	35	230mm	75mm	150mm
Drilling Machine	M001	75	25	200mm	75mm	75mm

5.5.3 Material selection module

An appropriate material is selected on the basis of part geometry, tolerances, strength, and physical and mechanical properties. The material selection module is coupled with the material database. Table 5-4 describes an example of a material database. The designer can specify his/her own material, or select the material from the system. In the case that the designer selects the material from the system, information related to material properties, such as material hardness, thermal conductivity, and tensile strength is provided. The system also allows the designers to specify their own material details by inserting material information such as density and unit cost.

Knowledge-based engineering and set-based concurrent engineering are facilitated by a material selection module, which supports appropriate material selection and identification of associated material properties from the database. These values present a solution space to take the right decisions; for example, the designer can evaluate alternative materials on the basis of material cost, environmental impact, crash strength and manufacturing time.

Table 5-4: An example of the material database

Material name	Material ID	Hardness (Bhn)	Density (Kg/m3)	Thermal conductivity (W/mK)	Tensile strength (MPa)	Maximum service temperature (oC)
Aluminium alloys (cast)	MAT-AL$$	40	2670	205	76	130
Steel, Low carbon	MAT-SLC$$	100	7800	50	310	344

5.5.4 Geometric features specification module

In this module, the designer specifies the component features information from the CAD file into a geometric features database. This information includes feature name, shape, length and width. An example of a geometric features database of a resistance spot welding (RSW) process is shown in Table 5-5.

The system has been developed to support designers in the conceptual and detailed design stages. During the conceptual design, since only a small amount of information is available only, special measures have therefore been taken to deal with this situation. The designer has to input minimum geometric features information, whereas the rest of the information is generated on the basis of rules stored in the geometric features database. For example, if the designer selects resistance spot welding (See Table 5-5), he/she needs to input length, width and thickness only. The remaining information, such as edge distance, resistance spot spacing and total number of spots, is generated through the rules stored in the system. However, in the detailed design stage, the designer is required to input complete geometric information.

Table 5-5: An example of the geometric features database of resistance spot welding (RSW)

Feature ID	Feature name	Feature type	Dim. Type	Value (mm)	Edge distance (mm)	Resistance spot spacing (mm)	Seam length (mm)	No of resistance spots
SW1001	Resistance spot Weld	Weld	Length Width Thickness	150 25 0.6	5	5	15	06

5.5.5 Geometric features and manufacturability assessment module

Once the designer provides geometric features information for a specific sub assembly, the system applies assessment rules to uncover the sub assembly's manufacturability. In addition, geometric features assessment rules have also been provided to identify that the product has been designed within a recommended range.

This particular module is grounded in mistake-proofing and knowledge-based engineering enablers. Furthermore, features are assessed using poka-yoke principles and enable designers to rectify the design at an early development stage. For example, the minimum recommended sheet thickness for a particular manufacturing process is 3.3mm; if the designer specifies a thickness less than this recommended number, the system generates an error message and offers a suitable value suggestion. Poka-yoke rules in Section 5.4.2 and the case studies in Chapter 6 demonstrate the above explained concept in detail.

5.5.6 Manufacturing time and cost estimation module

In the manufacturing time and cost estimation module, a feature-based cost estimation method has been employed to estimate the manufacturing time and cost for suitable manufacturing processes, and materials. Manufacturing cost has been divided into material, labour and equipment running costs. In this module, the designer is allowed to identify high cost and time consumption features.

5.6 System Scenario

The developed system supports the designers in both the conceptual and detailed design stages. In the conceptual design stage, it helps decision making, whereas, in the detailed design stage, it facilitates the design assessment and total cost of product at a detailed level. Figure 5-8 describes the capability of the system, which is divided into four options.

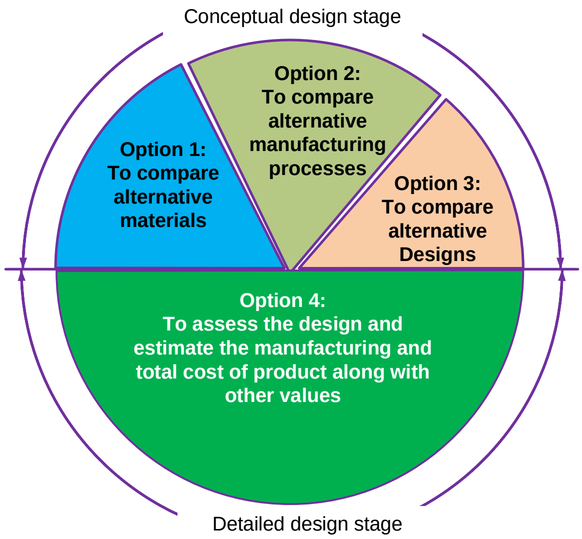


Figure 5-8: The system capability

Option 1: Compare alternative materials

Option 2: Compare alternative manufacturing processes

Option 3: Compare alternative designs

Option 4: Assess the design and estimate the manufacturing and total cost of product along with other values

It is commendable to note that the system scenario has been developed carefully to follow the set-based concurrent engineering process explained in Section 5.4.1, poka-yoke application explained in Section 5.4.2, and knowledge-based engineering explained in Section 5.4.3. The scenario of the cost estimation process for conceptual and detailed design is illustrated in Figure 5-9.

The detailed explanation of each option (Figure 5-8) has been provided in the following sections. It is important to note that the system scenario is explained with respect to the number of activities performed in the estimation process. This presentation scheme is chosen because it is easy to show the process flow.

5.6.1 Compare alternative materials at the conceptual design stage

If companies are required to investigate new materials, this option helps them to compare the alternative materials at the initial design stage. Prior to the estimation, the system identifies the materials' manufacturability, machines' availability in the manufacturing facility and machines' manufacturing capability on the basis of rules stored in the system. Once the materials are found to be suitable, the system generates the results and supports the selection of the best solution.

The system scenario to compare alternative materials has been provided in Figure 5-10 which consists of eight activities. The estimation process is initiated with the identification of values and design space mapping (Activity 1, Figure 5-10), i.e. the system prompts the designer to choose the values from a comprehensive option list. The designer not only selects the values, but also specifies preferences and targets. Section 5.4.1 provides the rationale and description of values and targets. Further explanation of values and targets is provided in Chapter 6, Section 6.2.1.3.

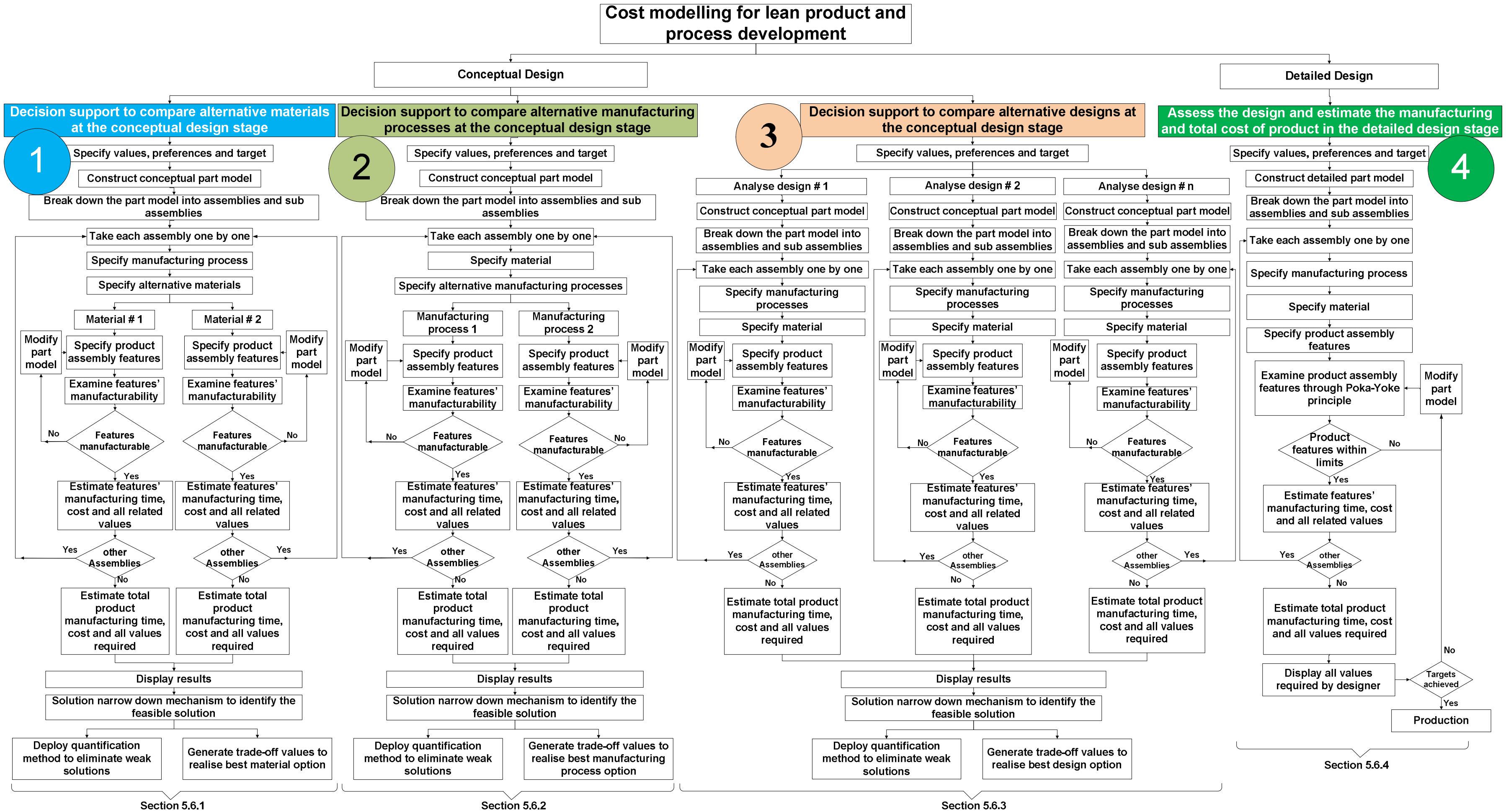


Figure 5-9: System scenario

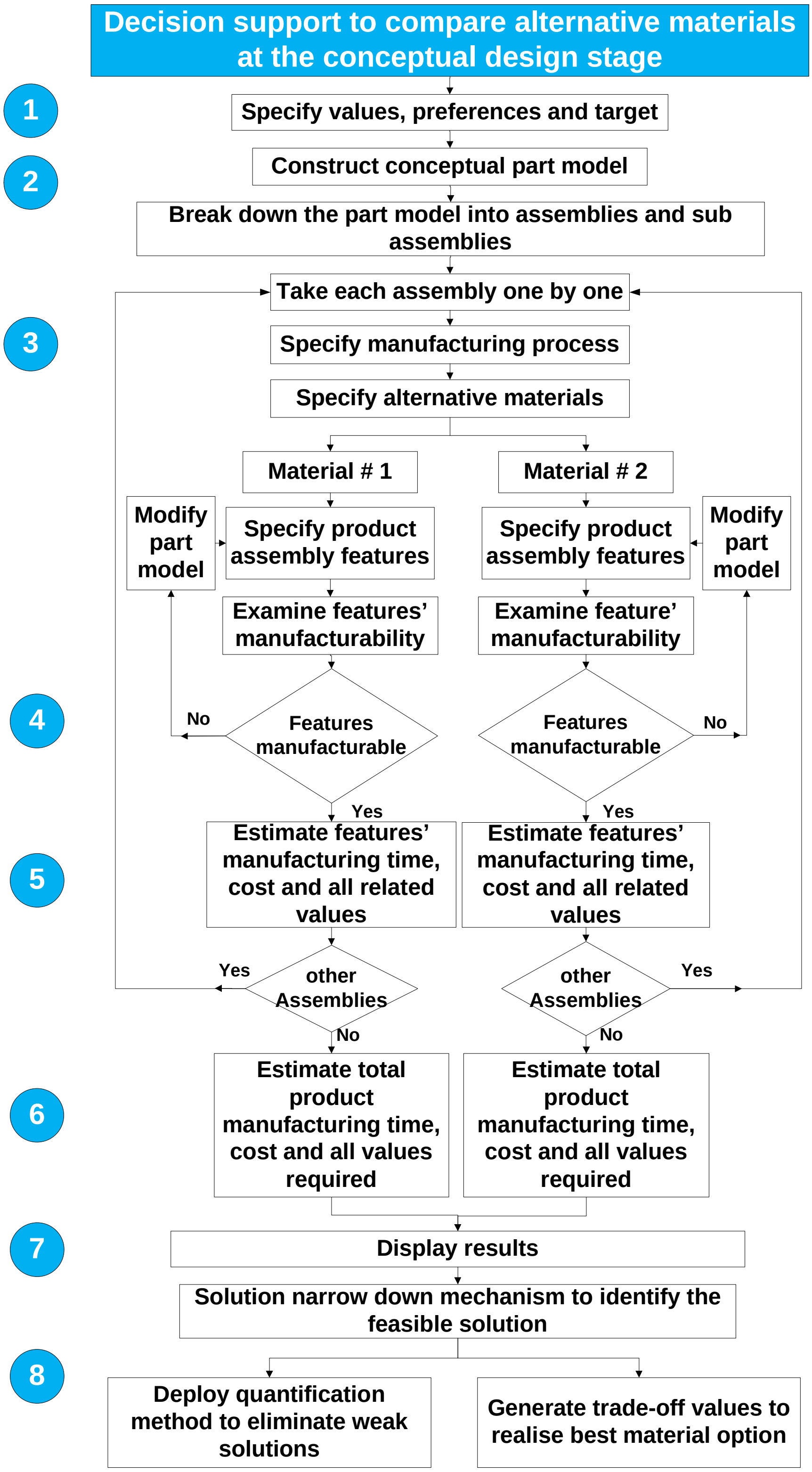


Figure 5-10: System scenario "To compare alternative materials at conceptual design stage"

In activity number 2 (Figure 5-10), the designer constructs a conceptual part model via the CAD system. He/she also breaks down a part model into assemblies and sub assemblies for the detailed cost estimation of each assembly separately. The assemblies and sub assemblies features dimensions are retrieved from CAD files and stored into an Excel file through CAD-Excel interface. Alternatively, the designer can specify the CAD model information manually. In the next activity (Activity 3), the system prompts the designer to specify the manufacturing process, alternative materials and geometric features information. Once the designer provides the information, the system examines each feature for its manufacturability by applying the poka-yoke manufacturability identification rules stored in the knowledge database (Activity 4, Figure 5-10).

If the feature does not accomplish the manufacturability criteria, then the system prompts the designer to modify the part model. The explanation of poka-yoke manufacturability identification is available in Section 5.4.2.1. Once each feature is found to be suitable for manufacturing, the system generates the estimate of manufacturing time, cost and all other values required by the designer (Activity 5). Activities 3, 4 and 5 are repeated until manufacturability, manufacturing cost and other values of the entire product are estimated (Activity 6). Activity 7 is associated with the presentation of results. In the developed system, results are displayed in two different ways. In the first representation scheme, the system presents the detailed manufacturing time and cost of each feature against alternative materials. In addition, total manufacturing time and cost of component are also displayed. However, in the second representation scheme, the system shows the summary of results, i.e. estimates of all the values against the specified alternative materials. The motivation behind these two representation schemes is to facilitate the designer in analysing each feature in depth and to visualise the overall picture respectively. The final activity (Activity 8) is concerned with the solution narrowing down mechanism; which not only enables the users to recognise alternative design options (alternative materials in this case) within target limits or exceeding the target limits, but it also proposes the best design option. For this purpose, quantification method has been provided. In addition, trade-off values has been used in the system to realise the best material option. A description of quantification method and trade-off values has been provided in Section 5.4.1. The designer can select individual or both options/tools to identify the best material.

5.6.2 Compare alternative manufacturing processes at the conceptual design stage

The system also supports the designers in comparing alternative manufacturing processes at the conceptual design stage. The system follows the same procedure as explained in option 1 (Section 5.6.1), i.e. the system identifies the materials' manufacturability, machines' availability in the manufacturing facility and machines' manufacturing capability, and finally generates the results to identify the best manufacturing process for the provided design.

Figure 5-11 illustrates the system scenario, which is composed of eight activities. These activities are almost the same as described in the previous section, with a difference in activity 3 and the final results. In Activity 3, the system prompts the designer to specify the material, alternative manufacturing processes and geometric features information. Activities 4 - 8 are similar to the previous section with the only difference being in the results. In this option, the results are generated for an alternative manufacturing process. It is important to note that this option is suitable if the whole product is made of one manufacturing process and the user wants to identify the cost and associated value estimates of different manufacturing process(es).

5.6.3 Compare alternative designs at the conceptual design stage

In the case that the design is composed of several manufacturing processes, then options 1 and 2 (Sections 5.6.1 and 5.6.2) are not suitable. For example, if a part is composed of 20 assemblies with resistance spot welding and the designer wishes to change five assemblies with laser welding and the remaining with resistance spot welding, or the user wants to see the effects of introducing a new machining process on a specific geometric feature, then in these cases, the options provided in sections 5.6.1 and 5.6.2 do not remain valid.

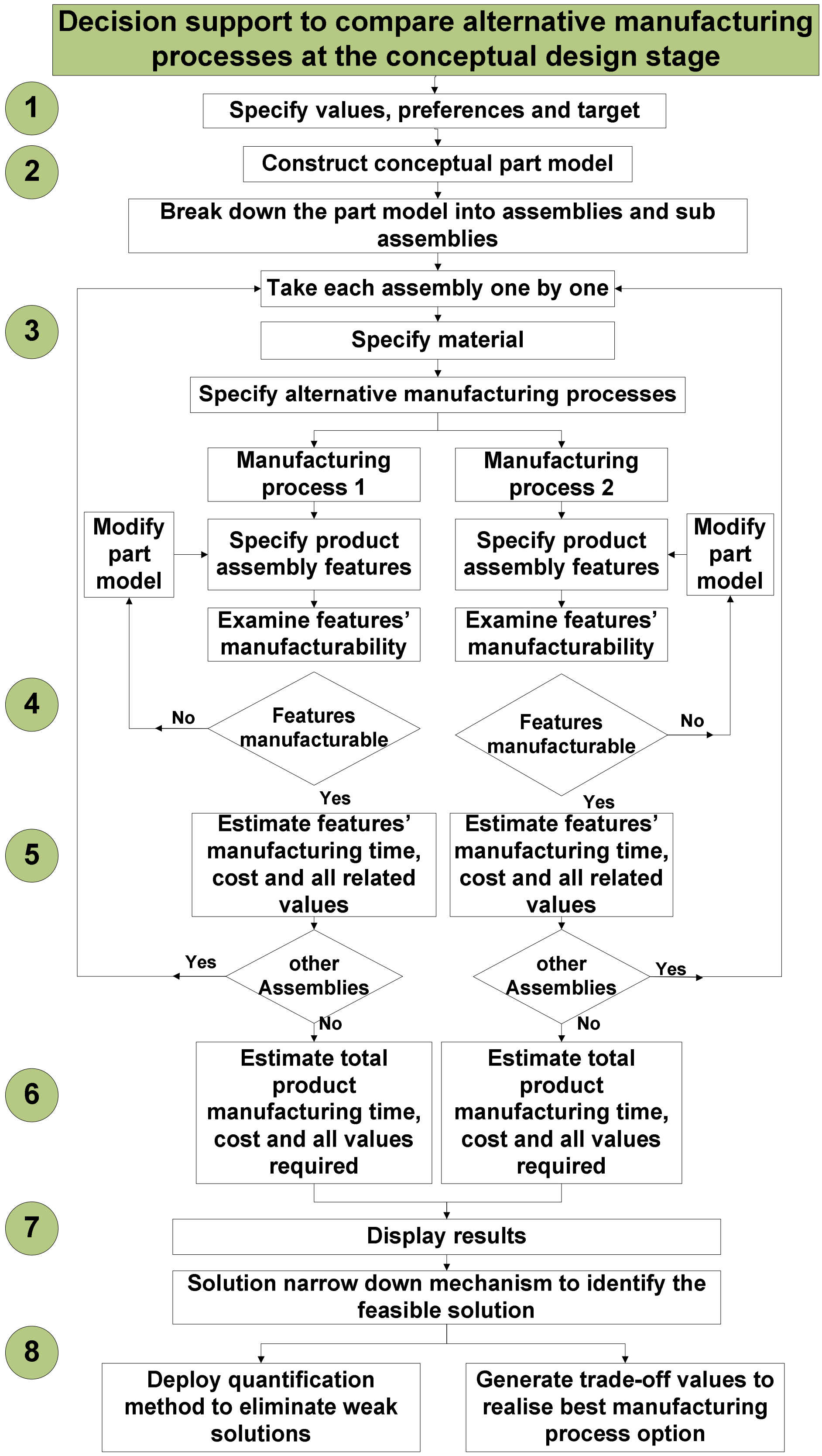


Figure 5-11: System scenario "To compare alternative manufacturing processes at the conceptual design stage"

In order to mitigate this problem, an alternative designs comparison option has been provided in the system. The system has the capability to compare five designs with an unlimited number of assemblies. The system scenario has been provided in Figure 5-12, which is composed of the same eight activities, as explained in Section 5.6.1. The only difference is that the user can specify one specific material and one manufacturing process for each sub assembly and feature. The system supports the designer in recognising the best design through the quantification method and trade-off values.

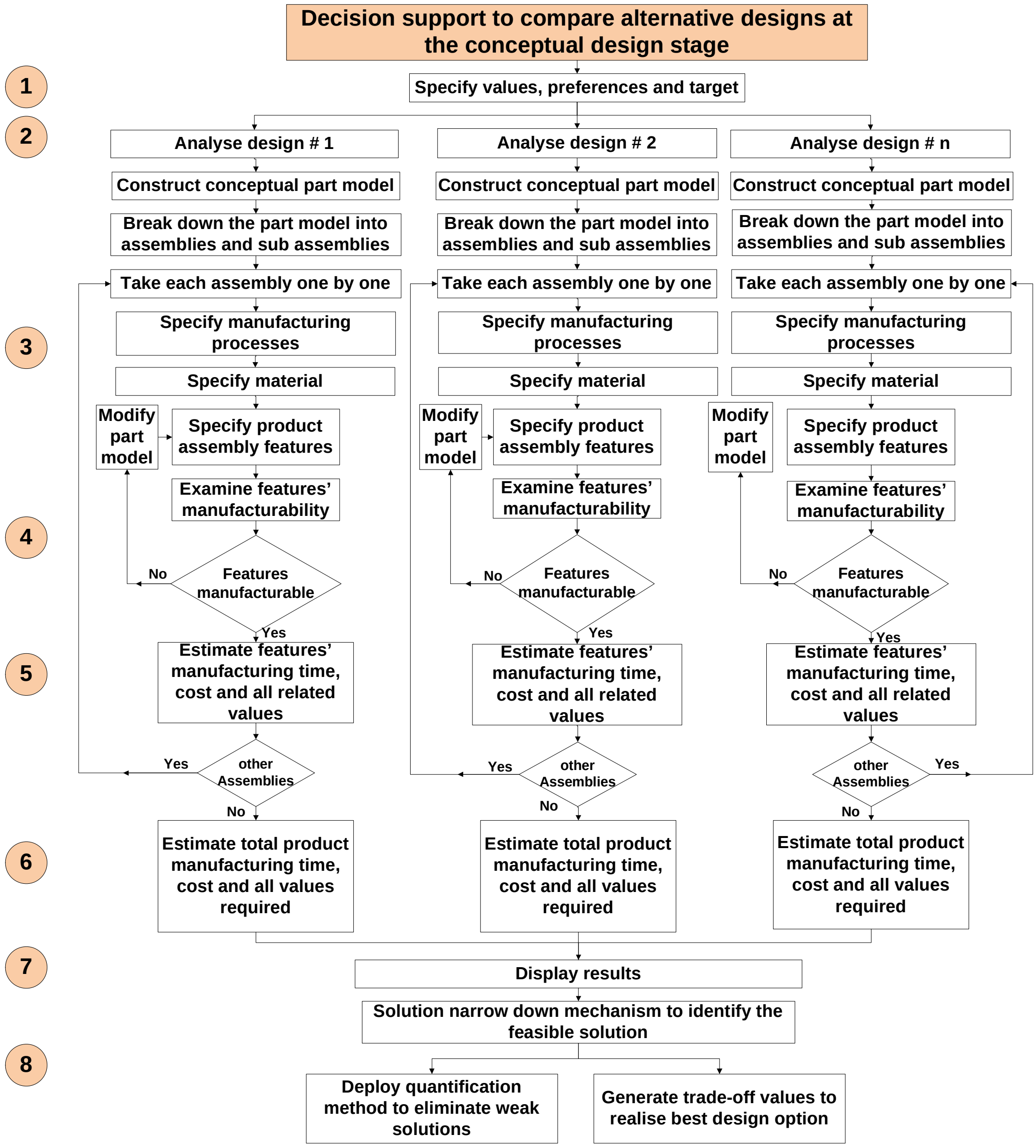


Figure 5-12: System scenario "To compare alternative designs at the conceptual design stage"

5.6.4 Assess the design mistakes and estimate the manufacturing and total cost of product along with other values

Once an optimum design is selected in the conceptual design stage, it is further developed in the detailed design stage. A detailed CAD model is finalised, tolerances are fixed and final testing is performed. Since the detailed design stage involves a large number of activities there are more chances of mistakes being present in this stage. This higher risk of mistakes ultimately leads to cost overrun issues. This option assesses the design mistakes and estimates the manufacturing and total cost of product along with other values in the detailed design stage. This option has been included into the system to tackle the cost overrun issue, which is the major problem faced by industry, identified during the industrial field study. Eliminating the mistakes and counterchecking the cost helps to keep the cost lower than, or equal to, targets.

The system scenario to assess the design mistakes and estimate the manufacturing and total cost of product along with other values has been provided in Figure 5-13, which consists of six activities. The estimation process begins with the specification of values and targets (Activity 1, Figure 5-13). In activity number 2, the designer constructs a detailed part model via the CAD system. He/she also breaks down the part model into assemblies and sub assemblies for detailed cost estimation. In the next activity (Activity 3, Figure 5-13), the designer specifies the manufacturing process, alternative materials and geometric features information into the system. Once the designer provides the information, the system assesses the design feature to identify any design mistake by applying the poka-yoke design assessment rules stored in the knowledge database (Activity 4). The system prompts any mistakes made by the designer. An explanation of the poka-yoke design assessment is available in Section 5.4.2.2. Once each feature is identified as mistake-proof, the system generates the estimate of manufacturing time, cost and all other values required by the designer (Activity 5, Figure 5-13). Activities 3 - 5 are repeated until manufacturability, manufacturing cost and other values of the entire product are estimated. Finally the results of all required values are demonstrated to user

(Activity 6). In addition, these results can be compared with targets to identify that targets have been achieved or not.

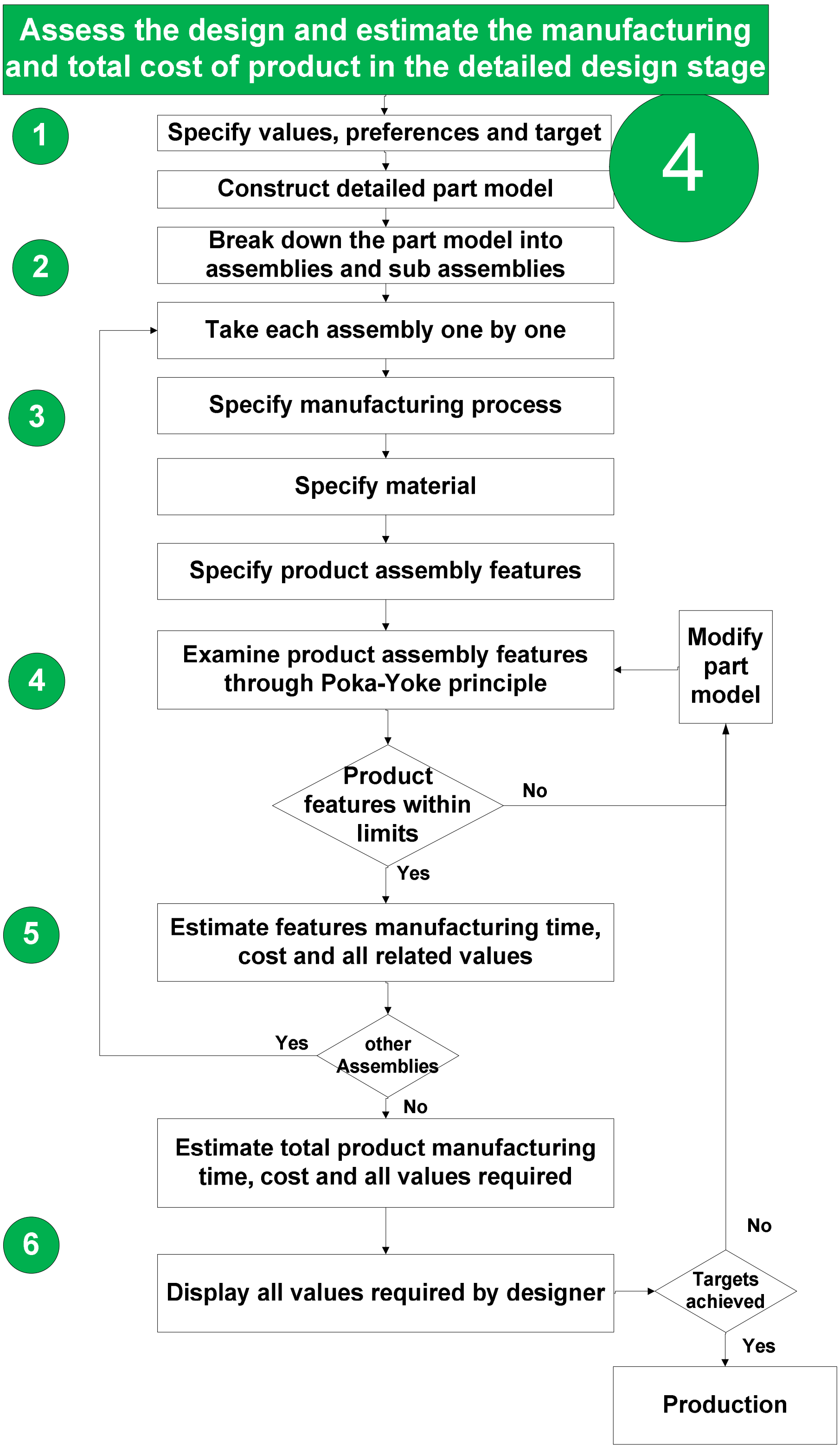


Figure 5-13: System scenario "To assess the design and estimate the manufacturing and total cost of product along with other values"

5.7 Cost Modelling

Two manufacturing processes, namely joining and machining processes, have been taken into consideration in the developed system. The cost model of these processes is explained in the following section.

5.7.1 Cost modelling of joining processes

In the developed system, the cost model of two joining processes, namely resistance spot welding and laser welding, has been considered. The following section discusses these cost models.

5.7.1.1 Resistance spot welding

Resistance spot welding is the process of joining the material by the combination of heat, pressure and time (Aslanlar, 2006). Since resistance spot welding is extremely suitable for automation with exceedingly high welding efficiency, it is widely applicable to sheet metal assemblies' joining processes in automobiles, rail vehicles and in home applications (Aslanlar et al., 2008).

In this process, pressure and high current is applied on the materials to be welded by a pair of electrodes. The resistance of the materials to be joined and current passed through the materials causes localised heating of the assembly and produces the molten weld nugget (Aslanlar, 2006; Aslanlar et al., 2008). The resistance spot welding process is illustrated in Figure 5-14.

The amount of heat generated during the resistance spot welding process can be found by using the equation 5-2 (Aslanlar, 2006; Aslanlar et al., 2008; Xu et al., 2007)

$$\mathrm{H} = \mathrm{I}^2\mathrm{RT} \qquad (5\text{-}2)$$

where

$$\mathrm{R} = \mathrm{R}_1 + \mathrm{R}_2 + \mathrm{R}_3 + \mathrm{R}_4 + \mathrm{R}_5 \qquad (5\text{-}3)$$

where:

H = Amount of heat generated in Joules

I = Amount of current flowing through the electrode in Amps

R = Electrical resistance of the different elements in Ω, and

T = Time in which the current is allowed to flow in the circuit in Secs

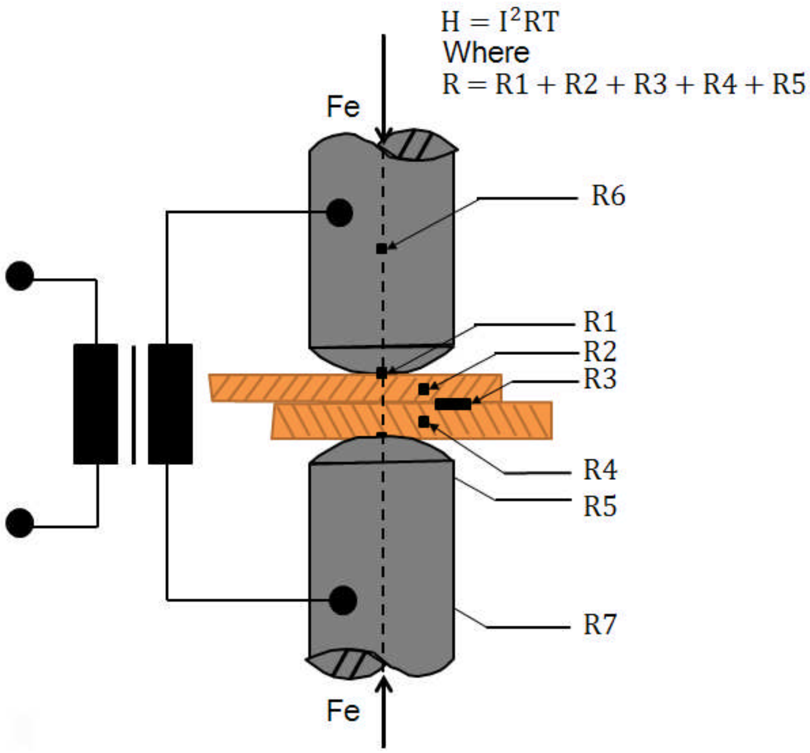


Figure 5-14: Resistance spot welding process
(Aslansar, 2006)

The current flow time is entirely dependent on material thickness, material type, amount of current, and the cross-sectional area of electrode tips and contact surface. During the welding process, the pressure is required to remain constant for a specific period of time in order to form a weld nugget (Aslanlar, 2006; Eisazadeh et al., 2010). It is important to note that in resistance spot welding, the current density and pressure should be maintained such that only a nugget is formed, but not so high that molten metal is thrown out of the weld zone; similarly the weld current must be kept adequately short to avoid a disproportionate heating of the electrode faces weld (Aslanlar, 2006; Aslanlar et al., 2008).

In order to identify the manufacturing cost of the resistance spot welding process, the manufacturing time is identified initially, followed by manufacturing cost in a later stage. The time and cost analysis of resistance spot welding is explained in the next section.

Time analysis of resistance spot welding (RSW)

Resistance spot welding (RSW) manufacturing time includes squeeze time, weld time and hold time, along with part setup and part removal time (Aslanlar, 2006; Xu and Zhai, 2008); where, squeeze time is the time period between the preliminary electrode force application on the work and the initial current application, weld time is the time when the current actually passes through the electrode and melts the parts to join them together, and hold time is the time required to solidify and chill the part. The setup and part removal times are the times when the part is prepared for welding and removed from the machine bed after joining respectively. In order to obtain the desired weld, the weld current should be prolonged until the electrode obtains the desired level. Figures 5-15 to 5-19 represent individual times in one complete cycle of a single resistance spot weld.

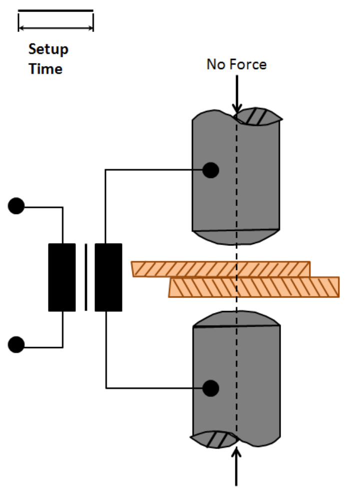


Figure 5-15: Resistance spot welding "setup time"

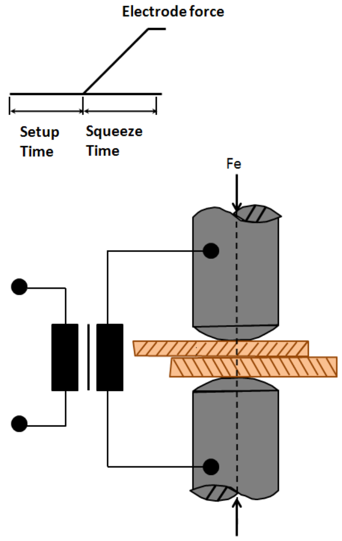


Figure 5-16: Resistance spot welding "squeeze time"

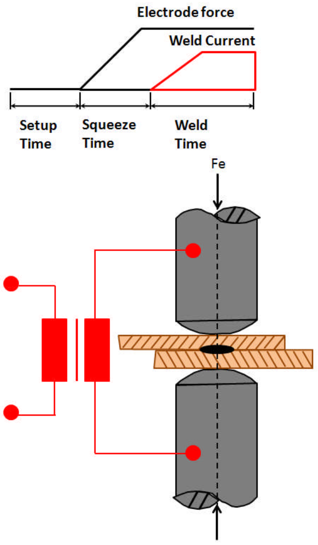


Figure 5-17: Resistance spot welding "weld time"

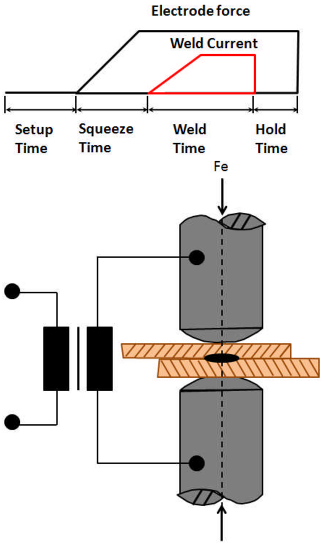


Figure 5-18: Resistance spot welding "hold time"

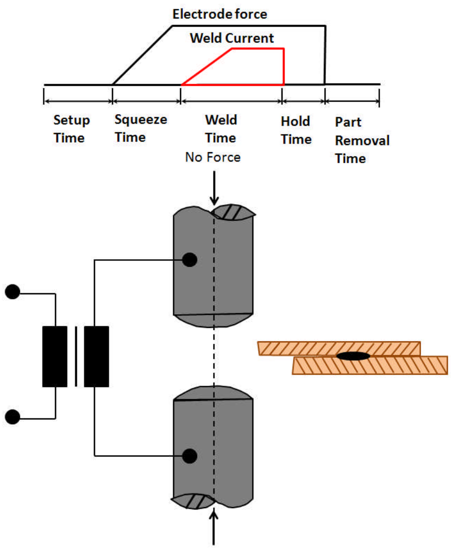
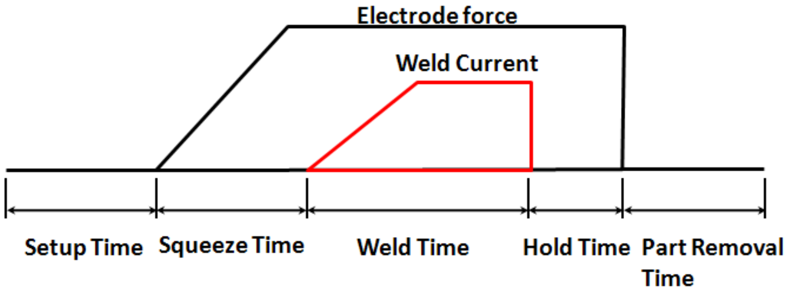
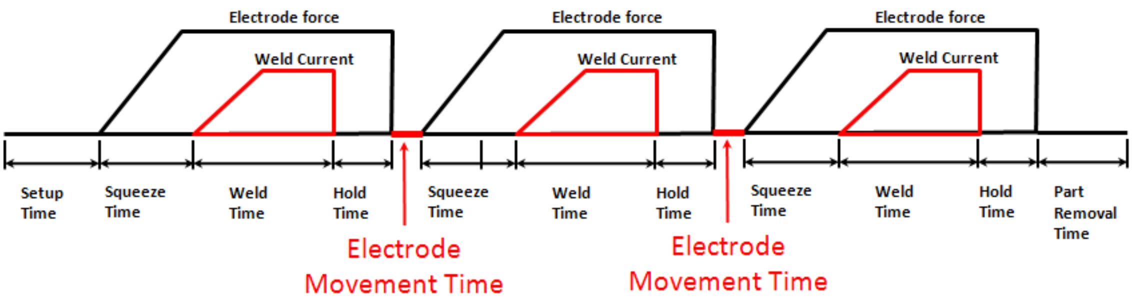


Figure 5-19: Resistance spot welding "part removal time"

Figures 5-20 and 5-21 show the manufacturing times for one weld and 'n' number of welds respectively.



5-20: Resistance spot welding time for one spot weld
(Adapted from Aslanlar, 2006, and Xu and Zhai, 2008)



5-21: Resistance spot welding time for “n” spot welds, n=3

In order to estimate the manufacturing time, equations 5-4 and 5-5 can be used for one and `n' number of welds respectively.

$$T_t = T_{su} + T_{sq} + T_{weld} + T_{hold} + T_{p-rem} \quad (5\text{-}4)$$

$$T_{t''} = T_{su} + n(T_{sq} + T_{weld} + T_{hold}) + (n-1)(T_{elec-m}) + T_{p-rem} \quad (5\text{-}5)$$

where

T_t = Resistance spot welding time for one weld in Secs

$T_{t''}$ = Resistance spot welding time for ‘n’ numbers of welds in Secs

n = Total number of spots

T_{sq} = Squeeze time in Secs

T_{weld} = Weld time in Secs

T_{hold} = Part holding time in Secs

T_{su} = Part setup time in Secs

T_{p-rem} = Part removal time in Secs, and

T_{elec-m} = Electrode movement time in Secs

Resistance spot Welding cost estimation

Predicting the welding cost mainly depends on the major cost drivers associated with the manufacturing process. In order to identify cost drivers, a comprehensive literature review was conducted. Since the research is associated with spot welding, laser welding and the machining process, special attention was, therefore, made to categorise drivers related to these processes, (see Table 5-6). Material cost, labour cost and equipment running cost are major drivers in welding cost estimation. For resistance spot welding, the equipment running process was further studied in detail and the following cost drivers were identified: power consumption, part holding and electrode movement costs. Once the cost drivers were fixed, a cost was designated to each driver.

Table 5-6: Cost drivers for manufacturing process (welding process)

Researcher / Cost drivers	(Ye et al., 2009)	(Chayoukhi et al., 2009)	(Ravisankar et al., 2006)	(Brinke, 2002)	(Feder, 1993) **as explained by** (Schreve, 1997)	(Benyounis et al., 2008)
Material	Material cost	Material cost		Part, geometry and material	Part, volume and density	
Labour	Labour cost	Labour cost	Labour cost			
Equipment running cost	Equipment cost	Electrode consumption cost	Electrode cost	Equipment cost	Equipment cost	Equipment cost
		Gas consumption cost	Shielding gas			
		Electric energy / power consumption cost	Power cost			
		Welding post consumption cost	Filler metal cost			

Material cost:

The material cost C_{mt} for resistance spot welding may be estimated as follows (Shehab, 2001).

$$C_{mt} = V\rho C_m \tag{5-6}$$

where:

V = Component volume in m^3

ρ = Material density in Kg/m^3, and

C_m = Material unit price in £/Kg

Labour cost:

The labour cost is the function of time required to complete the process multiplied by the labour unit cost. It can be calculated through the following expression (Ye et al., 2009).

$$C_{lb} = C_l \times \sum_{i=1}^{N} Lb_i \times T_i \tag{5-7}$$

where:

C_{lb} = Total labour cost in £

C_l = Labour unit cost in £/hrs

Lb_i = Number of labours in ith operation, and

T_i = Process time in ith operation in hrs

Power consumption cost:

In RSW, energy is consumed to weld the parts. Energy consumption depends upon weld time, welding power, machine efficiency and number of resistance spots. The following expression represents the power consumption cost in RSW (Klansek and Kravanja, 2006):

$$C_{pow} = C_p \times \frac{I_{weld} \times V_{weld} \times T_{weld}}{\eta_{weld} \times 3600} \times n \tag{5-8}$$

where:

C_{pow} = Power consumption cost of the electrode in £

C_p = Unit energy price in £/KWh

I_{weld} = Weld current in KA,

V_{weld} = Welding voltage in volts

η_{weld} = Welding machine efficiency

T_{weld} = Weld time in secs and

n = Number of spots.

Part holding cost:

In RSW, energy is consumed to hold the parts. It depends upon the holding force requirement, total holding time, holding equipment efficiency and number of spots. Part holding cost is estimated using the equation below.

$$C_{hold} = C_p \times \frac{P_{equip}}{\eta_{hold} \times 3600} \times \left(T_{sq} + T_{weld} + T_{hold}\right) \times n \qquad (5\text{-}9)$$

where:

C_{hold} = Part holding cost in £

C_p = Unit energy price in £/KWh

P_{equip} = Power of the holding equipment in KW

η_{hold} = Holding equipment efficiency

T_{sq} = squeeze time in Secs

T_{weld} = weld time in Secs

T_{hold} = hold time in Secs, and

n = total number of spots

Electrode movement cost:

Energy in RSW is also consumed during the electrode movement time and depends upon the electrode/robot speed, distance covered by the robot, i.e. total distance between spots, and equipment efficiency. The following relations (equations 5-10 and 5-11) can be applied to estimate the electrode movement cost.

$$C_{elec-m} = C_p \times \frac{P_{rob} \times d_{\Sigma}}{\eta_{rob} \times 3600 \times v} \times n \qquad (5\text{-}10)$$

where

$$d_{\Sigma} = \sum_{i}^{n} d_i \qquad (5\text{-}11)$$

where:

C_{elec-m} = Electrode movement cost in £

C_p = Unit energy price in £/KWh

P_{rob} = Power of the robot or electrode in KW

η_{rob} = Robot efficiency

d_{Σ} = Total distance covered by the robot in mm

d_i = Distance between each spot in mm and

v = Velocity of the robot in mm/sec.

Setup and part removal cost:

Setup and part removal costs and times are crucial in the mass production environment. These times include the times required to adjust the tooling and programme the robot. The times for different jigs and fixtures can be calculated and placed in the database to obtain a more accurate cost estimation. In addition, 20% additional cost can be added to overcome the overhead expenditures.

5.7.1.2 Laser welding

Laser welding, also known as laser beam welding, is a fusion welding technique used to join multiple parts by the application of a laser beam. Laser welding is preferred over arc welding and friction welding because less heat is required to join the parts, a small heat affected zone (HAZ) is produced and low material distortion occurs (Benyounis et al., 2008).

Laser welding is classified with respect to a number of parameters; for example (1) active medium (gas, liquid or solid); (2) output power (mW, W or kW); (3) wavelength (infrared, visible or ultraviolet); (4) operating mode (continuous wave, pulsed, or both); and (5) application (micro machining, macro processing etc.) (Ready, 1997). With respect to active medium, two major laser types common in practice are CO_2 lasers and the Nd:YAG (Neodymium Yttrium Aluminium Garnet) laser. Table 5-7 illustrates the difference between these two welding processes.

Table 5-7: comparison between CO_2 and Nd:YAG lasers (AWS, 1998)

	CO_2	Nd:YAG
Active medium	CO_2, N_2, He (Gases)	Nd:YAG Crystal
Excitation	Electric discharge	Lamp
Wavelength (microns)	10.6	1.06
Average power (KW)	0.1 - 45.0	0.1 - 5.5
Peak power (KW	0.1 - 50.0	0.1 - 100
Pulse frequency (kHz)	CW - 100	CW - 50
Efficiency (%)	5 - 15	1 – 4
Beam quality (M^2)	1 - 3	10 - 100(typical)
Consumables	CO_2, N_2, He (Gases)	Lamps
Transmissive optics	ZnSe, GaAs	Quartz
Reflective optics	Metal	Metal of dielectric
Fiber delivery	Not available	Quartz
Safety shield	Acrylic, Glass	Filters

Time analysis of laser welding

This research includes the mitigation from resistance spot welding to laser welding with lap joint. Since the mitigation from resistance spot welding to laser welding is not common practice, to overcome this issue, it was decided to replace each spot with a 10mm laser weld for a rough cost estimation. The total laser welding manufacturing time included laser welding time, robot movement time between two welds, along with part setup and part removal time. Equations 5-12 and 5-13 can be used to estimate the total laser manufacturing time for one weld and ‘n’ number of welds respectively.

$$\mathrm{T_t} = \mathrm{T_{su}} + \frac{d}{v} + \mathrm{T_{p-rem}} \qquad (5\text{-}12)$$

$$\mathrm{T}_{\mathrm{t}^{\because}} = \mathrm{T_{su}} + \mathrm{n}\left(\frac{d}{v}\right) + (\mathrm{n}-1)\left(\frac{d_{weld\_dist}}{v_{rob}}\right) + \mathrm{T_{p-rem}} \qquad (5\text{-}13)$$

where

$\mathrm{T_t}$ = Laser welding time for one weld in secs

$\mathrm{T}_{\mathrm{t}^{\because}}$ = Laser welding time for ‘n’ numbers of weld in secs

n = Total number of spots/welds

d = laser weld length (10mm in present case)

v = welding speed (mm/sec)

d_{weld_dist} = Distance between welds in mm

v_{rob} = Robot movement speed (mm/sec)

$\mathrm{T_{su}}$ = Part setup time in secs

$\mathrm{T_{p-rem}}$ = Part removal time in secs

Laser welding cost estimation

In the laser welding cost estimation, the major cost drivers include material cost, labour cost and machine running cost, as explained earlier in Table 5-6. Since the research is focus on the mitigation from resistance spot to laser welding, laser machine running cost drivers were fixed to be the same as the spot machine running cost driver, i.e. power consumption, part holding and robot movement costs. The cost of each driver is estimated as follows.

Material cost:

The material cost is a function of density, unit price and volume of part. Equation 5-6 in the previous section has been explained to estimate the material cost.

Labour cost:

Once the manufacturing time is identified, the labour cost is estimated by multiplying the labour unit cost with manufacturing time. Equation 5-7 presented in the previous section can be used to estimate the labour cost.

Power consumption cost:

The power consumption cost of laser welding machine can be found through the following equation (Benyounis et al., 2008)

$$C_{pow} = ((C_p \times \frac{P_{equip}}{P_{util}}) + (C_p \times P_{chill}) + (C_p \times P_{exh}) + \left(\frac{C_{laser\_gas\_bottle}}{V_{laser\_gas\_bottle}} \times Cons_{laser\_gas}\right) + (C_{laser\_gas\_rent}) + (C_{chill\_add}) + (C_{shield\_gas} \times Cons_{shield\_gas}) + (\frac{C_{nozz_{tip}}}{T_{oper_{Nozz}}}) + (\frac{C_{exh_{filt}}}{T_{oper_{exh_{filt}}}}) + \left(\frac{C_{focus\_lens}}{T_{oper\_focus\_lens}}\right) + (C_{lab\_maint} \times \frac{T_{maint}}{T_{machine\_work}})) \times (n\left(\frac{d}{v}\right)) \qquad (5\text{-}14)$$

where:

C_{pow} = Power consumption cost of laser machine in £

C_p = Unit energy price in £/KWh

P_{equip} = Power of equipment in KW

P_{util} = Utilised power from the actual power supplied (%)

P_{chill} = Power of chiller in KW

P_{exh} = Power of exhaust system in KW

$C_{laser\_gas\_bottle}$ = Unit price of laser gas bottle in £

$V_{laser\_gas\_bottle}$ = Gas volume per bottle in liter/bottle

$Cons_{laser\_gas}$ = Laser gas consumption in liter/hr

$C_{laser\_gas\_rent}$ = Laser gas bottle rent in £/hr

C_{chill_add} = Chiller additive rental in £/hr

C_{shield_gas} = Unit cost of shielding gas in in £/litre

$Cons_{shield\_gas}$ = Shielding gas consumption in litre/hr

C_{nozz_tip} = Price of nozzle tip in £

T_{oper_Nozz} = Expected operating time of nozzle tip in hours

C_{exh_filt} = Price of exhaust filter in £

$T_{oper\_exh\_filt}$ = Operating time of exhaust filter in hours

C_{focus_lens} = Unit cost of focus lens in £

$T_{oper\_focus\_lens}$ = Expected operating hours of focus lens

C_{lab_maint} = Labour maintenance cost in £/hr

T_{maint} = Maintenance time in hours

$T_{machine\_work}$ = Expected available machine operating time before breakdown in hours

n = Total number of laser welds

d = Length of laser weld in mm, and

v = Speed of laser in mm/hr.

Part holding cost:

In laser welding, energy is consumed to hold the parts, and depends upon the holding equipment power, the part holding time and holding equipment efficiency. The following equation can be used to measure the part holding cost.

$$C_{hold} = C_p \times \frac{P_{equip}}{\eta_{hold} \times 3600} \times (n\left(\frac{d}{v}\right) + (n-1)(\frac{d_{weld\_dist}}{v_{rob}}) \qquad (5\text{-}15)$$

where:

C_{hold} = Part holding cost in £

C_p = Unit energy price in £/KWh

P_{equip} = Power of holding equipment in KW

η_{hold} = Holding equipment efficiency

n = Total number of laser welds

d = Length of laser weld in mm, and

v = Speed of laser in mm/sec

Robot movement cost:

Energy in laser welding is also consumed in the movement of the robot carrying the laser beam, and depends upon robot speed, distance covered by the robot, i.e. total laser welds' length, and equipment efficiency. Equations (5-16 and 5-17) can be used to estimate the robot movement cost.

$$C_{rob\_move} = C_p \times \frac{P_{rob} \times d_{\sum weld\_dist}}{\eta_{rob} \times 3600 \times v} \times n \qquad (5\text{-}16)$$

where

$$d_{\sum weld\_dist} = \sum_i^n d_i \qquad (5\text{-}17)$$

where:

C_{rob_move} = Robot movement cost in £

C_p = Unit energy price in £/KWh

P_{rob} = Power of robot in KW

η_{rob} = Robot efficiency

$d_{\sum weld\_dist}$ = Total distance covered by the robot

d_i = Distance between each laser weld, and

v = Velocity of robot in mm/sec

Setup and part removal cost:

Setup and part removal times are entirely dependent on the jig and fixtures and vary from case to case. These times need to be calculated for precise cost estimation. The times for different jigs and fixtures can be calculated and placed in the database to obtain a more accurate cost estimation.

5.7.2 Cost modelling of machining processes

Machining is a manufacturing process which aims to remove material from a workpiece with the help of a sharp cutting tool to achieve the desired geometry. There are a large number of machining processes such as turning, drilling, milling, shaping, planing etc. This research is concerned with identifying the cost associated with the milling, turning and drilling processes. The time and cost of these machining processes are explained in the sections below. It is noteworthy that a machining cost estimation was initially not the part of the research. However, as the research progressed, it was realised that there is a need to validate research with other manufacturing processes. Therefore, a cost model for the machining process was developed and linked to join with the cost estimation model. The case study in Chapter 6 has also been provided to show the machining process cost estimation.

Time analysis of machining processes

Turning and boring

Turning is the manufacturing process in which the part is rotated against a single point cutting tool to achieve the desire cylindrical shape, whereas, boring is the processes of providing a shaped bore and internal groves (Black et al., 1996). The turning can be simple turning, step turning, or taper turning. The machining time of turning and boring can be estimated by using the following equation (Scallan, 2003).

$$T = \frac{L+A}{f_r N} \qquad (5\text{-}18)$$

where:

T = Machining time in $\min$

L = Length of workpiece in mm

A = Machining allowance in mm

f_r = Feed rate in mm/rev, and

N = Revolution of workpiece in $rev/\min$

Facing and parting off

Facing and parting off are considered under the umbrella of turning operations (Black et al., 1996). Facing is the machining process in which the edge of the workpiece is machined by rotating against a cutting tool. Parting off is the machining process in which the edge of the workpiece is machined until it is parted off into two pieces. Facing and turning time can be estimated through the following equation (Scallan, 2003).

$$T = \frac{(\frac{D}{2})+A}{f_r N} \qquad (5\text{-}19)$$

where:

T = Machining time in $\min$

D = Diameter of workpiece in mm

A = Machining allowance in mm

f_r= Feed rate in mm/rev, and

N = Revolution of workpiece in $\mathrm{rev/min}$.

Milling and drilling

In the case of milling and drilling, the rotating cutting tool is fed across the workpiece to achieve the desired geometrical shape. The milling and drilling time can be estimated through the following equation (Scallan, 2003).

$$\mathrm{T} = \frac{\mathrm{L+2A}}{\mathrm{f_r N}} \quad (5\text{-}20)$$

where:

T = Machining time in min

L = Length of cut in mm

A = Machining allowance for tool approach and exit in mm,

$\mathrm{f_r}$ = Feed rate in $\mathrm{mm/rev}$, and

N = Spindle speed in $\mathrm{rev/min}$

In equation 5-20, if the diameter of cutting tool "D" is greater than depth of cut “d”, then the machining allowance "A" can be estimated with the following relation (Scallan, 2003).

$$\mathrm{A} = \sqrt{Dd} \quad (5\text{-}21)$$

Machining cost estimation

Once the machining time is identified, the machining cost is estimated by relating the cost to each machining cost driver. The machining costs drivers employed in this research are labour cost, material cost, machine power consumption cost, setup and part removal cost. These cost drivers have been identified for initial rough cost estimation. Precise cost can be estimated by populating more cost drivers.

Material and labour costs:

Equations 5-6 and 5-7, as explained earlier, can be used to estimate the material and labour costs respectively.

Power consumption cost:

The machine power consumption cost can be identified through the following relation

$$C_{pow} = C_p \times \frac{P_{mach}}{\eta_{mach} \times 60} \times T \quad (5\text{-}22)$$

where:

C_{pow} = Power consumption cost of turning, milling or drilling machine in £

C_p = Unit energy price in £/KWh

P_{mech} = Power of machine in KW

η_{mach} = Machine efficiency

T = Turning, boring, milling, drilling, facing or parting off time in min.

Setup and part removal cost:

In the case of machining, setup and part removal times were calculated by identifying the times with jigs and fixtures.

5.8 Summary

This chapter presents the cost modelling system to support lean product and process development. It initially describes the proposed cost estimation process for lean product and process development followed by the architecture of the developed system. The developed system constitutes three enablers of lean product and process development, namely set-based concurrent engineering, poka-yoke and knowledge-based engineering, all of which have been clarified with detailed explanations and suitable examples. Within set-based concurrent engineering, in addition to laying down its process, a quantification mechanism has been provided which guides the elimination of the weaker solution. Poka-yoke not only helps to eliminate three kinds of mistakes in product development, i.e. mistakes elimination in manufacturability identification, mistakes elimination in product design and mistakes elimination in process parameters selection, the exclusion of these mistakes in product development supports decreasing the cost of product. In the case of knowledge-based engineering, a systematic knowledge life cycle approach has been followed during the development of the system. The critical stage of the knowledge life cycle is the dynamic knowledge capture stage, where the facility has been provided to capture the cost of new products dynamically to utilise in future product cost estimation.

The system's six modules have been explained which follow an organised process to estimate the cost of product. The chapter also described the system scenario within the conceptual and detailed design stages. In conceptual design, the system helps the designer to take decisions by comparing alternative materials, alternative manufacturing processes and alternative designs; in the detailed design stage, the system guides the assessment of design mistakes and estimates the manufacturing and total cost of product along with other values. Finally a cost modelling for the joining and machining processes has been reported.

In the next chapter, the author describes the validation of the developed system through case studies and experts' opinion.

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6 VALIDATION OF DEVELOPED SYSTEM

6.1 Introduction

In Chapter 5, the components, modules and scenario of the cost modelling system to support lean product and process development have been discussed in detail. The cost modelling of the joining and machining processes was also described.

The purpose of this chapter is to describe the validation of the developed system through case studies from the automotive and petroleum industries, as well as qualitative validation with experts from different fields. The intention of validation through case studies and experts is to ensure the quality and strength of the research. There are four parts to this chapter, as illustrated in Figure 6-1.

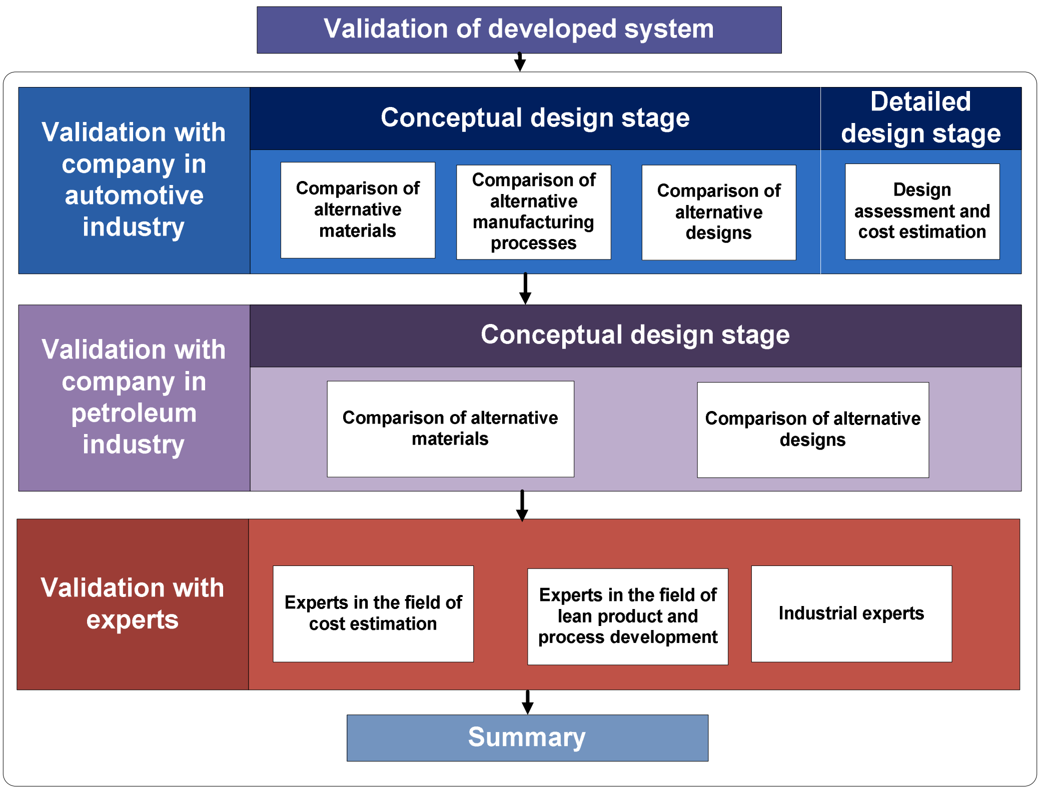

Figure 6-1: Outline of Chapter 6

6.2 Validation through Case Studies

The system has been validated through two case studies from different industries. The aim of validating the developed system from different industries is to demonstrate and confirm that the research has broad applications in different industrial sectors. The validation is explained in the sections below.

6.2.1 Case study 1: Car seat

This case study is related to a company in the automotive industry. The company background, product development process in the company, problems faced by the company, the aims of analysing the case study and the validation are all explained.

6.2.1.1 Collaborator Company

The system has been validated through a case study with one of the industrial partners involved in the LeanPPD project, which is a well-known company in Europe. The main business of the company is the development and manufacture of backrest steel structures of seats for vehicles (Figure 6-2). The company has its development and manufacturing facilities in Poland, Germany and China. The company initiated manufacturing in 1999 and produces approximately nine million seat structures annually. Volkswagen, Audi, Skoda and Porsche are the major customers of the collaborator company. The company has manufactured seat structures for the Passat and Polo.

6.2.1.2 Challenges faced by the company

The product development process in the company is shown in Figure 6-3. Within the quotation acceptance stage, the company has to spend a considerable amount of time with the customer (OEM in this case) to develop a conceptual design before quotation acceptance. In addition, time is spent on crash test and quotation development. The company considers this concept development stage as a crucial stage in their product development process, and places its best efforts to win a project.

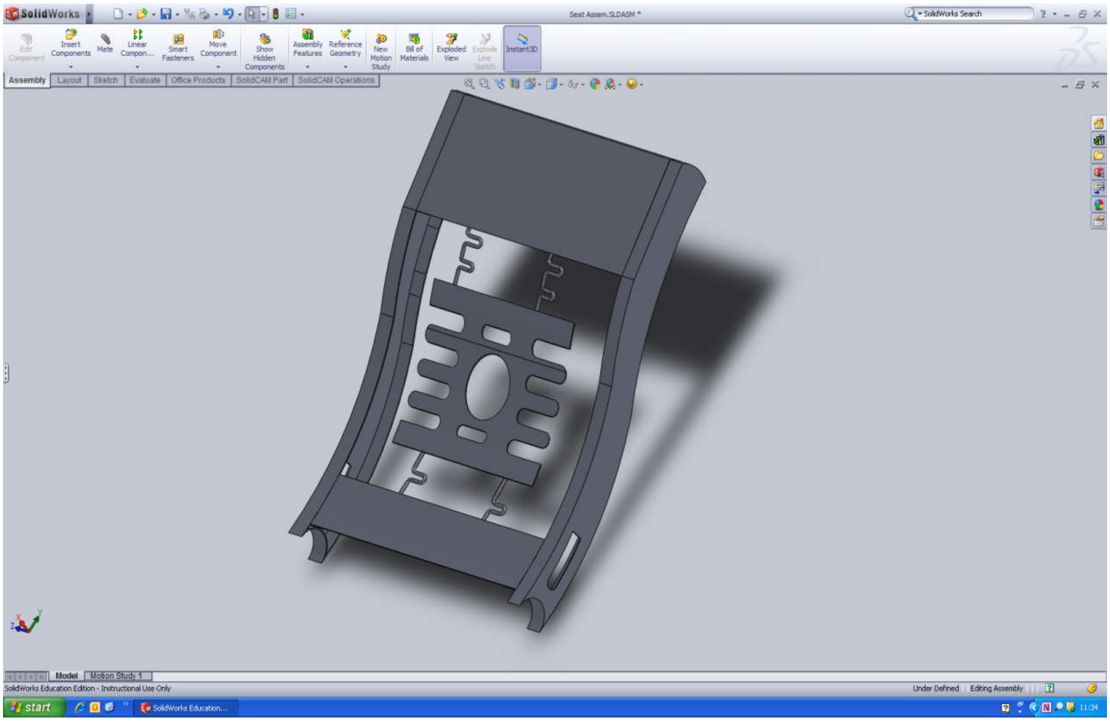

Figure 6-2: An example of back seat rest developed by the company

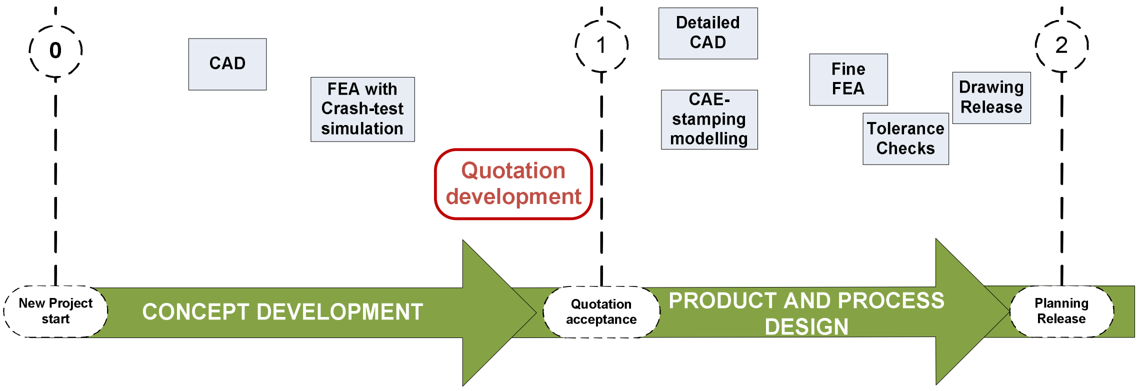

Figure 6-3: Product development process in the case study company

After a detailed analysis of the company's procedure, it was identified that the company had an unformalised cost estimation method. They mostly rely on expert judgement to develop the quotation. The company was looking to employ a standard process that would support the development team in general and designers in particular to take customer satisfied decisions during the product development conceptual design stage 1 (See Figure 6-3). Since the majority of the decisions were based on the company's values without any customer involvement which mostly resulted in customer dissatisfaction, it was the company's wish to incorporate customer values into the system in order to enhance customer satisfaction. The company was interested in investigating new materials for seat manufacturing. The company wanted to improve the strength of the material while keeping the weight as low as possible. The company was also facing challenges due to incorrect product design. Resistance spot welding (RSW) is a key process to join seat assemblies; however, the designers assigned the wrong number of spots from 50% to 80% of components. The wrong design caused a huge impact on product cost, production volume and required weight. Therefore, the company was facing pressure to eliminate these mistakes at the early product development stage. In the search for cost reduction, the company was looking to change the manufacturing process. Although mitigation from resistance spot welding to laser welding was a good solution, the higher initial cost was a problem for the company. The company was looking to compare the two manufacturing processes (resistance spot welding and laser welding) in order to find the best solution that would fulfil their requirement and provide a good return on investment.

6.2.1.3 Purposes of analysing the case study

The case study has been analysed to enable the system validation. Therefore, the main purposes of the present case study are to :

1. Compare new materials suitable for seat manufacturing in order to address high strength, lower weight issues with acceptable cost.
2. Compare alternative manufacturing processes in order to find the best solution for the customer.
3. Support designers in the identification of the best seat design among several designs alternatives.
4. Assess the design at the detailed design stage for capturing design mistakes, and to estimate the total cost of product along with other values.

After summing up all the purposes (Figure 6-4), purposes 1, 2 and 3 are related to the conceptual design stage, whereas purpose 4 is concerned with the detailed design stage.

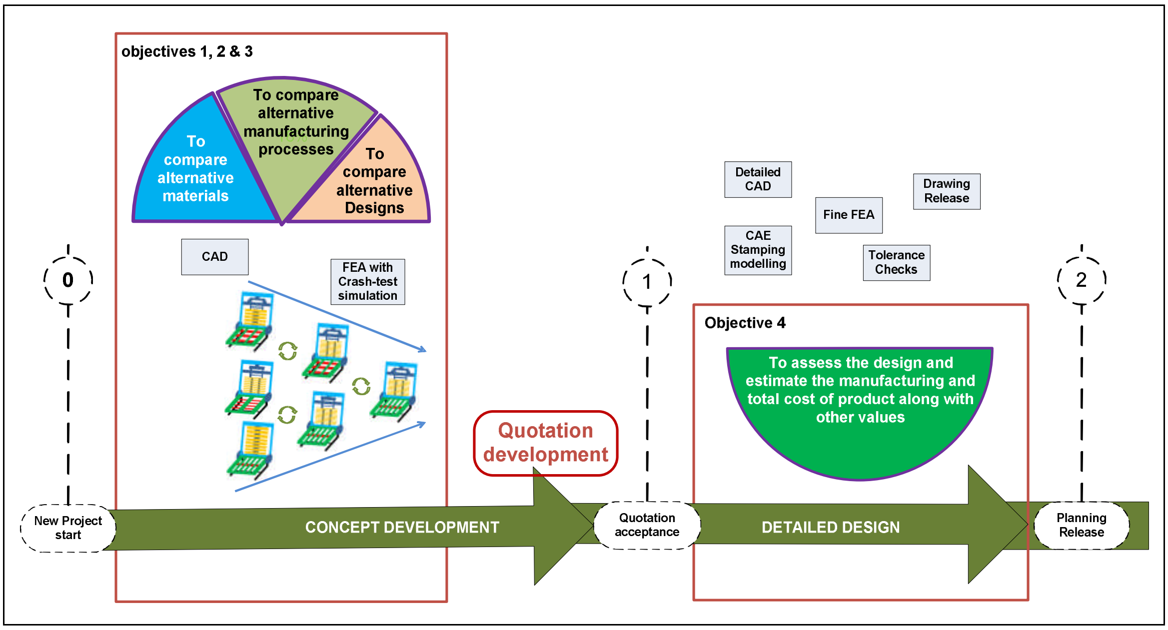

Figure 6-4: Case study aims in conjunction with the product development process in the case study company

The seat assembly selected for the validation is illustrated in Figure 6-5. It is a frame with eight components that assemble together as presented in Figure 6-6. Components information has been provided in Table 6-1.

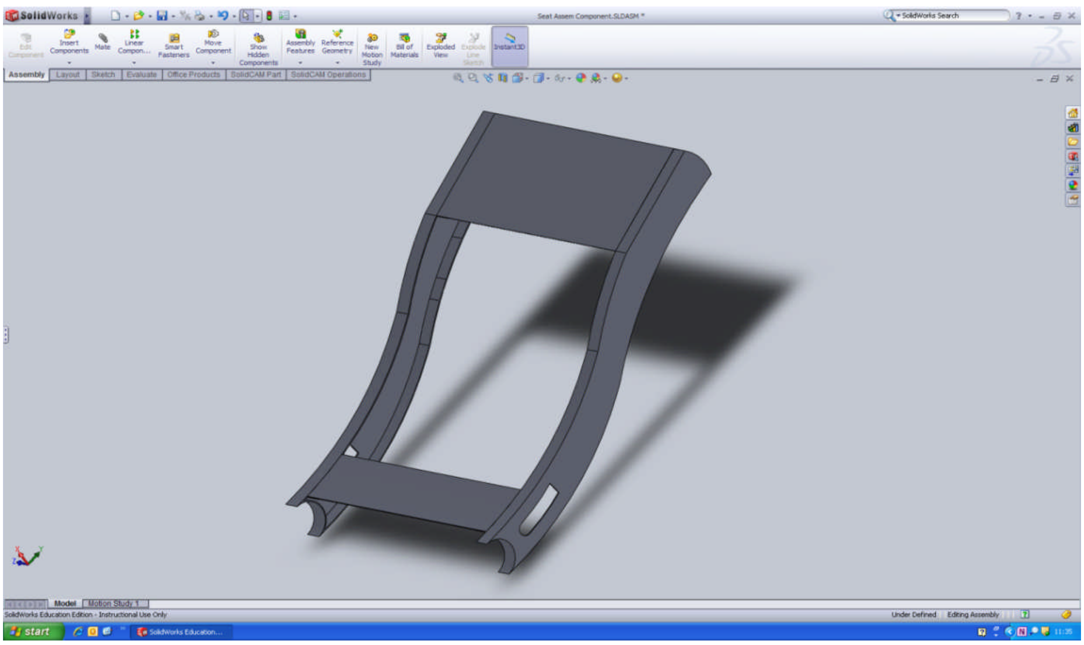

Figure 6-5: Seat structure selected for case study validation

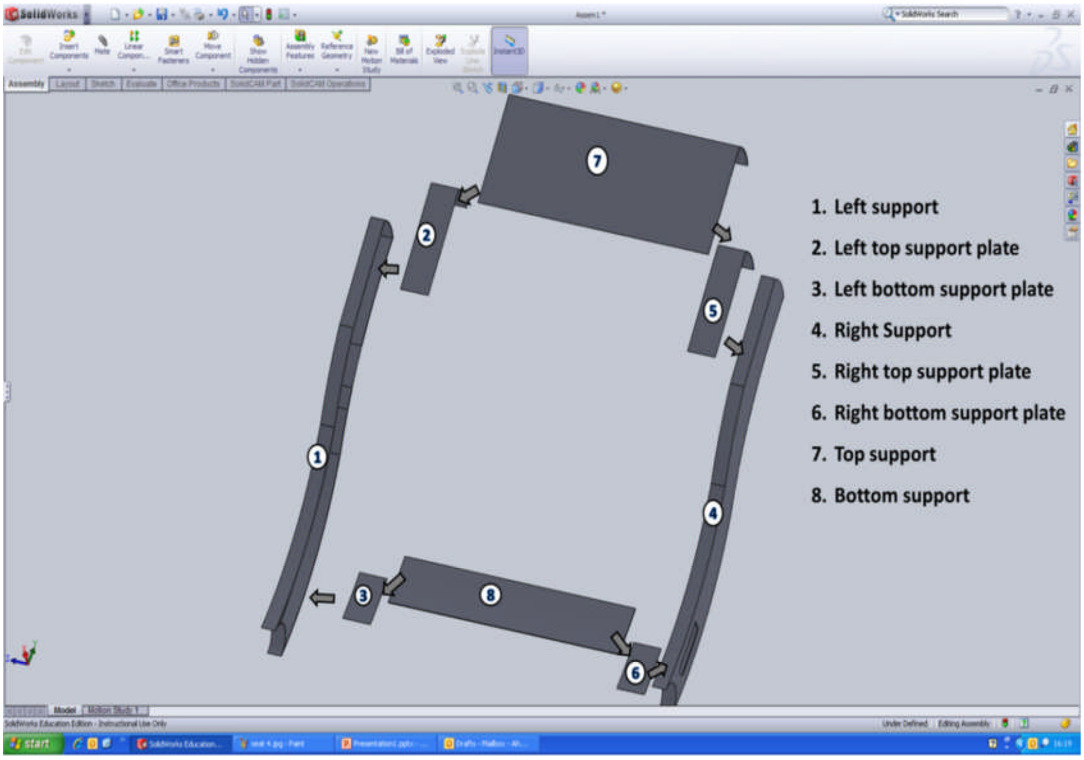

Figure 6-6: The assembly of components (Seat structure)

Table 6-1: The components of seat assembly

Component number	Name of component	Quantity
1	Left support	1
2	Left top support plate	1
3	Left bottom support plate	1
4	Right Support	1
5	Right top support plate	1
6	Right bottom support plate	1
7	Top support	1
8	Bottom support	1

Purpose 1: Compare new materials suitable for seat manufacturing in order to address high strength and lower weight issues with acceptable cost

Since the company has to improve the product value for providing a better customer satisfied solution, as compared to their competitors, the first purpose of case study was, therefore, to identify the alternative material solutions for a given seat design. Currently the seat is composed of steel which is not preferred due to its weight. The customer required the weight to be reduced but still to have an acceptable crash strength. In addition, one of the design parameters in car design is the high temperature in the case of a crash. Although low carbon steel is the best design option with respect to crash strength and high service temperature, its higher weight has a number of consequences on car design. Therefore, the company has investigated aluminium alloy as a suitable alternative. Both materials were compared with the developed system. The produced results helped the designers to take the decisions in time. The validation process is explained below.

In the validation process, the system scenario explained in Chapter 5 (Figure 5-10) was followed. The first step was identification of values, value preferences and targets. The company representative was asked to provide both the company and customer values. The company was interested in seven values: product cost, product manufacturing time, production volume, tensile strength, product weight, thermal conductivity and maximum service temperature. In addition, the customer and company values were also discriminated to identify their owner. It is essential to discriminate these values because the product development team may use them at the time of negotiation. The value preferences and their targets are presented in Table 6-2. The values, value preferences and their respective targets input into the system are shown in Figure 6-7. After this, other necessary information such as the manufacturing process, alternative materials and geometric features were input into the system as illustrated in Figure 6-8. It is important to note that the CAD model geometric features information was input into the system from the CAD-Excel-SQL interface (see Figure 6-8). Since it was the conceptual design stage, therefore the information such as length, width and thickness of the welding assembly was extracted from the CAD file. Other information such as edge distance, spot spacing and number of spots is generated automatically through the rules embedded within the system.

Table 6-2: Values, value preferences and targets

Value	Company value	Customer Value	Preferences	Targets			
				Unacceptable x	Marginal ▲	Acceptable ●	Excellent ☺
Product cost (£)	Yes	Yes	8	Greater than £90	Less than £90	10% Decrease	20% Decrease
Product manufacturing time (hours)	Yes	No	7	Greater than 1.0Hour	Less than 1.0Hour	20% Decrease	40% Decrease
Production volume (Units per day)	Yes	No	7	Less than 8 Units per day	Greater than 8 Units per day	20% Increase	40% Increase
Tensile strength (MPa)	Yes	Yes	8	Less than 50MPa	Greater than 50MPa	15% Increase	30% Increase
Product weight (Kg)	Yes	Yes	9	Greater than 7.0Kg	Less than 7.0Kg	10% Decrease	20% Decrease
Product thermal conductivity (W/mK)	Yes	Yes	6	Less than 45W/mK	Greater than 45W/mK	25% Increase	50% Increase
Product maximum service temperature (^{o}C)	Yes	Yes	7	Less than 100^{0}C	Greater than 100^{0}C	25% Increase	50% Increase

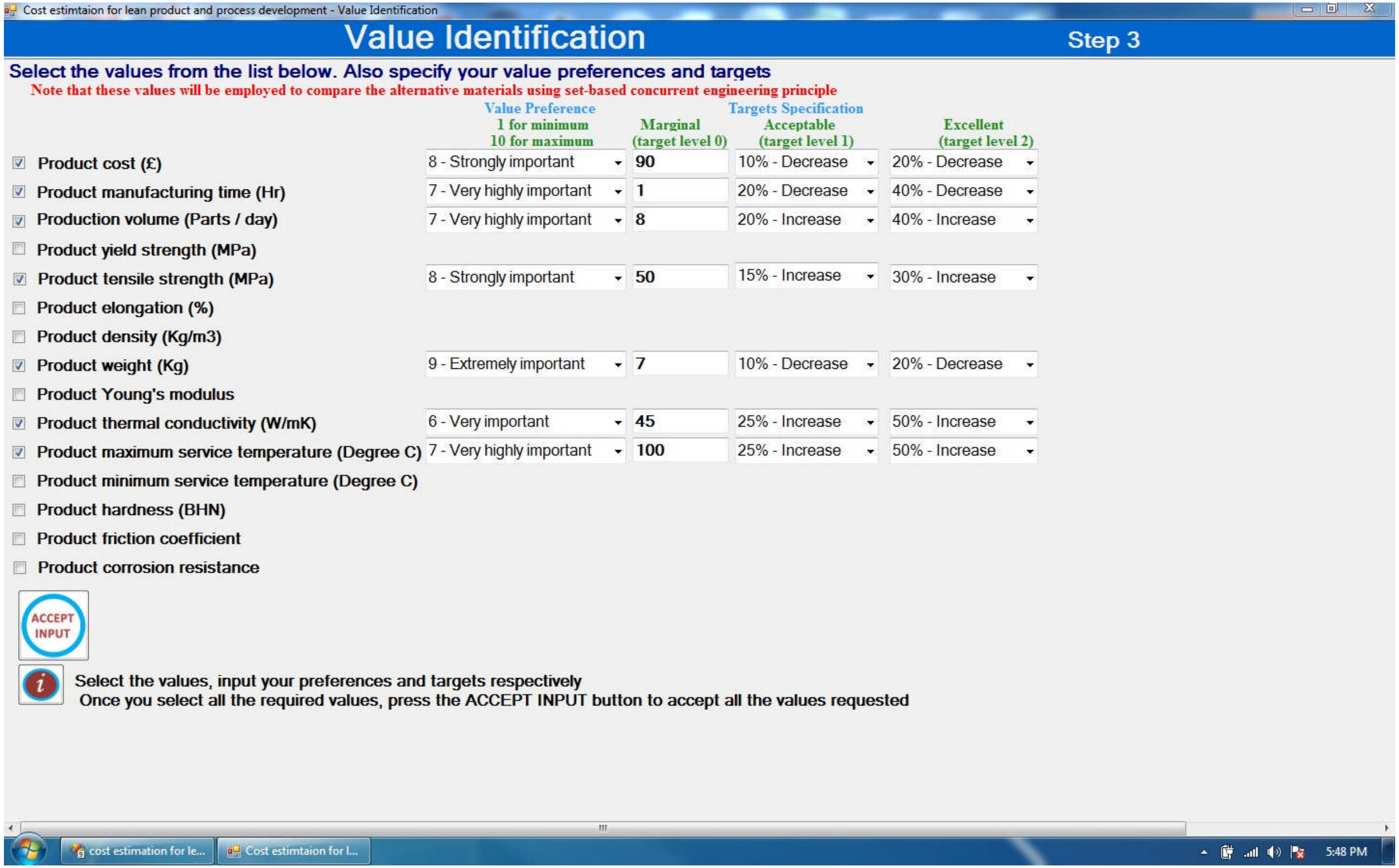

Figure 6-7: Values, their preferences and targets input method in developed system

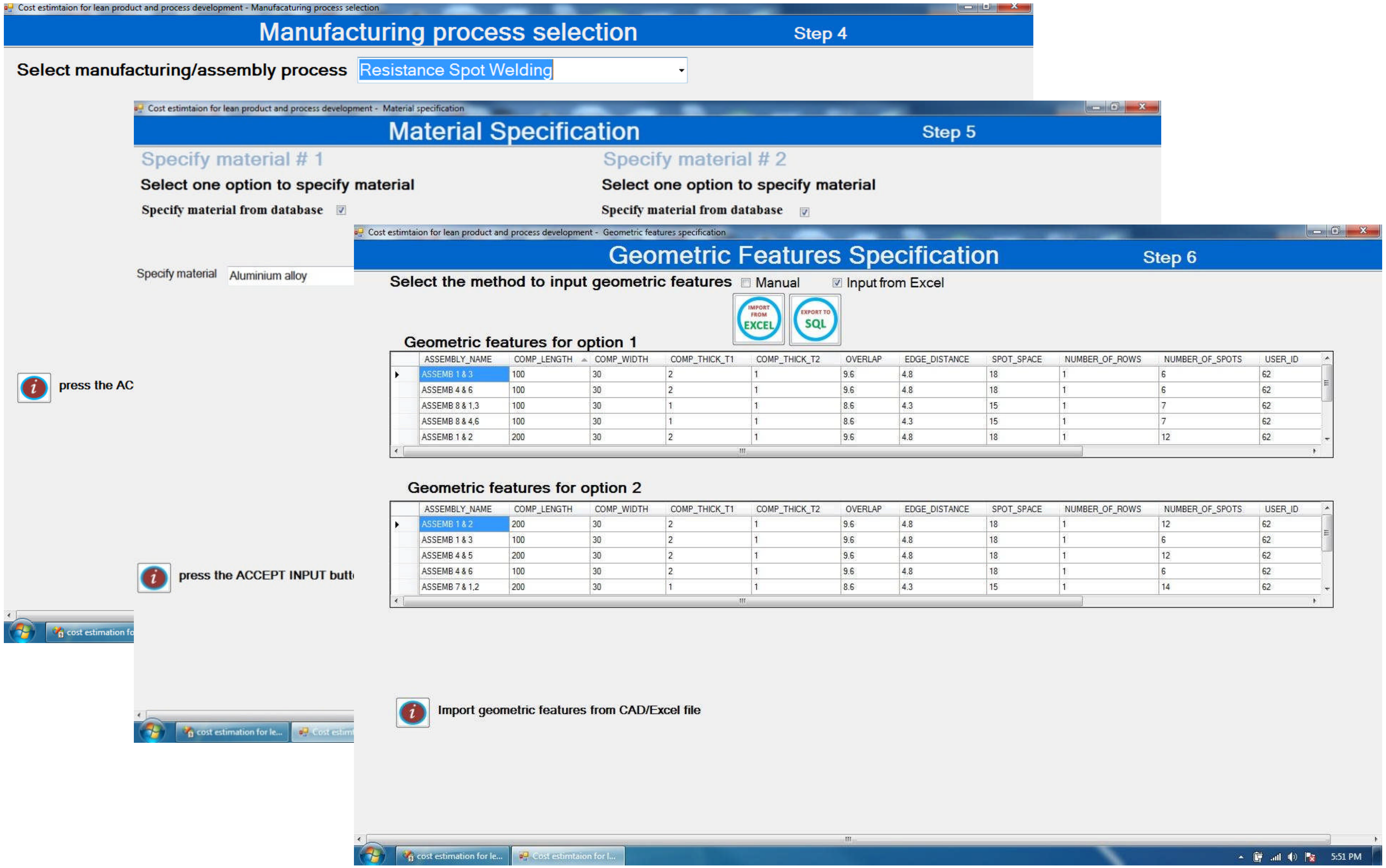

Figure 6-8: Snapshot of manufacturing processes, material and geometric features information input into the system

Once the required information was input into the system, the system applied the manufacturability assessment rules to find the materials' manufacturability, machines' availability, and machines' manufacturing capability as shown in Figure 6-9. When the product manufacturing assessment was deemed to be satisfactory, the system generated detailed estimates for manufacturing time and cost of each assembly (Figure 6-10). Note that this comprehensive results representation was added into the system to investigate the higher cost carrying components. The designer was allowed to avoid this option if s/he was interested in viewing the summary of results (Figure 6-11). After viewing the results, the designer was able to converge the solution with two options, i.e. quantification method and trade-off values. The quantification method option includes summary of results, matrix for communicating alternatives, quantification of individual value and total quantification number, as shown in Figure 6-12. The trade-off values option on the other hand comprises the graphs containing product cost versus production volume, and product cost versus product weight (Figure 6-13).

To understand the quantification method more clearly, matrix for communicating alternatives and quantification numbers have been presented in Table 6-3 and equation 6-1 respectively.

Table 6-3: Matrix for communicating alternatives

Material	Aluminium Alloy	Low carbon steel
Product cost (£)	▲	●
Product manufacturing time (hours)	☺	●
Production volume (Units per day)	☺	●
Tensile strength (MPa)	☺	☺
Product weight (Kg)	☺	▲
Product thermal conductivity (W/mK)	☺	▲
Maximum service temperature (^{o}C)	●	☺

Legend: Excellent (☺) =10, Acceptable (●) = 7, Marginal (▲) = 3, Unacceptable (x) = 0

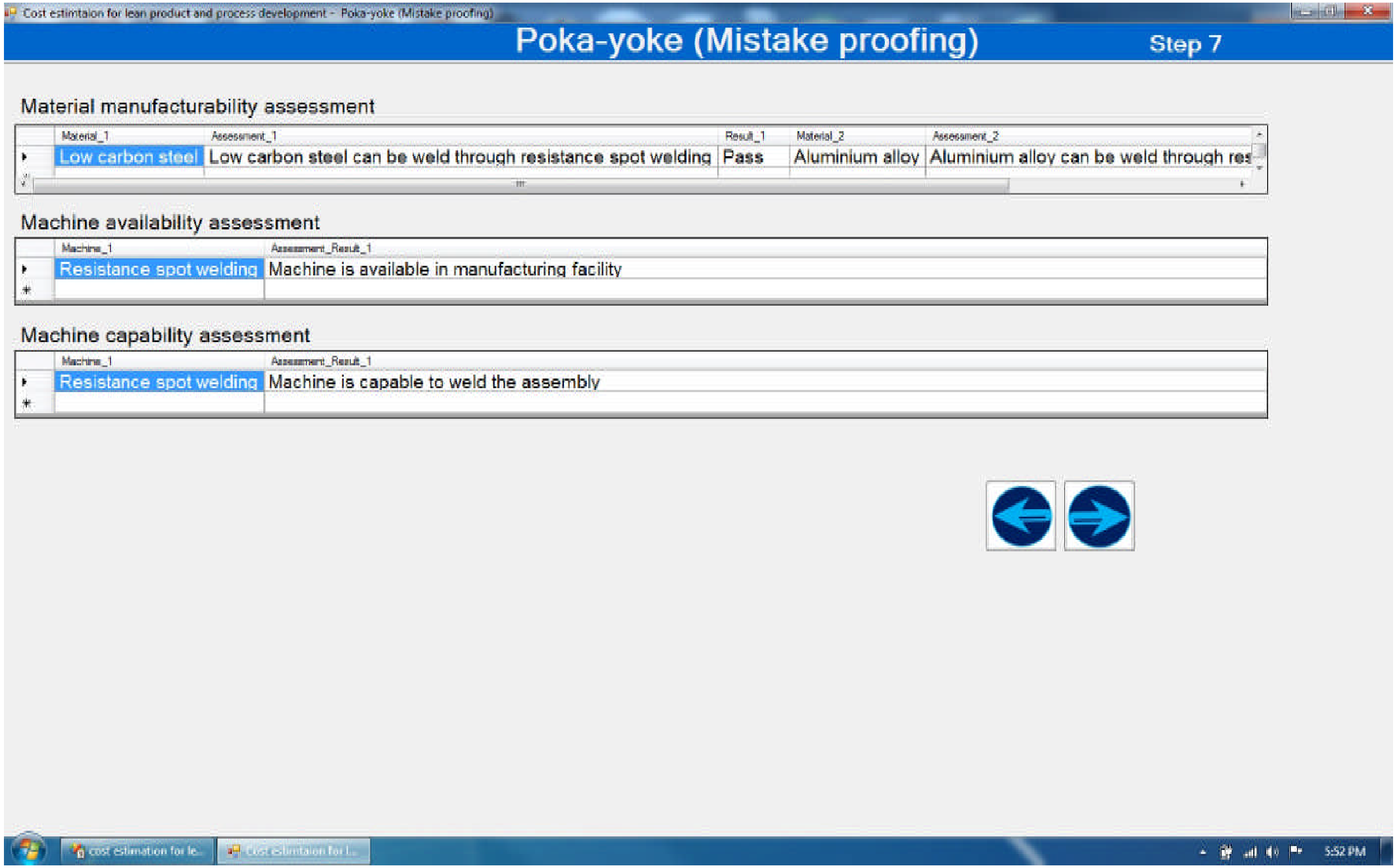

Figure 6-9: Application of poka-yoke for material manufacturability, machine availability, and machine capability assessment

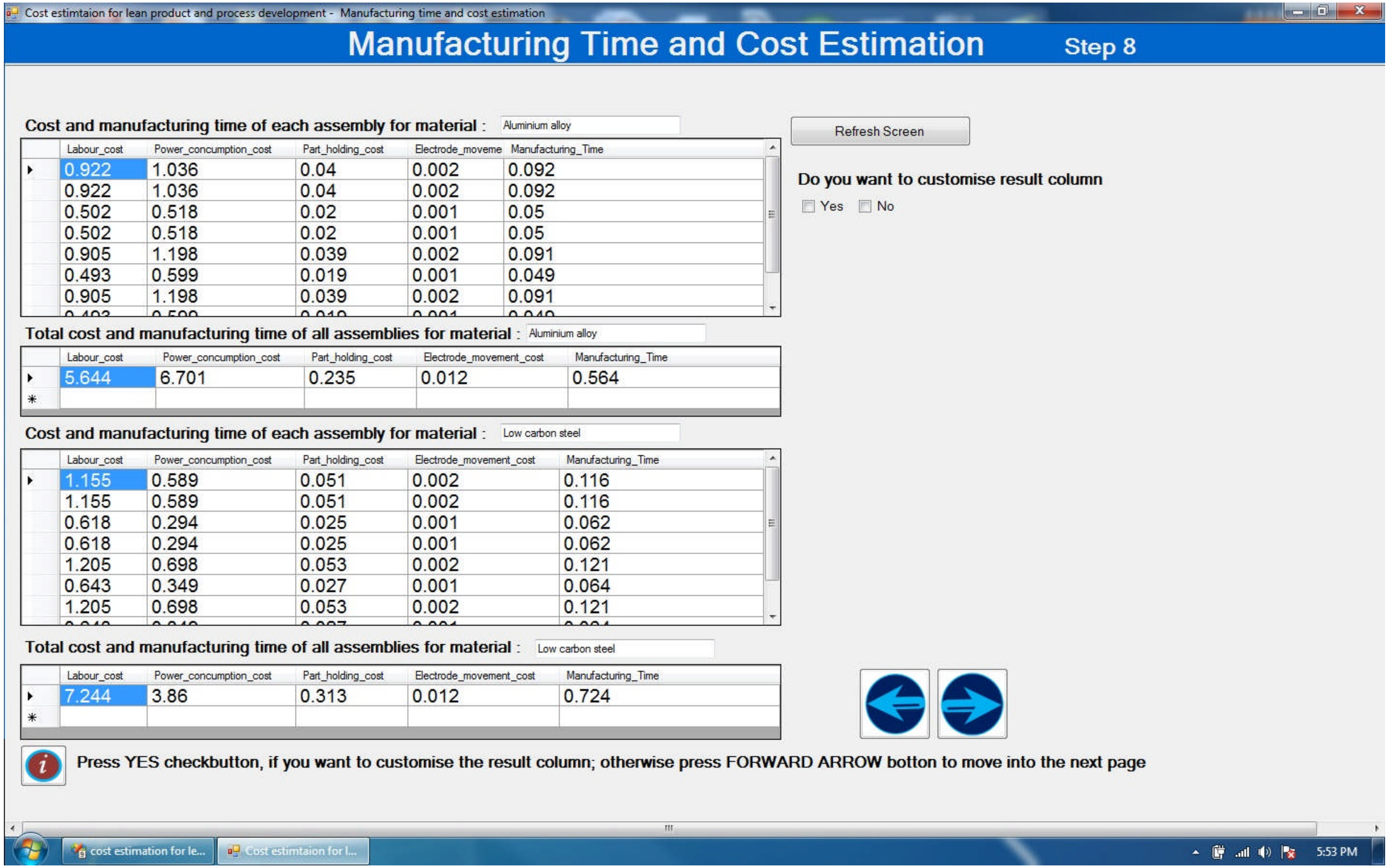

Figure 6-10: Detailed results of manufacturing time and cost estimation of each assembly

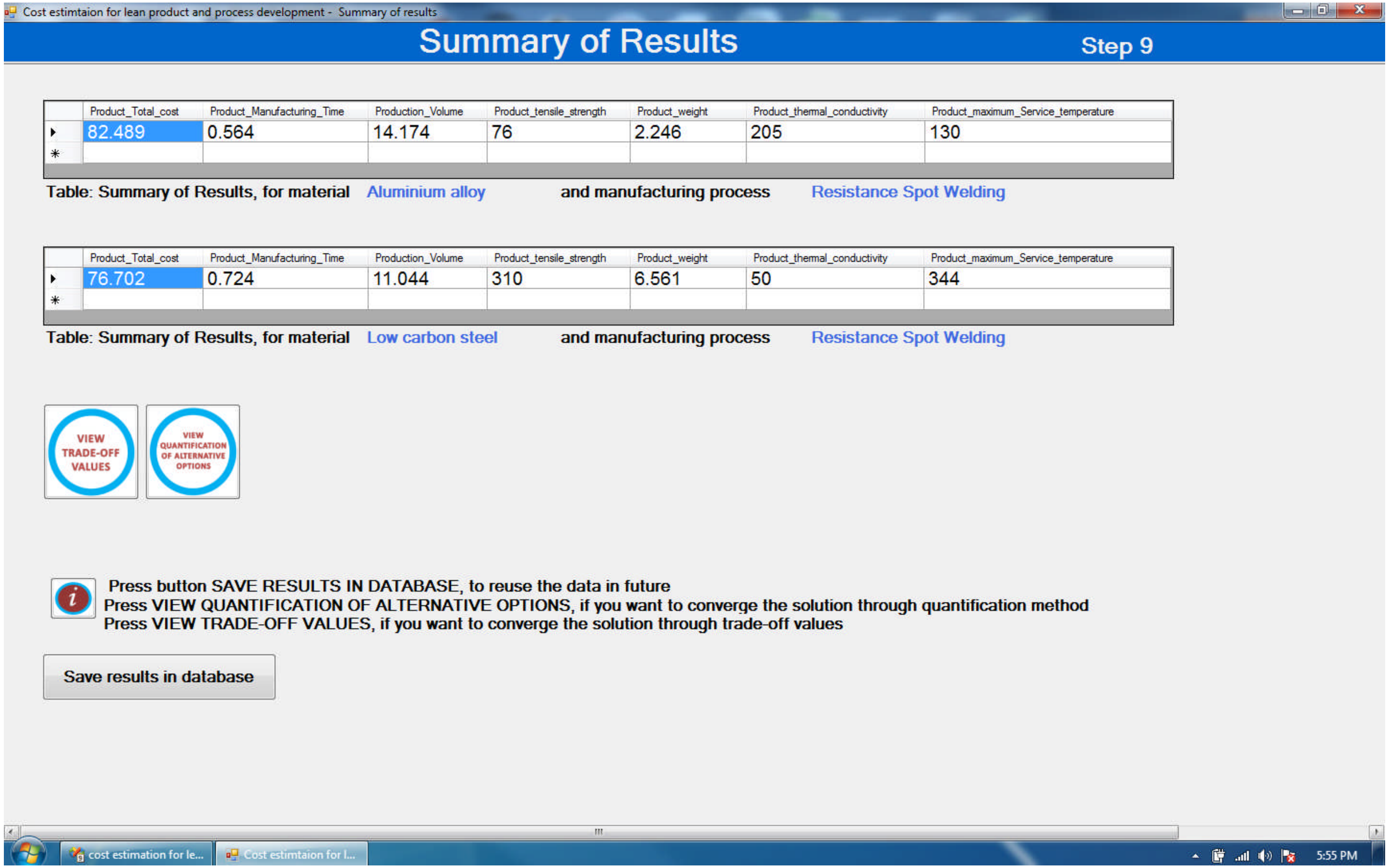

Figure 6-11: Summary of results

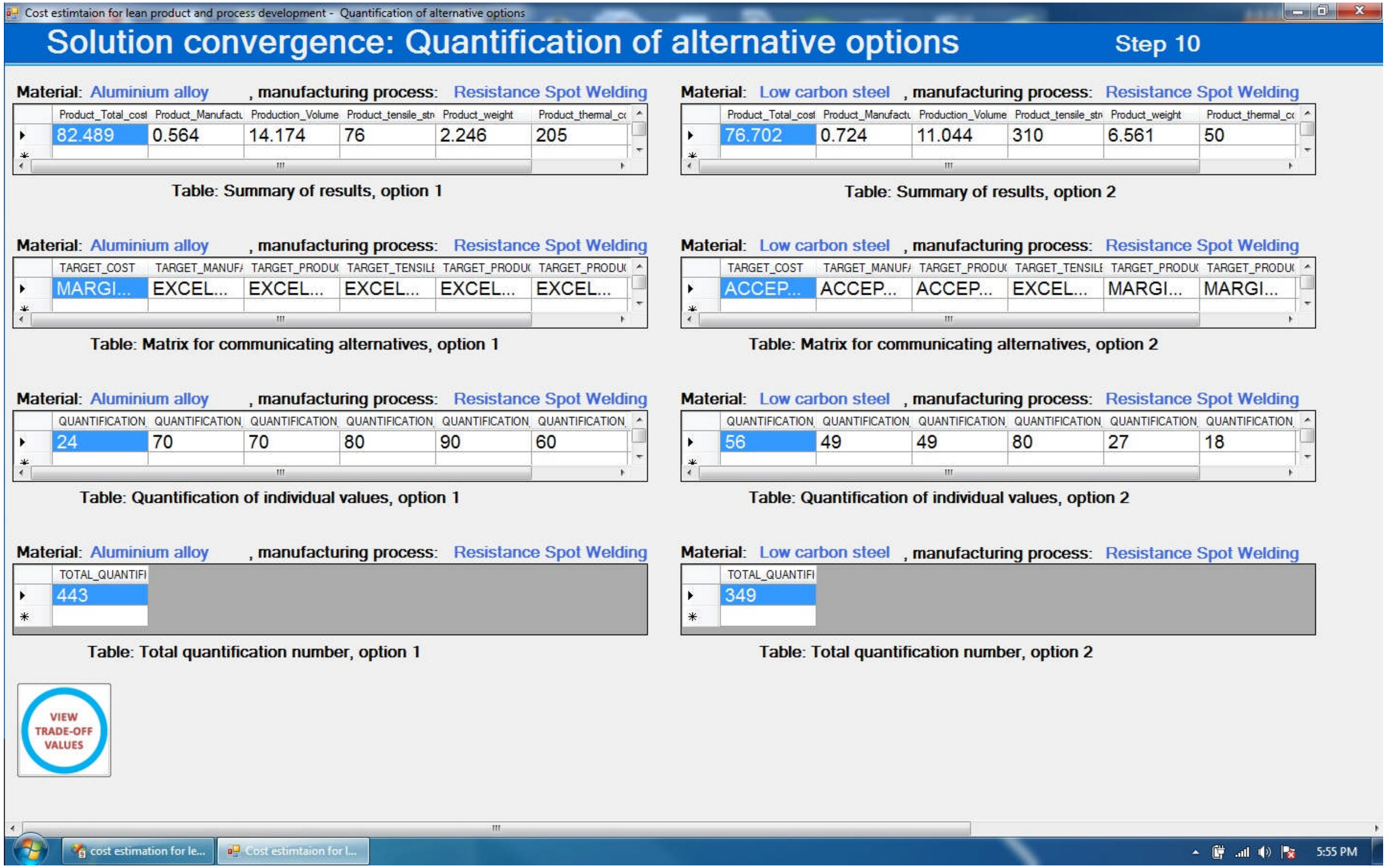

Figure 6-12: Solution convergence: quantification of alternative options

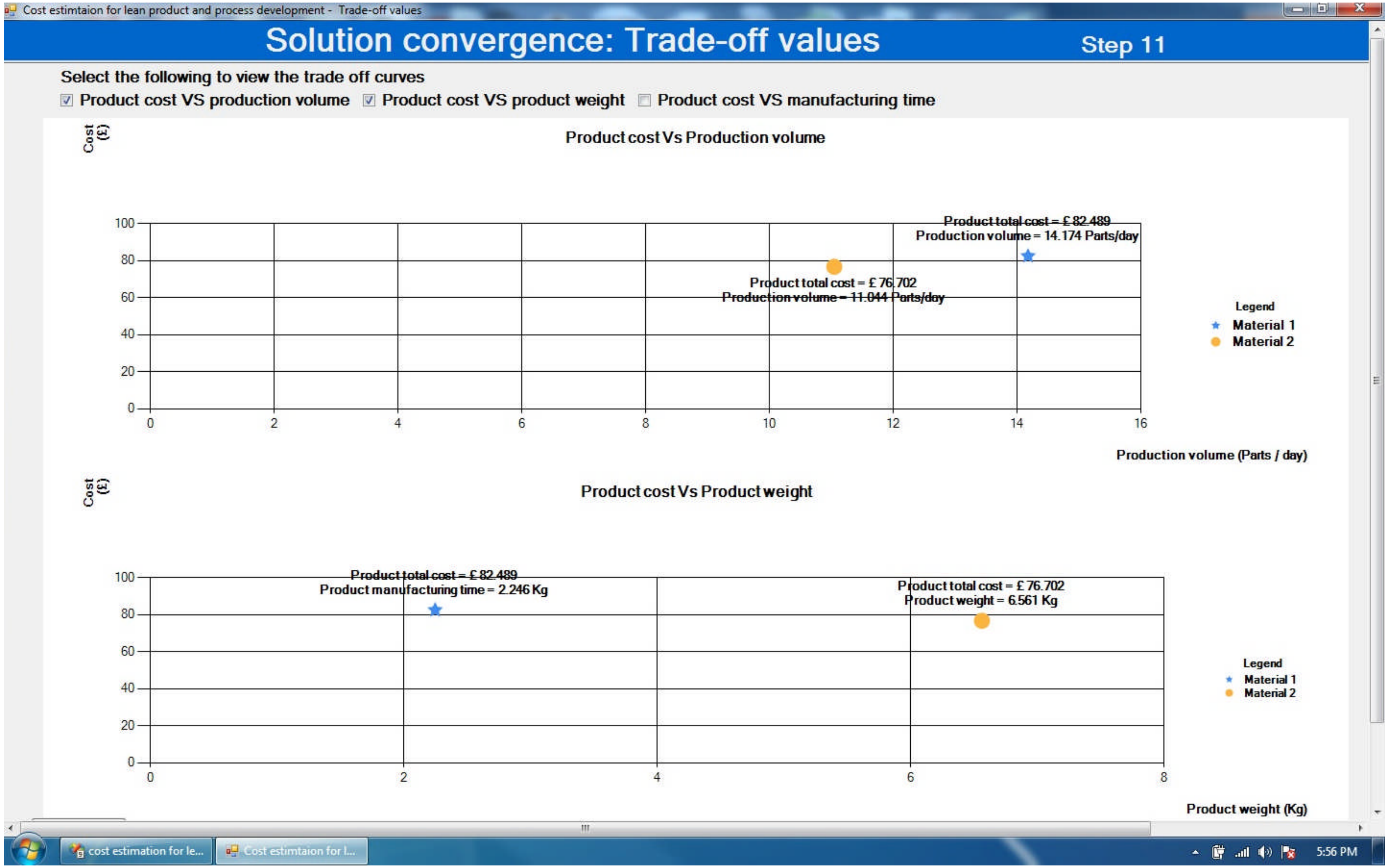

Figure 6-13: Solution convergence: trade off values

$$\begin{bmatrix} 3 & 10 & 10 & 10 & 10 & 10 & 7 \\ 7 & 7 & 7 & 10 & 3 & 3 & 10 \end{bmatrix} \times \begin{bmatrix} 8 \\ 7 \\ 7 \\ 8 \\ 9 \\ 6 \\ 7 \end{bmatrix} = \begin{bmatrix} 443 \\ 349 \end{bmatrix} = \begin{bmatrix} \text{Aluminum alloy} \\ \text{Low carbon steel} \end{bmatrix} \tag{6-1}$$

Since the low carbon steel has the lowest quantification number (349), therefore it was eliminated. Meanwhile the aluminium alloy is the only remaining solution; it can therefore be selected as the best solution.

Purpose 2: Compare alternative manufacturing processes in order to find the best solution for the customer

To enhance the value of product, the second option available to the company was the identification of suitable manufacturing processes. As explained earlier, the product was welded through resistance spot welding. Laser welding was another preferable option that the company was wishing to explore. At validation time, the company had no laser welding facility, but it was planning to invest in purchasing a laser welding machine. To validate this aim, the seat assembly provided in Figure 6-5 was selected. Since the company had no laser welding facility, it was, therefore, decided to keep the design the same as for resistance spot welding. However, each spot was proposed to change to 10mm laser welding. In addition, since aluminium alloy was the best material option in the previous estimation process, therefore it was chosen in this case. The validation process is explained below.

The validation process commenced with the values identification. The values, their preferences and targets employed in the validation of alternative materials (Table 6-2) were kept the same. Once the designer had input values, alternative manufacturing processes, material and geometric features information, the system applied the manufacturability assessment rules to find the materials' manufacturability, machines' availability, and machines' manufacturing capability. Since the company had no laser welding machine, the system prompted a message of laser machine non availability. The user ignored this message and attempted to generate the estimate. The summary of results has been provided in Figure 6-14. Solution convergences through quantification of alternative options and trade-off values are also provided in Figure 6-15 and Figure 6-16 respectively. In addition, a matrix for communicating alternatives and quantification number is described in Table 6-4 and equation 6-2 respectively.

Table 6-4: Matrix for communicating alternatives

Manufacturing process	Resistance spot welding	Laser welding
Product cost (£)	▲	☺
Product manufacturing time (hours)	☺	☺
Production volume (Units per day)	☺	☺
Tensile strength (MPa)	☺	☺
Product weight (Kg)	☺	☺
Product thermal conductivity (W/mK)	☺	☺
Maximum service temperature (^oC)	●	●

Legend: Excellent-☺=10, Acceptable-● = 7, Marginal-▲ = 3, Unacceptable-x = 0

$$\begin{bmatrix} 3 & 10 & 10 & 10 & 10 & 10 & 7 \\ 10 & 10 & 10 & 10 & 10 & 10 & 7 \end{bmatrix} \times \begin{bmatrix} 8 \\ 7 \\ 7 \\ 8 \\ 9 \\ 6 \\ 7 \end{bmatrix} = \begin{bmatrix} 443 \\ 499 \end{bmatrix} = \begin{bmatrix} \text{Resistance spot welding} \\ \text{Laser welding} \end{bmatrix} \quad (6\text{-}2)$$

The results indicate that laser welding is the best option for the given values and targets.

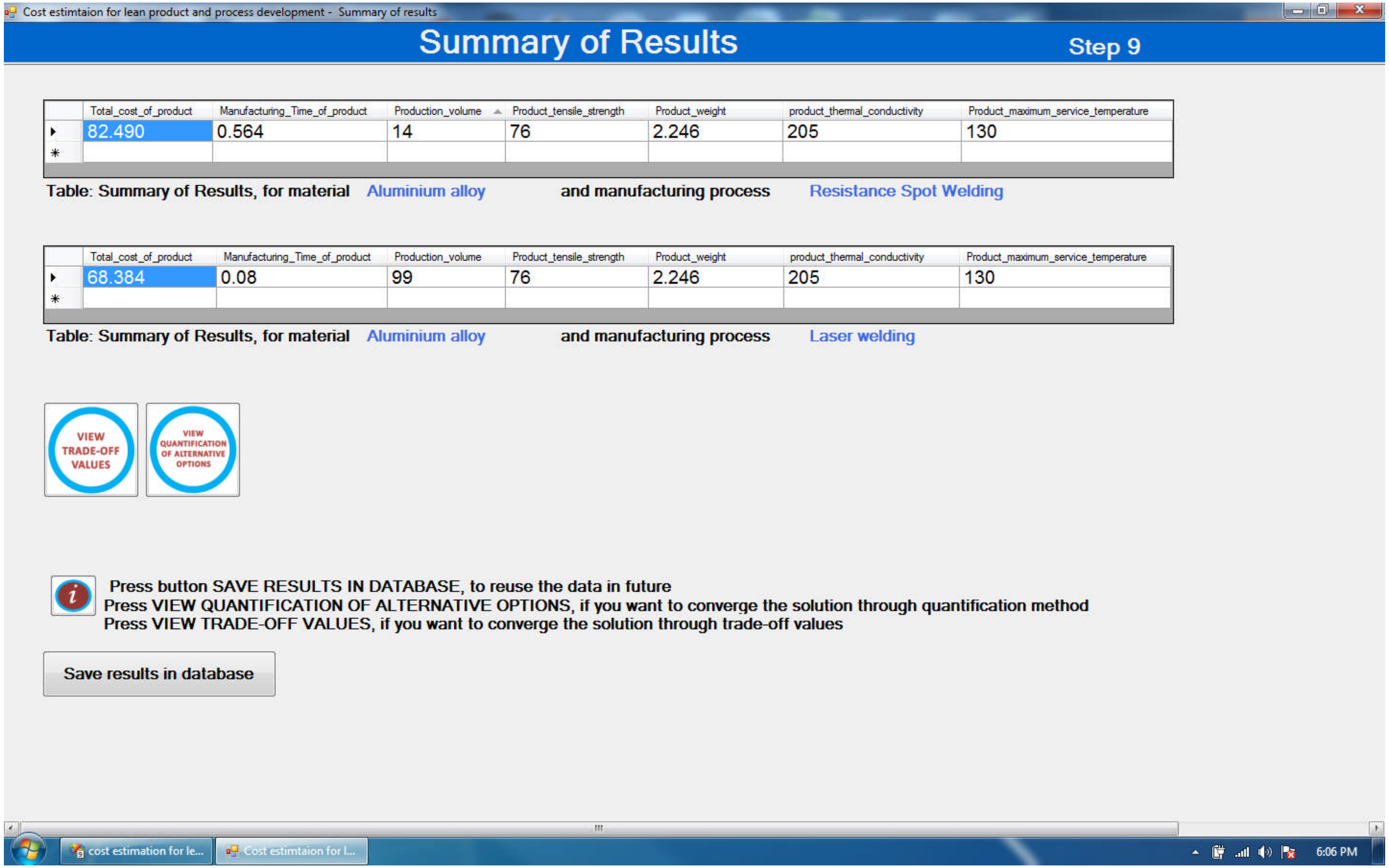

Figure 6-14: Summary of results

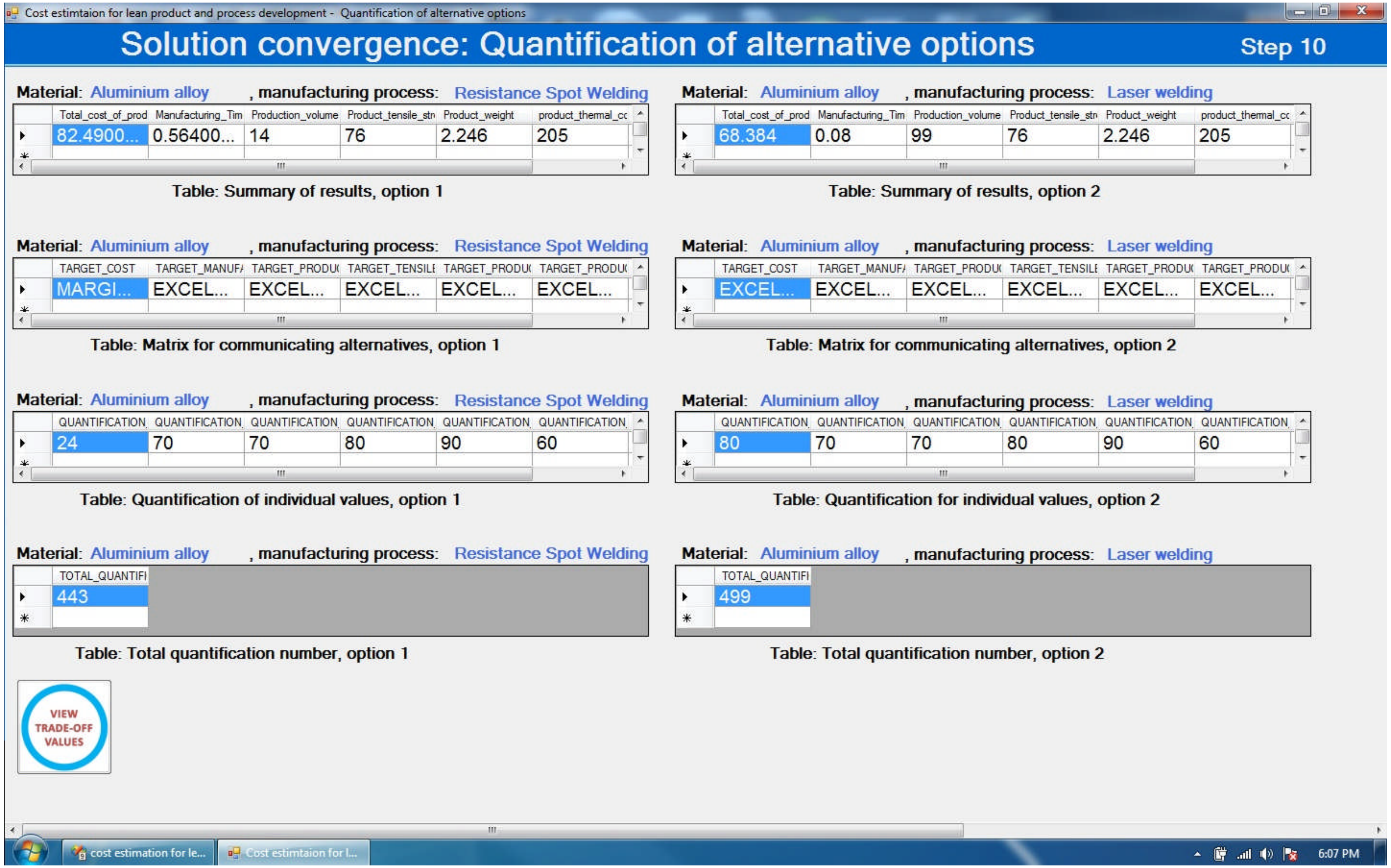

Figure 6-15: Solution convergence: quantification of alternative options

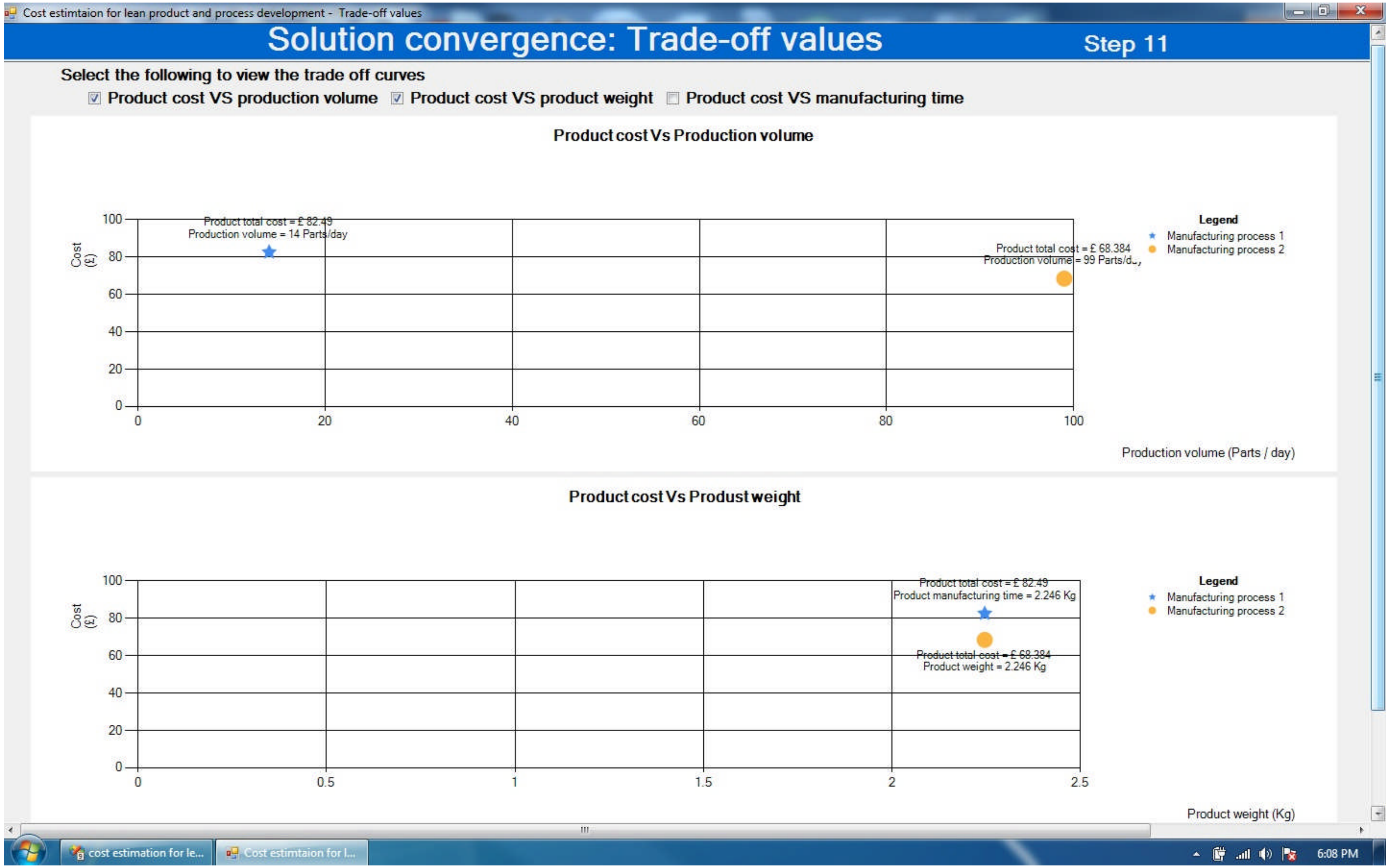

Figure 6-16: Solution convergence: trade off values

Purpose 3: Support the designer in the identification of the best seat design among several design alternatives

Another option available for the company was the development of alternative designs. However, the company has a small quotation development time, which does not allow them to propose a number of designs. Instead, the company showed its interest in identifying the estimates of alternative designs with different combinations of resistance spot welding and laser welding. The seat structure shown in Figure 6-5 was selected again. Five alternative designs with different combinations of manufacturing processes are provided in Table 6-5. The material for all these design is aluminium alloy. The validation process has been explained below.

Table 6-5: Five alternative designs with their manufacturing processes

Sr no	Assembly name	Design 1	Design 2	Design 3	Design 4	Design 5
1.	Assembly 1 & 2	Resistance spot welding	Resistance spot welding	Resistance spot welding	Laser welding	Resistance spot welding
2.	Assembly 1 & 3	Resistance spot welding	Resistance spot welding	Resistance spot welding	Resistance spot welding	Laser welding
3.	Assembly 4 & 5	Resistance spot welding	Resistance spot welding	Laser welding	Laser welding	Resistance spot welding
4.	Assembly 4 & 6	Resistance spot welding	Resistance spot welding	Laser welding	Resistance spot welding	Laser welding
5.	Assembly 1, 2 & 7	Resistance spot welding	Laser welding	Laser welding	Laser welding	Resistance spot welding
6.	Assembly 1, 3 & 8	Resistance spot welding	Laser welding	Laser welding	Resistance spot welding	Laser welding
7.	Assembly 4, 5 & 7	Laser welding	Laser welding	Laser welding	Laser welding	Resistance spot welding
8.	Assembly 4, 6 & 8	Laser welding	Laser welding	Laser welding	Resistance spot welding	Laser welding

The validation process initiated the values identification. The values, their preferences and targets are shown in Table 6-6. After the input of all the necessary information, the system generated the results. Detailed results of manufacturing time and cost estimation of each assembly is provided in Figure 6-17. Figure 6-18 presents the summary of results. Solution convergences through quantification of alternative options and trade-off values have also been provided in Figure 6-19 and Figure 6-20 respectively. In addition, a matrix for communicating alternatives and quantification number is described in Table 6-7 and equation 6-3 respectively.

Table 6-6: Values, value preferences and targets

Value	Company value	Customer Value	Preferences	Targets			
				Unacceptable x	Marginal ▲	Acceptable ●	Excellent ☺
Product cost (£)	Yes	Yes	8	Greater than £85	Less than £85	10% Decrease	20% Decrease
Product manufacturing time (hours)	Yes	No	7	Greater than 0.35Hour	Less than 0.35Hour	20% Decrease	40% Decrease
Production volume (Units per day)	Yes	No	7	Less than 23Units per day	Greater than 23 Units per day	20% Increase	40% Increase
Tensile strength (MPa)	Yes	Yes	8	Less than 50MPa	Greater than 50MPa	15% Increase	30% Increase
Product weight (Kg)	Yes	Yes	9	Greater than 7.0Kg	Less than 7.0Kg	10% Decrease	20% Decrease
Product thermal conductivity (W/mK)	Yes	Yes	6	Less than 45W/mK	Greater than 45W/mK	25% Increase	50% Increase
Product maximum service temperature (^{o}C)	Yes	Yes	7	Less than 100^{o}C	Greater than 100^{o}C	25% Increase	50% Increase

Table 6-7: Matrix for communicating alternatives

Manufacturing process	Design 1	Design 2	Design 3	Design 4	Design 5
Product cost (£)	▲	●	●	●	▲
Product manufacturing time (hours)	x	▲	☺	▲	x
Production volume (Units per day)	x	▲	☺	●	x
Tensile strength (MPa)	☺	☺	☺	☺	☺
Product weight (Kg)	☺	☺	☺	☺	☺
Product thermal conductivity (W/mK)	☺	☺	☺	☺	☺
Maximum service temperature (^{o}C)	●	●	●	●	●

Legend: Excellent (☺) =10, Acceptable (●) = 7, Marginal (▲) = 3, Unacceptable (x) = 0

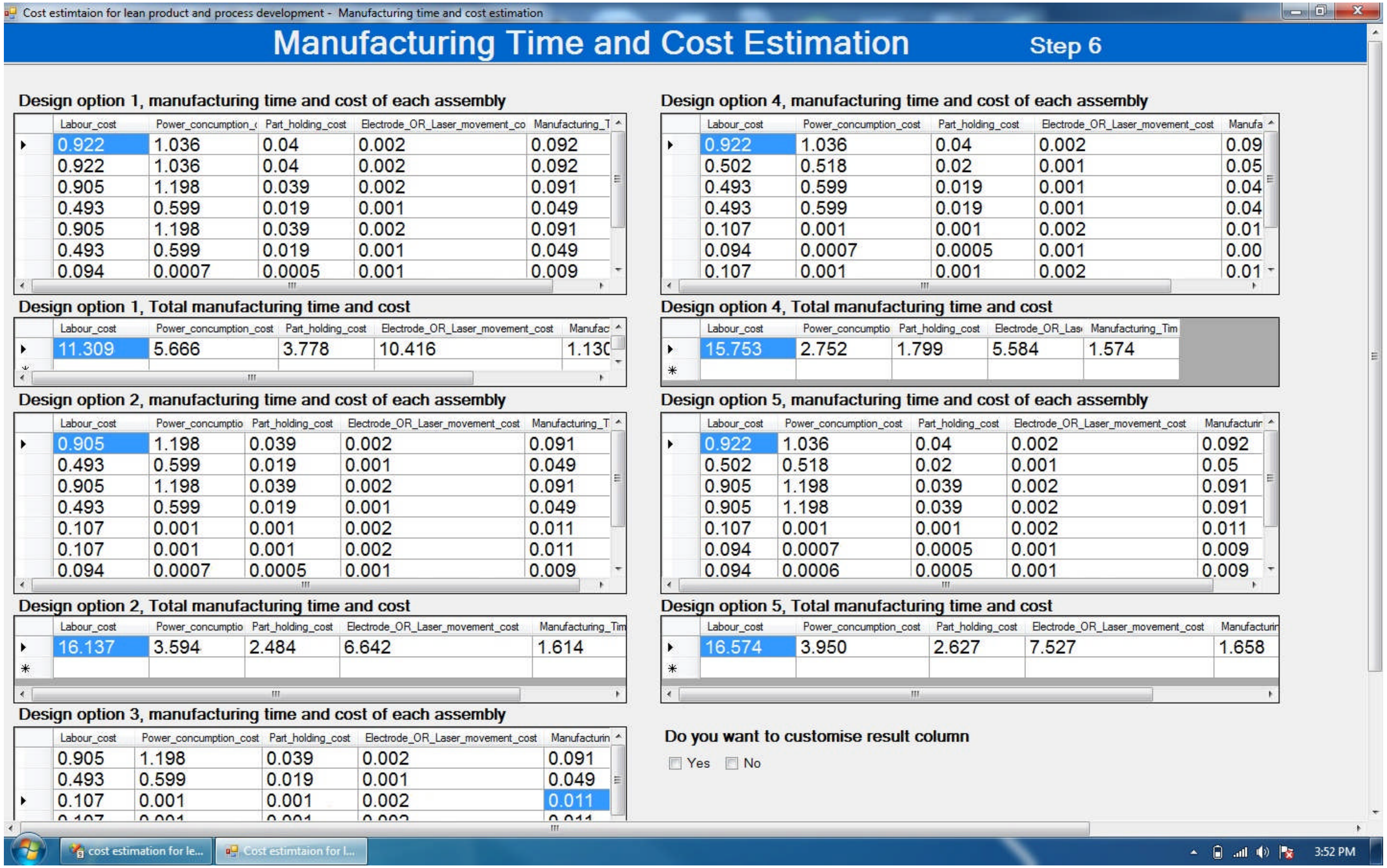

Figure 6-17: Detailed results of manufacturing time and cost estimation of each assembly

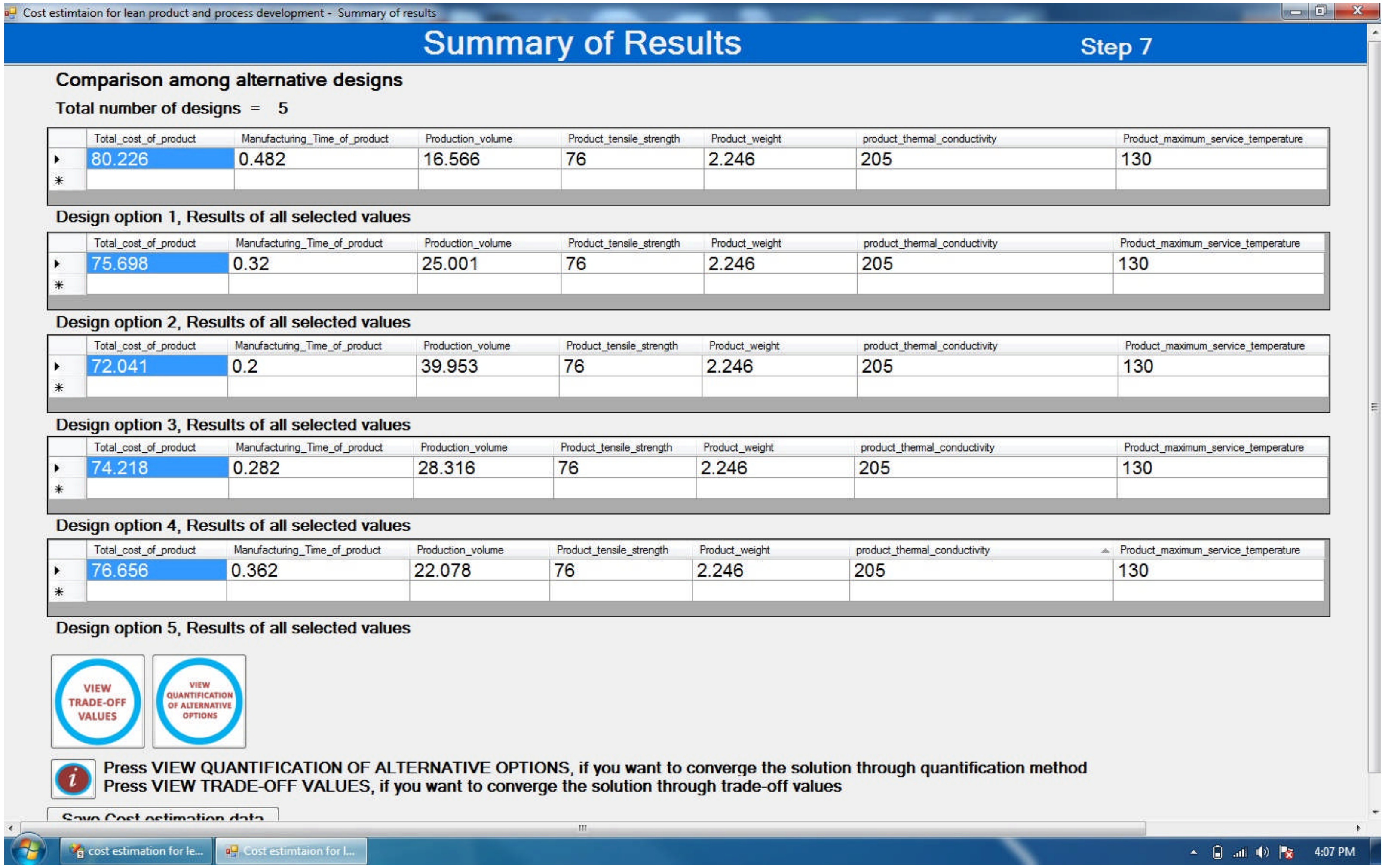

Figure 6-18: Summary of results

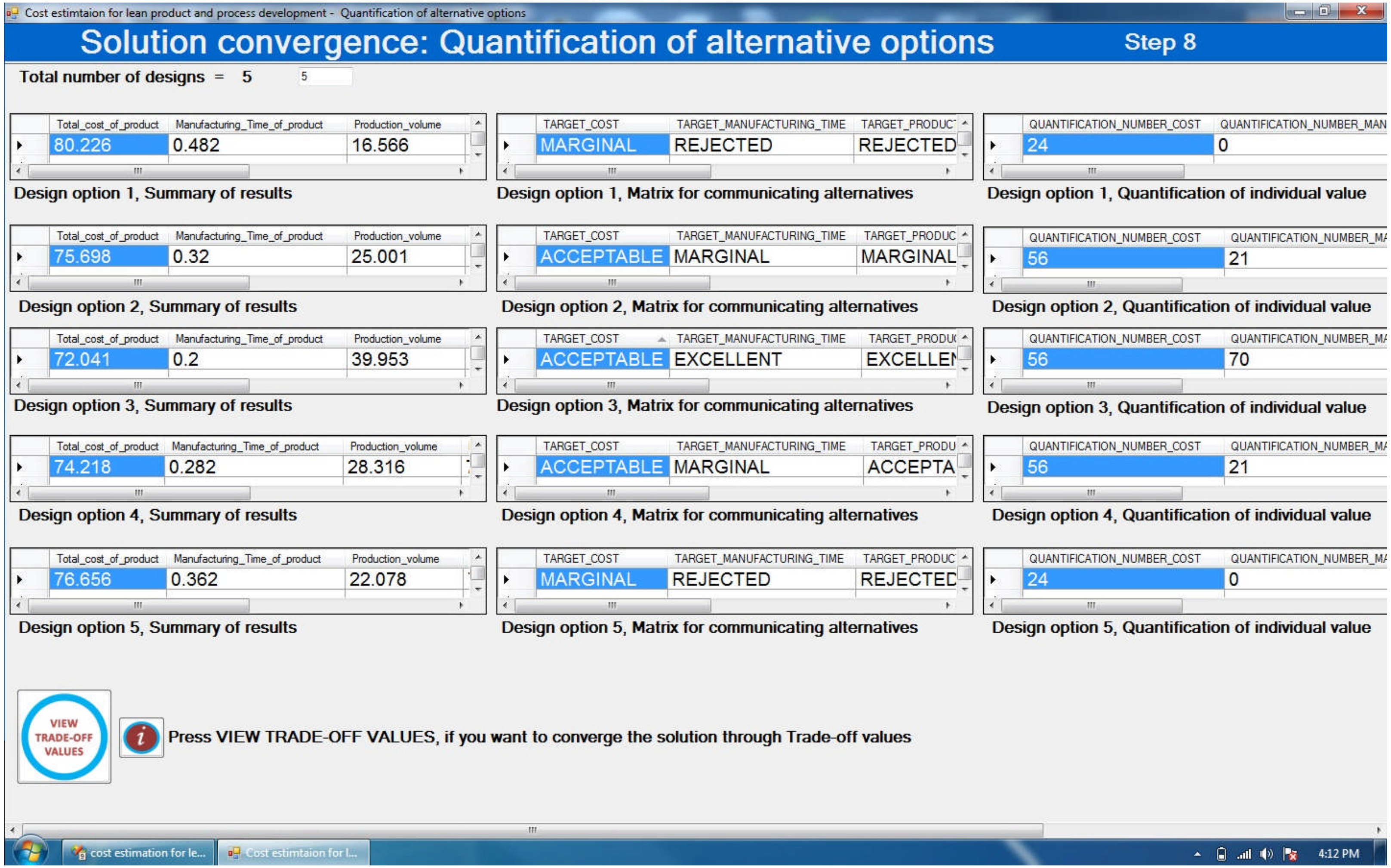

Figure 6-19: Solution convergence: quantification of alternative options

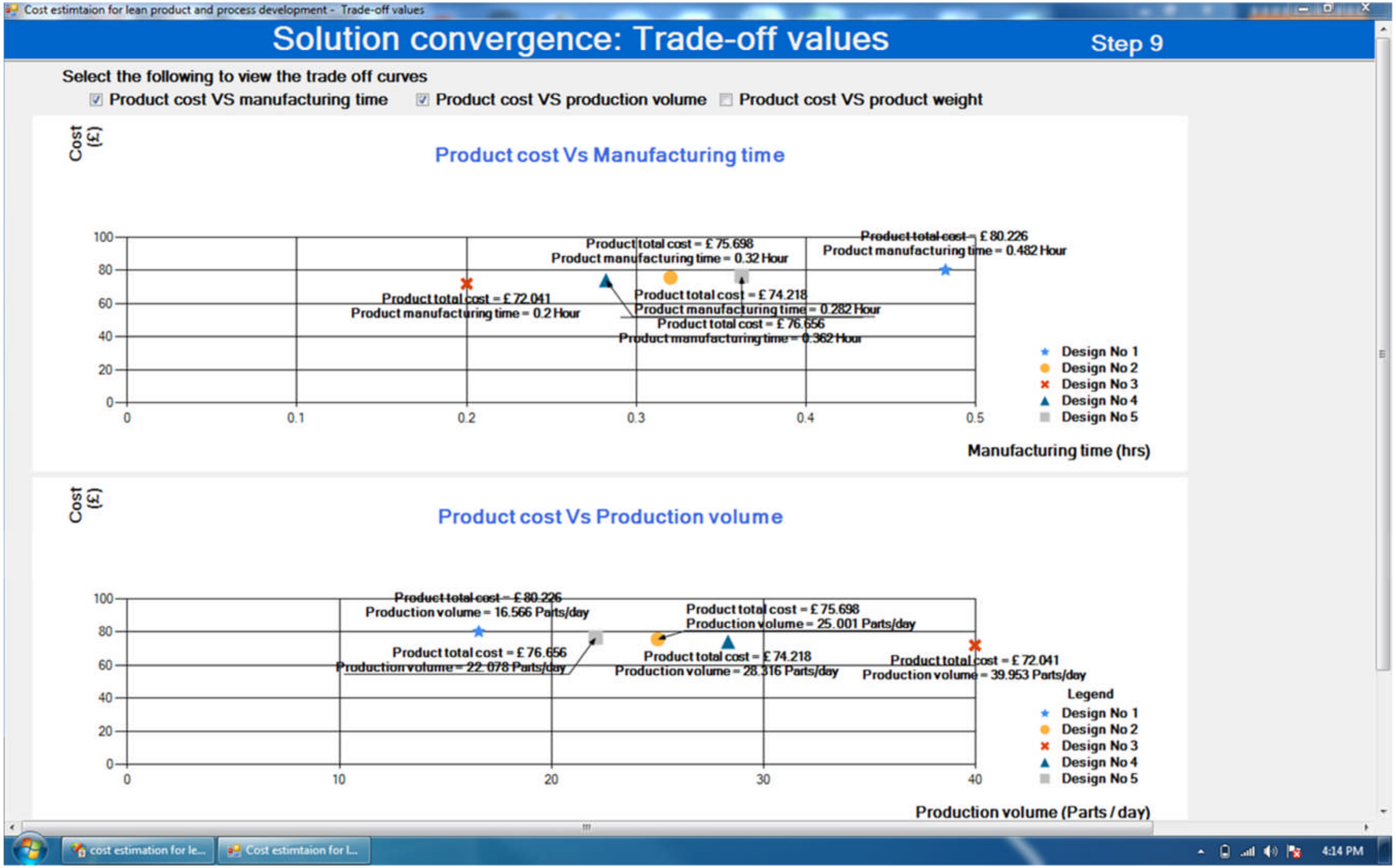

Figure 6-20: Solution convergence: trade off values

$$\begin{bmatrix} 3 & 0 & 0 & 10 & 10 & 10 & 7 \\ 7 & 3 & 3 & 10 & 10 & 10 & 7 \\ 7 & 10 & 10 & 10 & 10 & 10 & 7 \\ 7 & 3 & 7 & 10 & 10 & 10 & 7 \\ 3 & 0 & 0 & 10 & 10 & 10 & 7 \end{bmatrix} \times \begin{bmatrix} 8 \\ 7 \\ 7 \\ 8 \\ 9 \\ 6 \\ 7 \end{bmatrix} = \begin{bmatrix} 303 \\ 377 \\ 475 \\ 405 \\ 303 \end{bmatrix} = \begin{bmatrix} \text{Design 1} \\ \text{Design 2} \\ \text{Design 3} \\ \text{Design 4} \\ \text{Design 5} \end{bmatrix} \tag{6-3}$$

The results indicate that Design 1 and Design 5 have two values that do not fulfil the targets; therefore, these designs were eliminated in the first step. The remaining solution is shown in equation 6-4.

$$\begin{bmatrix} 377 \\ 475 \\ 405 \end{bmatrix} = \begin{bmatrix} \text{Design 2} \\ \text{Design 3} \\ \text{Design 4} \end{bmatrix} \tag{6-4}$$

Since Design 2 has the minimum total quantification number in equation 6-4 (377), it was eliminated in the second step. Two remaining solutions, i.e. Designs 3 and 4 were proposed to the designer as feasible solutions. The designer was asked to develop these designs further and compare them again in order to identify the best solution.

Purpose 4: Assess the design at the detailed design stage for capturing design mistakes, and to estimate the total cost of product along with other values

To validate the system for the detailed design stage, it was explained earlier that the company focused on the application of the poka-yoke (mistake-proofing) principle in their design facility. The CAD model provided in Figure 6-5 was designed in detail with resistance spot welding. The spots were designed properly using the design rules.

For validation purpose, the system scenario explained in Chapter 5 (Figure 5-13) was followed step by step, i.e. values, value preferences, value targets, CAD model, material and manufacturing process information were all provided in sequence. Since the manufacturing process was resistance spot welding, the design mistakes related to sheets overlap, edge distance, spot spacing and the total number of spots were therefore identified. The example of poka-yoke related to overlap is provided in Figure 6-21. Once all the mistakes were captured, manufacturing time, cost and all required values were estimated accordingly and compared with targets. In addition, the process parameters were generated from the system and supplied to the manufacturing shop floor for minimising the process parameters selection mistakes.

6.2.1.4 The benefits achieved from the case study

After the adoption of the developed system, the company expected to achieve tangible benefits. Some of the benefits achieved are explained in Table 6-8.

Table 6-8: Tangible benefits obtained after the adoption of the developed system

	Before	After
Design mistake	50%-80%	5-10%
Cost estimation time	25 days	12-15 days
Internal meetings to finalise design	4-6	2-3
Quotation response time	3 months	1 month
Formalised cost estimation process	No	Yes
Customer involvement in decision making	No	Yes

In addition to these benefits, since the company was looking to purchase a new laser machine, the results helped to convince the top management of a good return on investment. These benefits truly represent the advantages of cost estimation for lean product and process development.

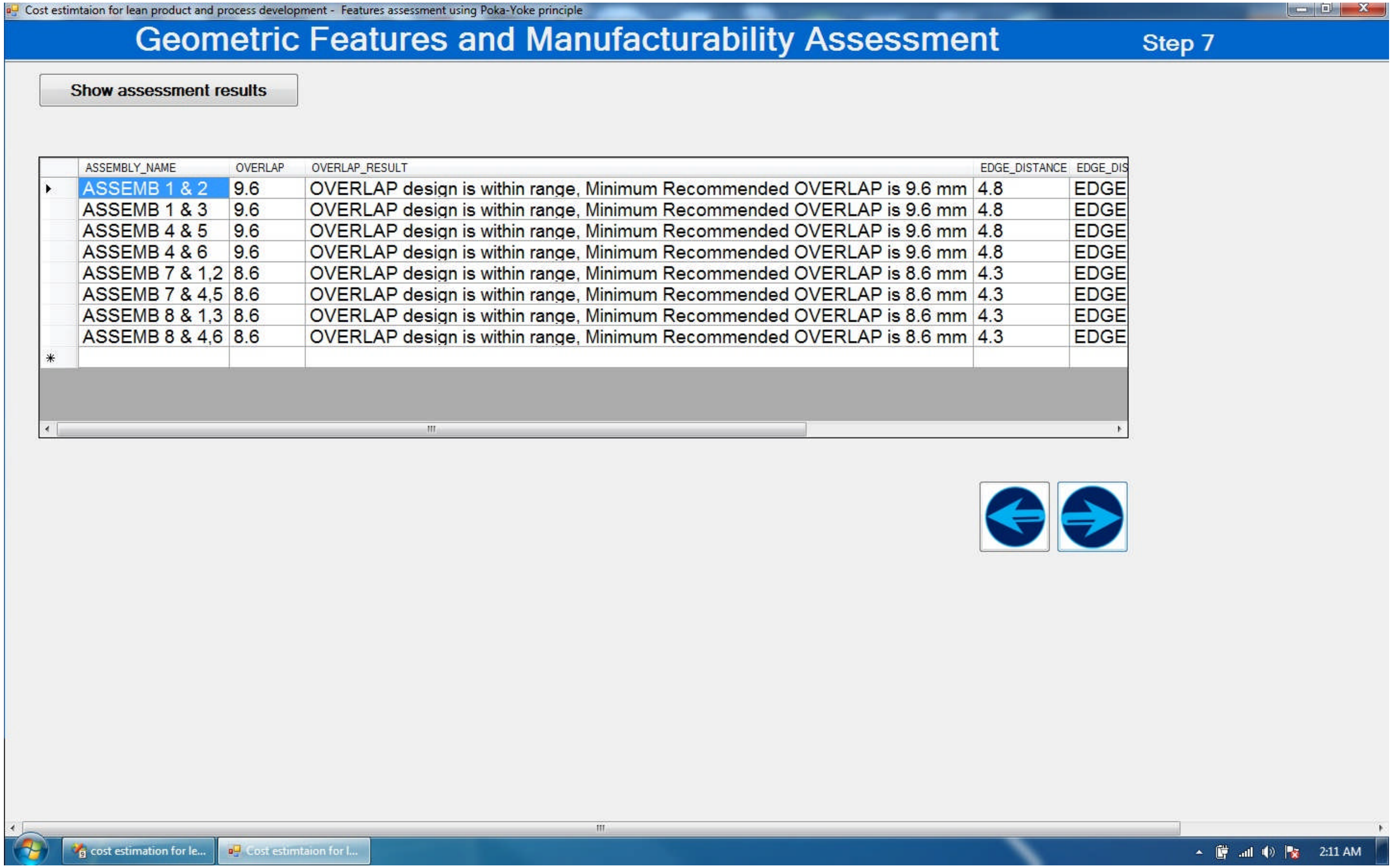

Figure 6-21: Application of poka-yoke

6.2.2 Case Study 2: Oil water separator

This case study is related to a company in the petroleum industry. The company's introduction, the product information, the problems faced by the company, the aims of analysing the case study and the validation are explained in the following sections.

6.2.2.1 Collaborator Company

The system has been validated through a second case study within the petroleum industry. The company designs, develops and supplies equipment for improving production from oil and gas wells. The company aims to significantly increase the volume of commercially extractable reserves from oil and gas fields, and reduce the environmental impact of such production. The production line of the company includes gas production boosting, multi-phase boosting, gas/liquid separation, flare recovery, de-gassing liquids and sand separation. Although the company is relatively new in the oil & gas sector, i.e. for only twelve years, it is nonetheless growing dynamically and generating solutions to real operational problems in the oil and gas industry. The company has completed more than 17 installations in Europe, Asia, America and Africa and a large number of orders are in the queue.

6.2.2.2 Introduction to product selected for validation

The product selected for validation is "Wx-12", an innovative Oil/Water separator. Wx-12 is used in off-shore oil platforms to extract water from the oil/water mixture. The Wx-12 can process 12,500 barrels of oil/water mixture per day and has the capability to separate the oil from the oil/water mixture at the quality of 500-1500ppm (parts per million). Figure 6-22 shows an internal view of the oil/water separator "Wx-12". The complete Wx-12 unit information is provided in Table 6-9.

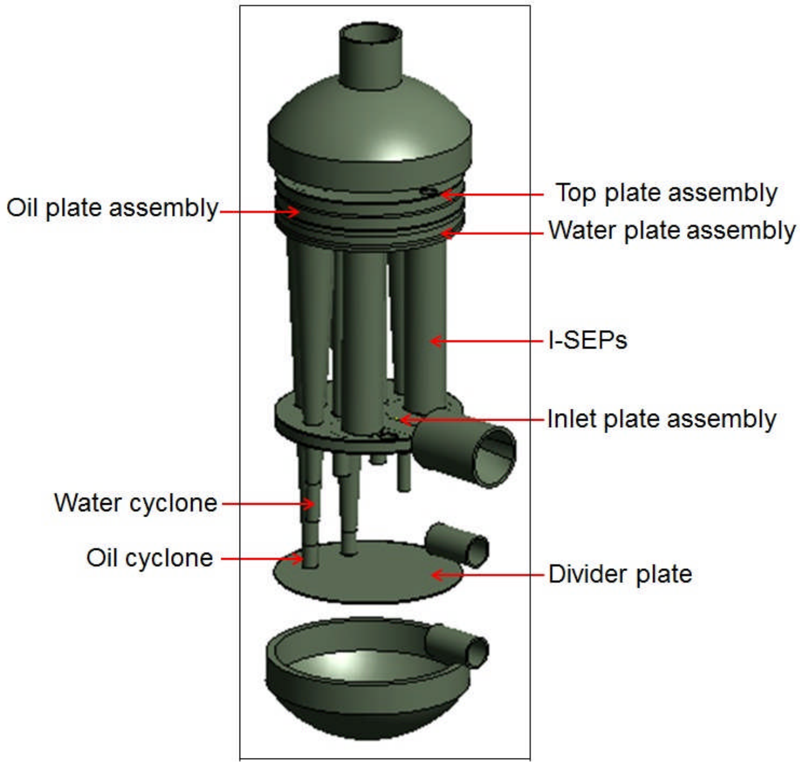

Figure 6-22: Oil/Water separator "Wx-12"

Table 6-9: Oil/Water separator "Wx-12" components' information

Sr No	Name of component	Quantity
1.	Top plate assembly	1
2.	Oil plate assembly	1
3.	Water plate assembly	1
4.	Inlet plate assembly	1
5.	Divider plate	1
6.	Water cyclones	2
7.	Oil cyclones	2
8.	I-SEPs	2

6.2.2.3 Problem Background

The oil/water separator "Wx-12" has a couple of advantages over the competitors, i.e. small pressure drop, compact and lightweight, easy to install and operate, simple, reliable, low maintenance, enhanced safety, and environmentally friendly. However, since the company is relatively new in the oil and gas sector, therefore it is facing severe challenges from its competitors. Some of the problems faced by the company are given below:

1. The Company has no manufacturing facility; therefore, the manufacturing time and cost is entirely dependent on its suppliers.
2. The company has to negotiate the prices with its suppliers, which consumes a large amount of time in setting the selling price.
3. The quotation from the suppliers is a lengthy process.
4. A new design is always difficult to validate within limited time. When the company has to take decisions on alternative designs, it has to follow the lengthy quotation process. To shrink the development time, the company sometimes accepts quotations from a limited number of suppliers. This practice results in missing the optimal supplier identification.
5. Due to high work pressure on designers, the top management has to negotiate with suppliers, whereas the designers do not even get the chances to meet the suppliers. This situation results in entire changes to the proposed solution after feedback from the suppliers. Sometimes the changed solution does not work and designers have to propose a new solution again.
6. Another problem faced by the company is the confidentiality issue. The company faces serious threats from suppliers if quotations are collected from a large number of suppliers.

All the above explained problems lead to high manufacturing cost and time as compared to competitors. This high unit manufacturing cost makes it a difficult choice for buyers to purchase the oil/water separator. The company believes that there are always opportunities to rectify the above explained problems, to enhance the design and reduce the overall cost of the product. Therefore the intention of the company is to reduce the manufacturing cost by developing new designs, investigating new materials and testing alternative manufacturing processes within a reasonably acceptable time.

6.2.2.4 Purposes of analysing the case study

The case study has been analysed to enable the system validation. Therefore, the main purposes of the present case study are to :

1. Compare possible alternative materials in order to support decision making for the selection of a better oil/water separator option.
2. Compare alternative oil/water separator designs in order to identify the best choice for the customers.

Purpose 1: Compare possible alternative materials in order to support decision making for the selection of a better oil/water separator option

The component selected for validation is the water cyclone illustrated in Figure 6-23. The water separated from the oil/water mixture is collected in the water cyclone. Currently the water cyclone is manufactured in stainless steel by applying the machining process. Duplex steel and Teflon are other suitable materials options. The company was looking to identify alternative materials that not only fulfil the minimum design requirements, but improve the design as well.

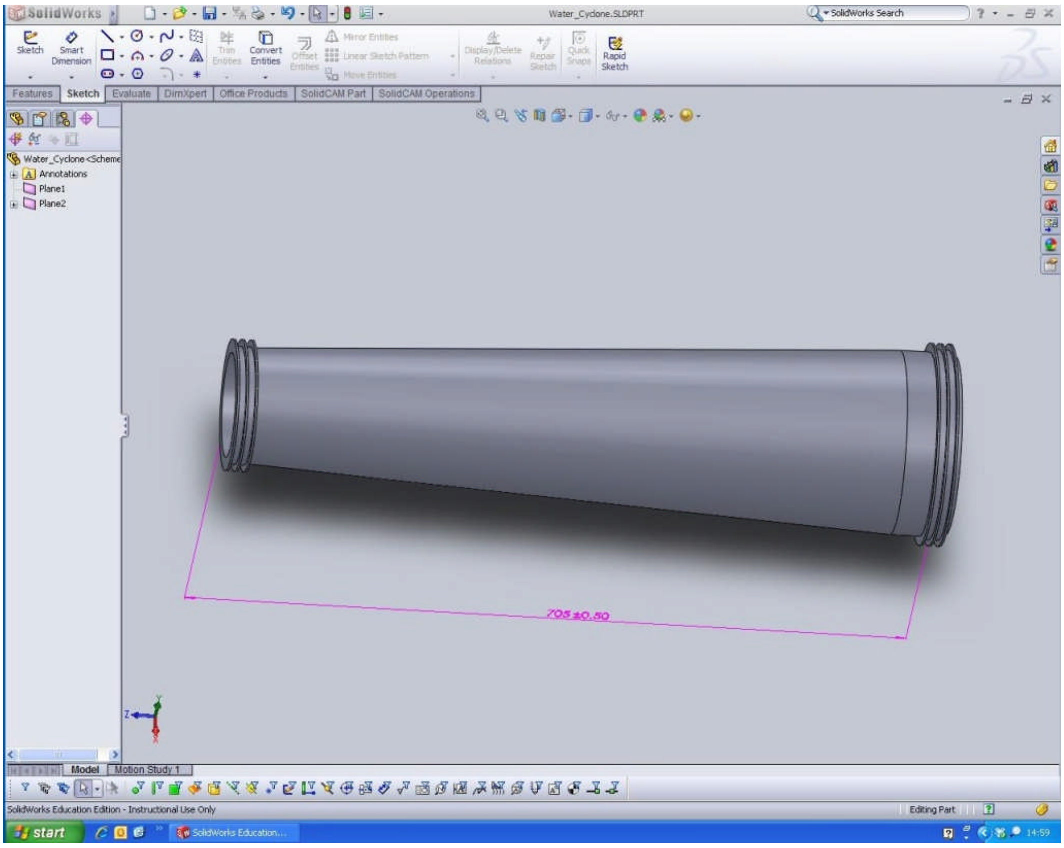

Figure 6-23: Water cyclone

For validation purpose, the values, their preferences and targets of the water cyclone were collected in the first step as shown in Table 6-10. The values, manufacturing process, materials and geometric features information were input into the system. The results are discussed below.

Table 6-10: Values, preference and targets of the water cyclone

Value	Company value	Customer Value	Preferences	Targets			
				Unacceptable x	Marginal ▲	Acceptable ●	Excellent ☺
Product cost (£)	Yes	Yes	9	Greater than £150	Less than £150	10% Decrease	20% Decrease
Production volume (Units per day)	Yes	No	6	Less than 2 Units per day	Greater than 2 Units per day	10% Increase	20% Increase
Product yield strength (MPa)	Yes	Yes	8	Less than 15MPa	Greater than 15MPa	20% Increase	40% Increase
Product tensile strength (MPa)	Yes	Yes	7	Less than 15MPa	Greater than 15MPa	20% Increase	40% Increase
Product weight (Kg)	Yes	Yes	8	Greater than 14Kg	Less than 14Kg	10% Decrease	15% Decrease
Product thermal conductivity (W/mK)	Yes	Yes	7	Less than 0.2W/mK	Greater than 0.2W/mK	15% Increase	30% Increase
Product maximum service temperature (^{o}C)	Yes	Yes	6	Less than 75^{0}C	Greater than 75^{0}C	20% Increase	30% Increase

Since the company had no manufacturing facility, the system, therefore, prompted the message of the machine's non availability (Figure 6-24). This message was ignored and results were generated as illustrated in Figure 6-25. Solution convergences through the quantification of alternative options and trade-off values are also provided in Figure 6-26 and Figure 6-27 respectively. In addition, a matrix for communicating alternatives and quantification number has been described in Table 6-11 and equation 6-5 respectively.

Table 6-11: Matrix for communicating alternatives

Material	216L Stainless steel	Duplex steel	Teflon
Product cost (£)	▲	☺	●
Production volume (Units per day)	☺	☺	▲
Product yield strength (MPa)	☺	☺	▲
Tensile strength (MPa)	☺	☺	●
Product weight (Kg)	▲	▲	☺
Product thermal conductivity (W/mK)	☺	☺	●
Maximum service temperature (^{o}C)	☺	☺	☺

Legend: Excellent-☺=10, Acceptable-● = 7, Marginal-▲ = 3, Unacceptable-x = 0

$$\begin{bmatrix} 3 & 10 & 10 & 10 & 3 & 10 & 10 \\ 10 & 10 & 10 & 10 & 3 & 10 & 10 \\ 7 & 3 & 3 & 7 & 10 & 7 & 10 \end{bmatrix} \times \begin{bmatrix} 9 \\ 6 \\ 8 \\ 7 \\ 8 \\ 7 \\ 6 \end{bmatrix} = \begin{bmatrix} 391 \\ 454 \\ 343 \end{bmatrix} = \begin{bmatrix} \text{216L Stainless steel} \\ \text{Duplex steel} \\ \text{Teflon} \end{bmatrix} \quad (6\text{-}5)$$

The results indicate that Teflon was the weakest solution; it was therefore eliminated. The remaining two options can be developed further and compared again to identify the better option.

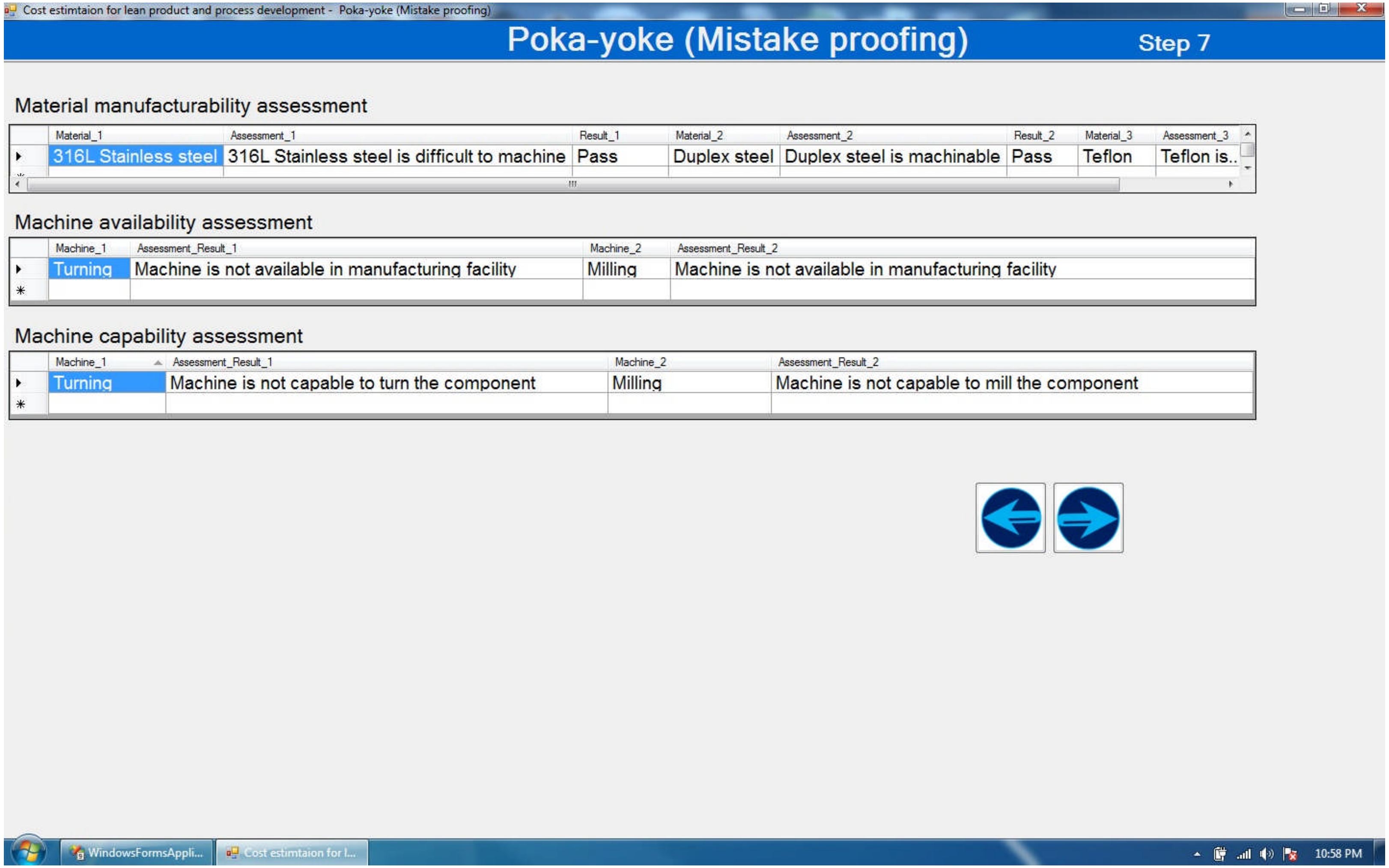

Figure 6-24: Application of poka-yoke

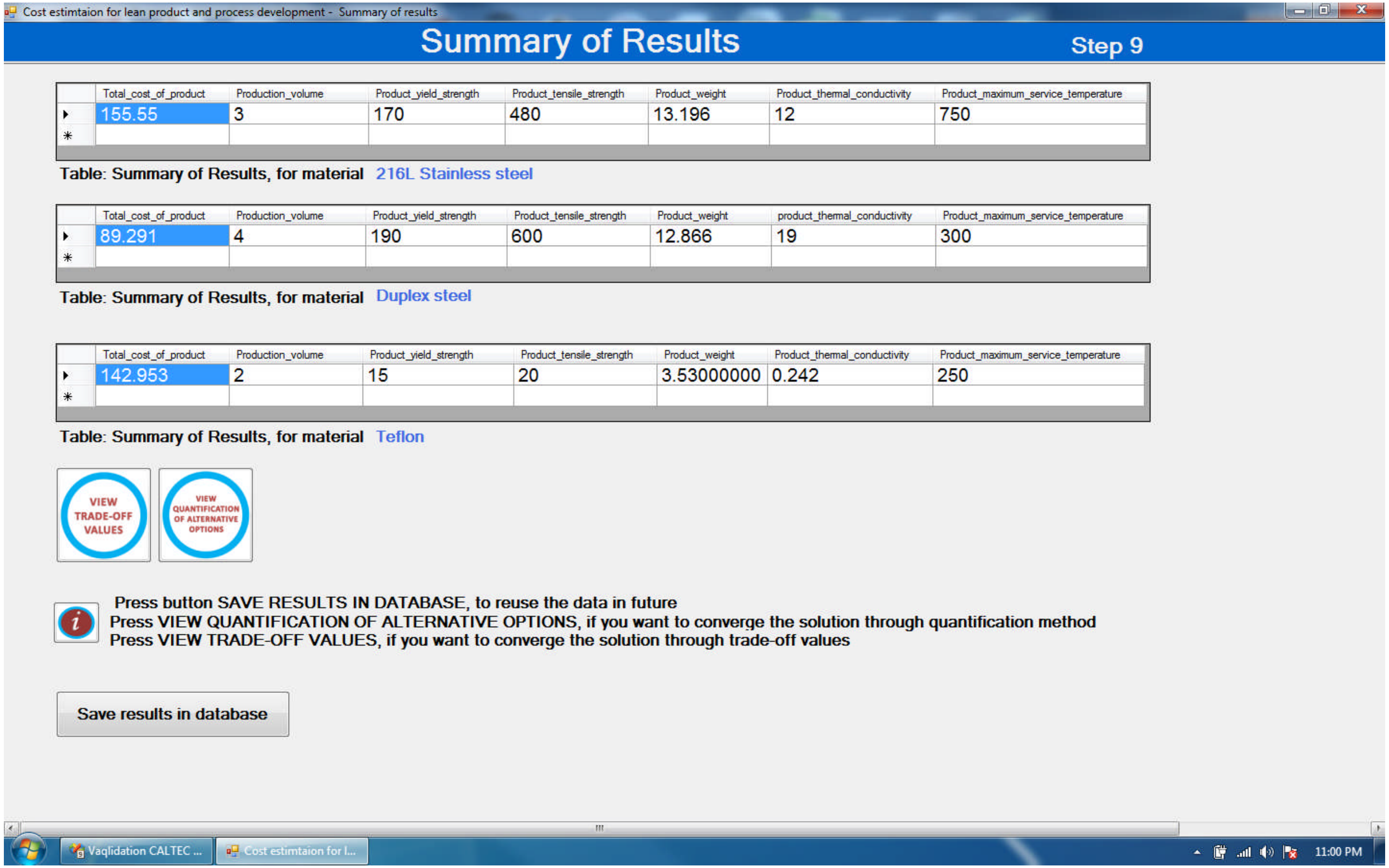

Figure 6-25: Summary of results

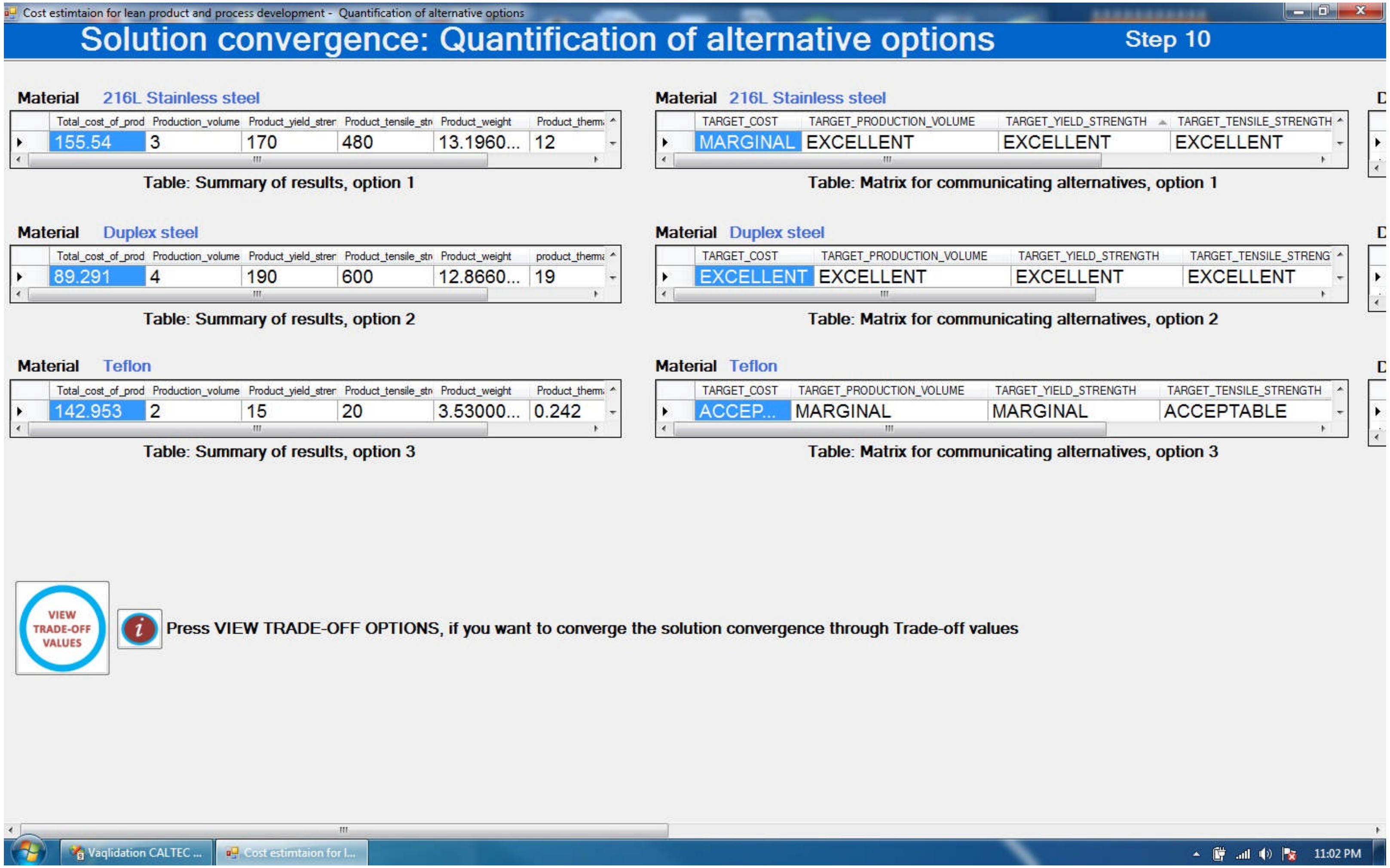

Figure 6-26: Solution convergence: quantification of alternative options

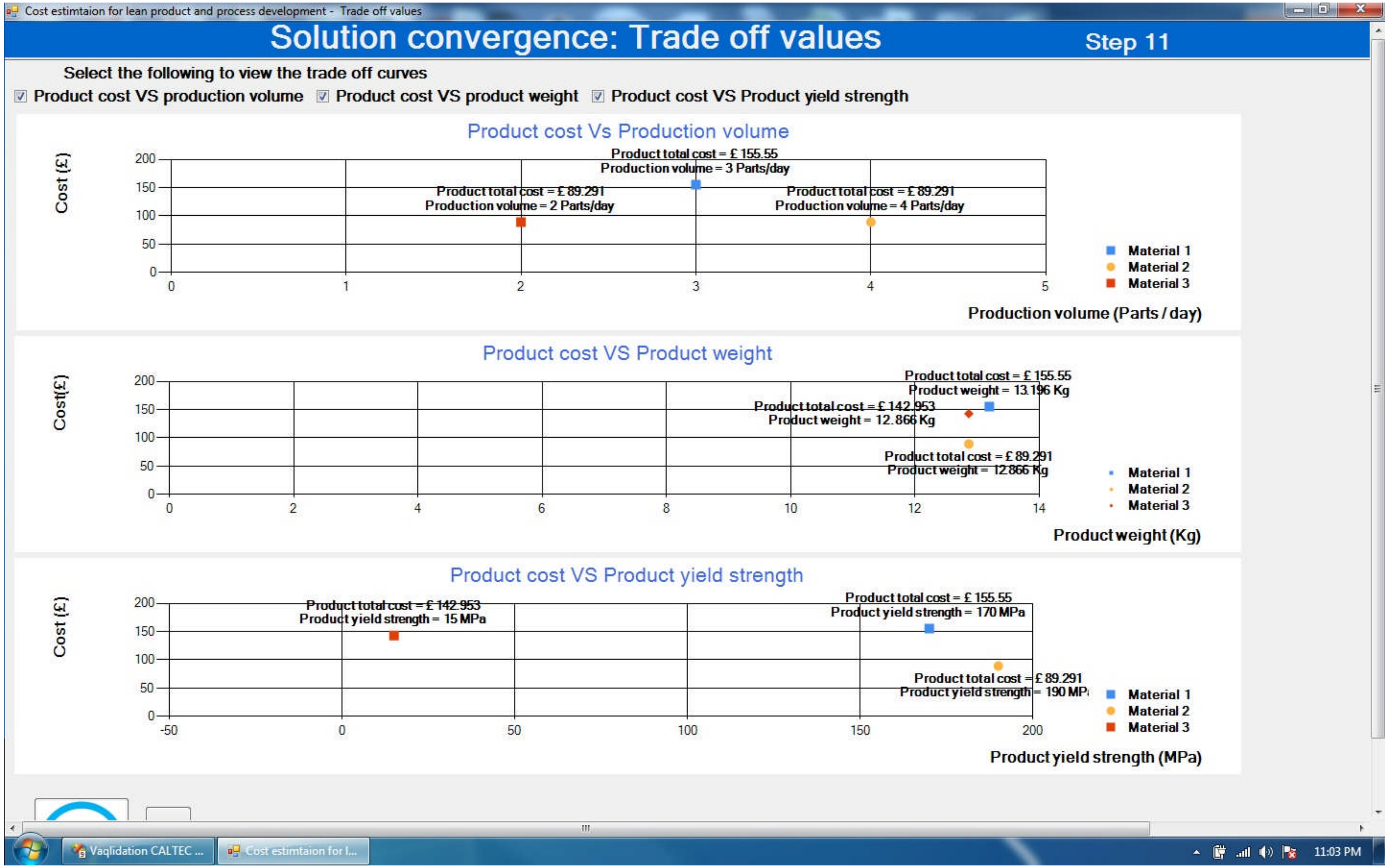

Figure 6-27: Solution convergence: trade off values

Purpose 2: Compare alternative oil/water separator designs in order to identify the best choice for the customers

The company also showed an interest in developing alternative designs for satisfying their customers. A water plate assembly taken for validation is shown in Figure 6-28 and 6-29. As explained earlier, the company was looking to reduce the cost of product for providing a better solution for the customers. One of the major cost drivers in off-shore products is the running cost of equipment. The oil producing company has to bear a cost of approximately £1.0million per square metre of equipment. Therefore the company was looking to reduce the size of the component. Another associated problem faced by the company was the off the shelf diameter of the water plate, i.e. 657mm diameter is not commercially available. Therefore the company was looking to reduce the diameter to 548mm which is easily available in the market. The designer analysed the existing design in detail and proposed a new design.

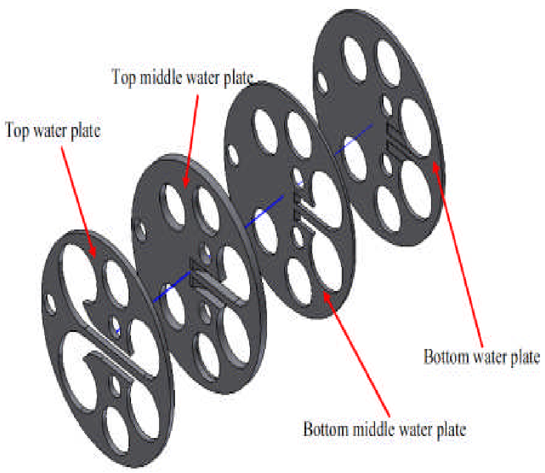

Figure 6-28: Water plate assembly, exploded view Current design

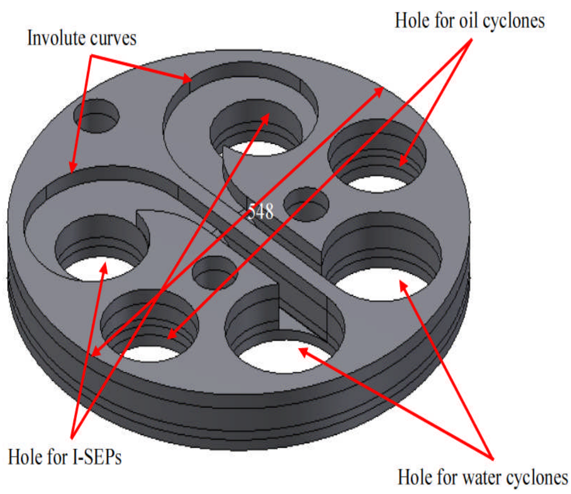

Figure 6-29: Water plate assembly (Current design)

It can be seen from Figure 6-29 that the water plate includes two involute curves, two holes for water cyclones and two holes for oil cyclones. In the new design proposed by the designer, the position of these two involute curves were changed from side-by-side to top-down as shown in Figure 6-30 and 6-31. The position of the water cyclone and oil cyclone were kept similar. This change in design decreased the diameter of the water plate; however, the side effects were an increase in the number of parts from 4 to 8. A comparison between the new and existing design is shown in Table 6-12.

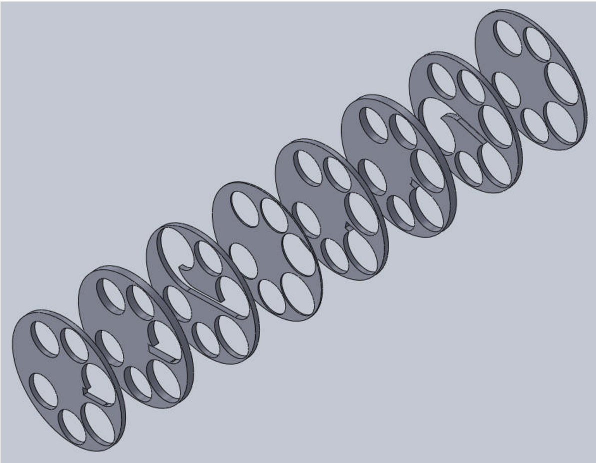

Figure 6-30: Water plate assembly, exploded view (New design) (Lu, 2011)

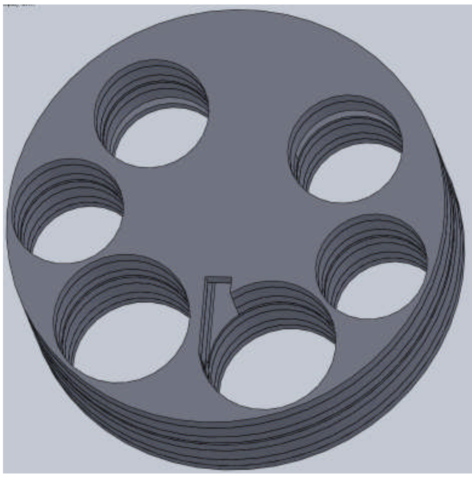

Figure 6-31: Water plate assembly (New design)

Table 6-12: Comparison between new and existing design

	New Design (Design 1)	Existing design (Design 2)
Diameter	548mm	657mm
Number of parts	8	4
Material	316L Stainless steel	316L Stainless steel

For validation purposes, the values, their preferences and targets of the water plate were collected in the first step, as shown in Table 6-13. The values, manufacturing process, materials and geometric features information was input into the system. The results are discussed below.

Table 6-13: Values, preference and targets of water plate assembly

Value	Company value	Customer Value	Preferences	Targets			
				Unacceptable x	Marginal ▲	Acceptable ●	Excellent ☺
Product cost (£)	Yes	Yes	9	Greater than £3000	Less than £3000	15% Decrease	30% Decrease
Production volume (Units per day)	Yes	No	6	Less than 1.2 Units per day	Greater than 1.2 Units per day	10% Increase	20% Increase
Product yield strength (MPa)	Yes	Yes	8	Less than 15MPa	Greater than 15MPa	20% Increase	40% Increase
Product tensile strength (MPa)	Yes	Yes	7	Less than 15MPa	Greater than 15MPa	20% Increase	40% Increase
Product weight (Kg)	Yes	Yes	8	Greater than 14Kg	Less than 14Kg	10% Decrease	15% Decrease
Product thermal conductivity (W/mK)	Yes	Yes	7	Less than 0.2W/mK	Greater than 0.2W/mK	15% Increase	30% Increase

Since the company had no manufacturing facility, the system, therefore, prompted the message of the machine's non availability. This message was ignored and the results were generated as illustrated in Figure 6-32. Solution convergences through quantification of alternative options and trade-off values are also provided in Figure 6-33 and Figure 6-34 respectively. In addition, the matrix for communicating alternatives and quantification number has been described in Table 6-14 and equation 6-6 respectively.

Table 6-14: Matrix for communicating alternatives

Material	**Design 1 (New design)**	**Design 2 (Existing design)**
Product cost (£)	▲	●
Production volume (Units per day)	●	☺
Product yield strength (MPa)	☺	☺
Tensile strength (MPa)	☺	☺
Product weight (Kg)	▲	☺
Product thermal conductivity (W/mK)	☺	☺

Legend: Excellent (☺) =10, Acceptable (●) = 7, Marginal (▲) = 3, Unacceptable (x) = 0

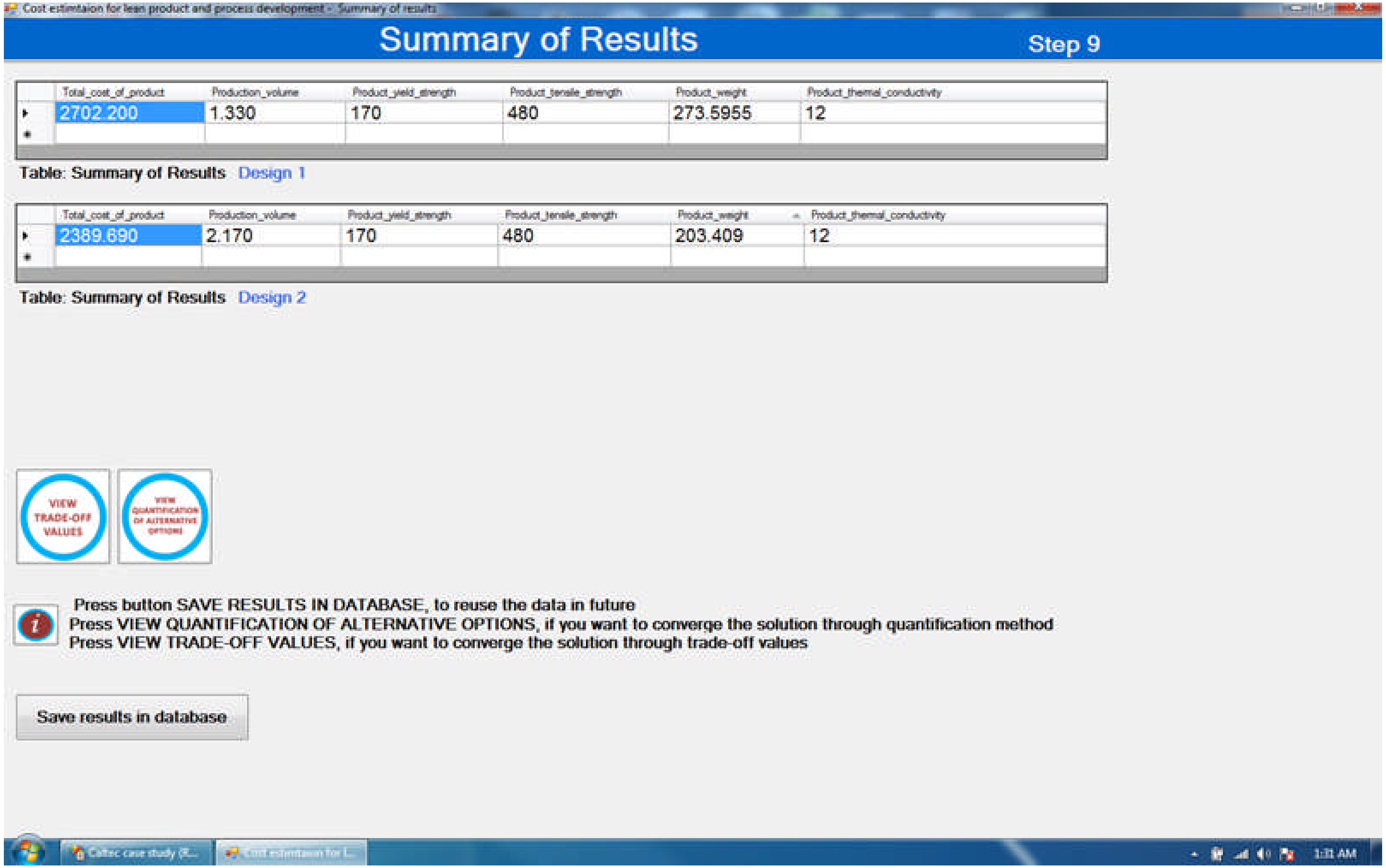

Figure 6-32: Summary of results

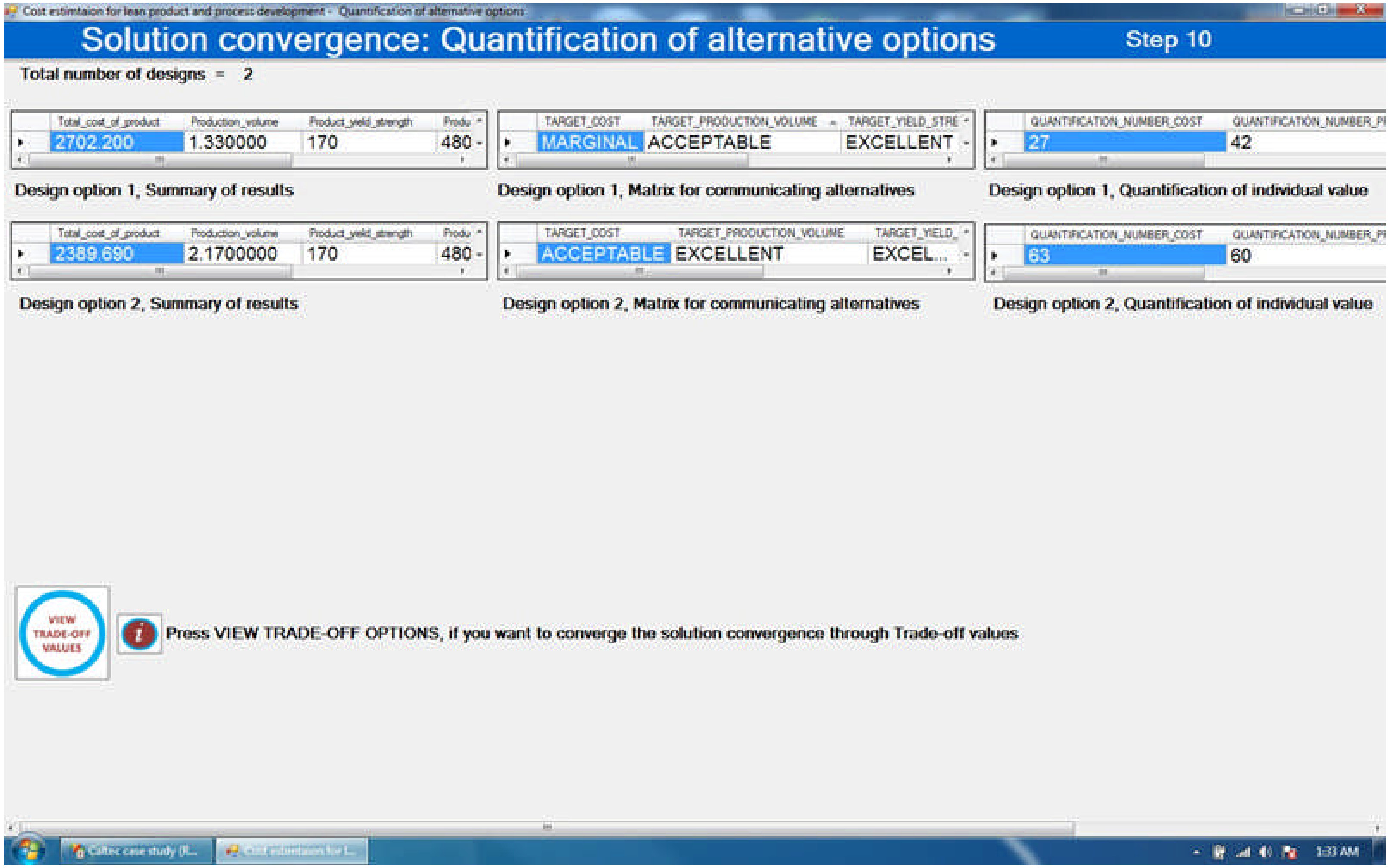

Figure 6-33: Solution convergence: quantification of alternative options

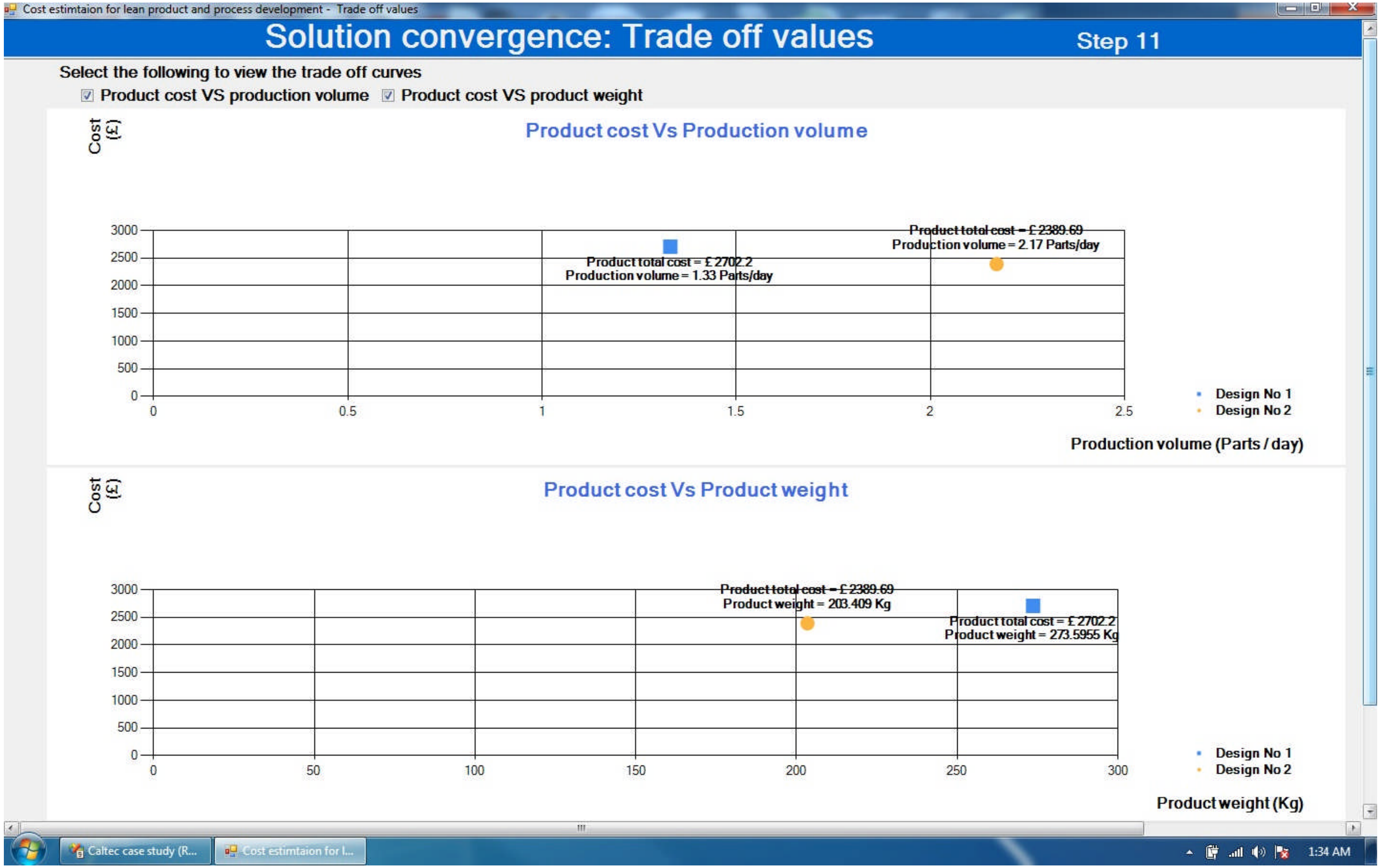

Figure 6-34: Solution convergence: trade off values

$$\begin{bmatrix} 3 & 7 & 10 & 10 & 3 & 10 \\ 7 & 10 & 10 & 10 & 10 & 10 \end{bmatrix} \times \begin{bmatrix} 9 \\ 6 \\ 8 \\ 7 \\ 8 \\ 7 \end{bmatrix} = \begin{bmatrix} 313 \\ 423 \end{bmatrix} = \begin{bmatrix} \text{Design 1 (New design)} \\ \text{Design 2 (Existing design)} \end{bmatrix} \quad (6\text{-}6)$$

The results indicate that the new design is the weakest solution on the basis of provided values. However, the same design may satisfy the customer if they appreciate the decrease in unit size.

6.2.2.5 The benefits achieved from the case study

After the adoption of the developed system, the company obtained tangible benefits, as explained in Table 6-15.

Table 6-15: Tangible benefits obtained after the adoption of the developed system

	Before	After
Selling price negotiation	Suppliers were at leading edge	It became possible for the company to set the selling price
Confidentiality of design due to negotiation with a large number of suppliers	At risk	No risk
Formalised cost estimation process	No	Yes
Customer involvement in decision making	No	Yes
Cost estimation time	15 days	10-12 days

6.3 Validation through Experts' Opinion

The developed system was also validated through experts in the related field. Since this research includes three parts i.e.; (i) the cost modelling system was developed, (ii) to support lean product and process development, and (ii) the developed system has wide application in industry; therefore, it was decided to validate the system through experts related to three different fields i.e. cost estimation experts, lean product and process development experts, and industrial experts. Another reason behind this grouping was to analyse the experts' views about the differences they feel after the application of the developed system. For example, the cost estimators have a particular opinion about cost estimation. Therefore, only those experts were contacted for validation, which have wide range of industrial or academic experience in above explained fields. The plan was to capture their views after presenting the developed system. A total number of eight face to face interviews and WebEx teleconferences were performed in the validation process. Detail of the experts involved in the validation study is provided in Table 6-16. The detailed validation methodology is explained in Section 6.3.1.

Table 6-16: List of experts interviewed

Expert Number	Organisation	Role	Years of Experience	Experience area
01	Industry	Product design and development manager	12	Product design and development
02	Industry	Product development engineer	10	Product design and development
03	Academic	LeanPPD Research Fellow	1.5	Lean product and process development
04	Academic	LeanPPD Researcher	3	Lean product and process development
05	Industry	Managing Director, Product Development	8	Lean product and process development
06	Academic	LeanPPD Researcher	3	Lean product and process development
07	Academic	Cost estimator / Research Fellow	4+	Cost Estimation
08	Academic	Cost estimator	7+	Cost Estimation

6.3.1 Detailed methodology for experts validation

The validation methodology is explained in Figure 6-35. First of all, a power point presentation of about 30 minutes was developed and presented to the experts. The purpose of this presentation was to explain the aim, objectives and structure of the developed system. Both face to face interviews and WebEx teleconferences were employed in the validation process. The structure of the system was explained to each expert, together with a demonstration of the developed system. Any question that the experts had regarding the system structure or system usage was clarified during the session. After that the experts were asked to fill in the validation questionnaire (see Appendix B). In the questionnaire, the following issues were discussed:

- Is the logic to build the cost modelling system to support lean product and process development valid?
- Is the system truly generalisable to other business sectors?
- What are the potential benefits and limitations of the system?
- Is the system flexible and easy to use?
- Has the system been developed for three lean product and process development enablers as per their true principles?

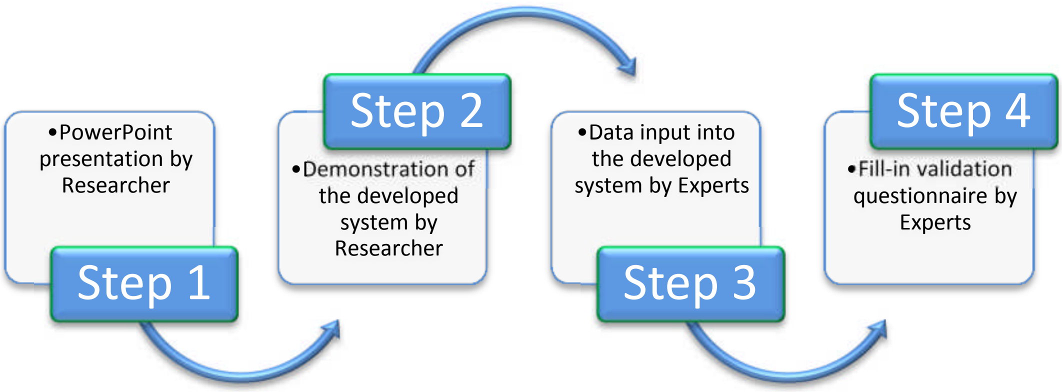

Figure 6-35: Methodology for Validation

6.3.2 Analysis of experts' responses

Analysis and comparison has been carried out based on the responses that the experts provided in their questionnaire during validation. The results are presented as follows:

- **Logic**

The responses to the question "How logical is the cost modelling system to support lean product and process development?", as well as the scale used to capture them in the questionnaire, are illustrated in Table 6-17.

Table 6-17: How logical is cost modelling system to support lean product and process development? - Ratings

1	2	3	4	5	6	7	8	9	10
Totally Unsuitable	Suitable with major deficiencies				Suitable with minor deficiencies				Totally suitable

Experts	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8	AVG
Scores	7	7	8	9	7	8	8	8	7.75

All eight experts agreed that the logic to develop the cost modelling system to support lean product and process development is truly valid; however, some of them identified minor deficiencies. For example, expert 1 suggested a geometric features assessment inside the CAD model rather than in the cost estimation. Expert 5 highlighted adding more values for identification of potential design solutions.

The responses to the question "Is the system suitable for the conceptual and detailed design stages?", as well as the scale used to capture them in the questionnaire are explained in Table 6-18.

Table 6-18: Is the system suitable for the conceptual and detailed design stages? - Ratings

1	2	3	4	5	6	7	8	9	10
Totally Unsuitable	Suitable with major deficiencies				Suitable with minor deficiencies				Totally suitable

Experts	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8	AVG
Scores	7	7	8	9	7	9	8	8	**7.875**

The eight experts were agreed that the developed system is entirely suitable for the conceptual and detailed design stages, although some of them pointed out minor deficiencies. For example, Expert 1 highlighted that the system generates the results as per requirements in the conceptual design stage; however, the system needs to consider tolerances in the detailed design stage. Expert 5 proposed providing a colour scheme at the matrix for communicating alternatives. This colour scheme can work on a traffic lights principle to pinpoint the excellent or rejected values in a given design solution. Expert 3 indicated that at the detailed design stage, more elements of poka-yoke are required to be added.

In response to the question "Can the system be applied in other product development stages?" all the experts agreed that the system is applicable in other product development stages as well. Expert 2 suggested that the system can be applied in the product manufacturing stage; however, there is a need to add the cost estimation of more manufacturing processes. Expert 4 indicated that the system can be used in the product development planning stage, or at the project initiation stage. Expert 7 proposed that it can be used in other product development stages, but it will affect the utilisation of the system in the concept development stage.

- **Generalisability**

The responses to the question “Do you think that the system can be generalisable and easily integrated into your business, (or any business)?”, as well as the scale used to capture them in the questionnaire, are presented in Table 6-19.

Table 6-19: Do you think that the system can be generalisable and easily integrated into your business (or any business)? - Ratings

1	2	3	4	5	6	7	8	9	10
Strongly disagree	Disagree		Slightly disagree		Slightly agree		Agree		Strongly agree

Experts	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8	AVG
Scores	7	8	8	8	9	8	8	8	8

All the experts agreed that the elements for the cost estimation used in the system are quite generic and flexible; therefore, the system can be easily generalisable in any business.

- **Benefits of using the system**

Benefits for the development team

Expert 1 highlighted that the system supports decision making, shows directions to the designer and helps them to find the hidden things. Expert 2 explained that small and medium enterprises (SMEs) have the capability to manufacture a large range of products because of the availability of a number of machines. The developed system can provide a good solution for those companies. Expert 3 stated that designers do not necessarily make decisions on the basis of cost. The system provides decision support to the designers and helps them to consider other values for decision making. Expert 4 explained that less time is required for estimating the cost by using the system. Experts 5 and 7 said that the use of the system speeds up the selection process during the conceptual design stage to select alternative options. In addition, the mistakes prevention reduces the wastes at the early design stage. Experts 6 and 8 highlighted that the system increases the confidence of choosing the optimal design solution at the early design stage by considering cross-functional aspects such as cost, manufacturing time, etc.

Benefits of set-based concurrent engineering consideration in the developed system

Expert 2 highlighted that the system explores the cost of assemblies and sub-assemblies having alternative manufacturing processes. The users can develop several scenarios and generate the results accordingly. Therefore the system helps to explore several results. Expert 8 stated that the chances of selecting the optimal design concept from several alternatives within the specification/expectations are high.

Benefits of poka-yoke considerations in the developed system

Expert 8 explained that the machines' capability is a consideration at the early stage and helps to eliminate the mistakes that occur in the later stages. Expert 5 highlighted that machine availability/capability identification is good at the initial design stage. The system generates mistake-proof results and helps to improve the design. Expert 6 explained that the engineers are prevented from choosing incompatible manufacturing processes and materials. Expert 7 suggested that uncertainties can be eliminated with the poka-yoke consideration.

Benefits of the knowledge-based engineering consideration in the developed system

Expert 3 highlighted that the capability identification, cost estimation, comparison of alternatives through a number of values and quantification are excellent. Expert 1 commented further that design solution quantification is excellent for improved decision making. Expert 7 stated that material manufacturability, machines' availability and capability identification rules embedded into the system help to develop reliable estimates. Expert 2 stated that the trade-off values representation is worthwhile for decision making. Expert 5 highlighted that the Excel interface makes it easy to input the geometric features and facilitates the capturing of design rules.

- **Limitations of the system**

Limitations with respect to the system and its use

Expert 1 highlighted that new technologies are required to be added into the system. Expert 3 commented that during the concept development stage, designers are not willing to perform extra job, particularly cost estimation. Although the developed system supports the estimation with little input, there is still the need to minimise the number of inputs to reduce the estimation time. Expert 4 pointed out that although the designers are aware of the values, targets identification is not their business. Top management, marketing experts or the finance people are mostly concerned with the targets. Therefore, if the system input the targets directly from the company's associated data, then it would be easier for designers to use the system. Expert 6 stated that the system does not deal with the qualitative values. Expert 7 highlighted the importance of capturing the quality data as it is a challenging but necessary job.

Limitations with respect to the system application in the organisation

Experts 1 and 2 pointed out the compatibility issue. They highlighted that the companies manage their data in their own legacy system, therefore the system should be capable of integrating with that system. Expert 6 stated that each organisation requires the subjective data as per their manufacturing technology and therefore it is necessary to add more manufacturing processes into the system. Expert 7 explained that people at different locations have different product values and different cost units. The system should be capable of changing the units as per the location.

- **Usability of the system**

All eight experts agreed that the system is easy to use, even without assistance, the layout is excellent, the navigation is good, and the information provided in the system guides the user properly. In addition, they highlighted that the terminologies and concepts used are consistent. The strongest and weakest features are provided below.

Strongest features in the system

Expert 1 highlighted that automatic generation of cost information and comparison with different manufacturing technologies is the feature that makes it more suitable than other developed systems. Expert 3 acknowledged that the easy to use and user-friendly interface is the strongest feature. Expert 8 appreciated the detailed cost of each assembly/feature. Expert 6 valued the drop down menu which helps to input the required information.

Weakest features in the system

Expert 2 stated that some additional data input during the conceptual design stage is time-consuming. Expert 5 stated that the visualisation of the results needs to be enhanced, i.e. some colour coding is required to enhance the system interface. Experts 4 and 6 stated that the targets are difficult to understand at first sight.

- **Assessment of the system**

The experts were asked to assess the system for its suitability for lean product and process development. The experts were also asked to give their opinion on the question of whether the system has been developed for three lean product and process development enablers as per their true principles. The responses to the question “Assess the set-based concurrent engineering application in the developed system”, as well as the scale used to capture them in the questionnaire are illustrated in Table 6-20.

Table 6-20: Assess the set-based concurrent engineering application in the developed system – Ratings

1	2	3	4	5	6	7	8	9	10
Totally incomprehensive	Suitable with major deficiencies				Suitable with minor deficiencies				Totally comprehensive

Experts	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8	AVG
Scores	8	8	9	8	8	8	7	7	7.875

All eight experts agreed that the system works properly within the concept of set-based concurrent engineering, although some of them pointed out minor deficiencies. Expert 1 pointed out that the system works according to its true principle, but there is a need to improve the results presentation. Expert 6 stressed that although the system helps to make decisions among alternatives, it does not propose the improvement areas in product design and development.

The responses to the question "Assess the poka-yoke application in the developed system", as well as the scale used to capture them in the questionnaire are illustrated in Table 6-21.

Table 6-21: Assess the poka-yoke application in the developed system – Ratings

1	2	3	4	5	6	7	8	9	10
Totally incomprehensive	Suitable with major deficiencies				Suitable with minor deficiencies				Totally comprehensive

Experts	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8	AVG
Scores	8	7	8	8	8	8	7	8	7.75

All eight experts agreed that the system works on the principle of poka-yoke, although one of them pointed out minor deficiencies. Expert 2 highlighted that there is need to add more poka-yoke elements in the conceptual design to realise the impact of poka-yoke.

The responses to the question "Assess the knowledge-based engineering application in the developed system", as well as the scale used to capture them in the questionnaire are illustrated in Table 6-22.

Table 6-22: Assess the knowledge-based engineering application in the developed system – Ratings

1	2	3	4	5	6	7	8	9	10
Totally incomprehensive	Suitable with major deficiencies				Suitable with minor deficiencies				Totally comprehensive

Experts	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8	AVG
Scores	8	8	7	8	9	8	8	9	8.125

All eight experts agreed that the system works on the principle of knowledge-based engineering, although some of them pointed out minor deficiencies. Expert 1 highlighted that there is a need to link the previous cost estimation in the form of an equation, so that the curve fit within the equation would help to estimate the cost of the new product easily. Expert 5 explained that alternatives are compared according to values and targets only. Expert 4 highlighted the importance of the dynamic capture of knowledge and utilisation in the future.

The responses to the question “The process of cost estimation for lean product and process development is aligned with the developed system”, as well as the scale used to capture them in the questionnaire are illustrated in Table 6-23.

Table 6-23: Is the process of cost estimation for lean product and process development aligned with the developed system? – Ratings

1	2	3	4	5	6	7	8	9	10
Totally misaligned	Aligned with major deficiencies				Aligned with minor deficiencies				Totally aligned

Experts	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8	AVG
Scores	8	8	10	10	9	7	8	7	8.375

All eight experts agreed that the process of cost estimation for lean product and process development is fully aligned and works as per expectation, although some of them pointed out minor deficiencies. Expert 8 pointed out that the system should be capable of comparing an infinite number of alternative solutions. Expert 6 suggested that after eliminating the first, weakest solution, the system should propose an improvement area in the design to improve the remaining solutions.

6.4 Summary

This chapter presents the validation of a developed cost modelling system to support lean product and process development. Two case studies, along with eight experts' opinions, were carried out for this purpose.

Two case studies, which are related to two different industrial sectors, were used to validate the developed system. The first case study was from the automotive industry. It was validated for four purposes, i.e. comparison of alternative materials, comparison of alternative manufacturing processes, and comparison of alternative designs in the conceptual design stage, and design assessment along with cost estimation in the detailed design stage. The second case study was from the petroleum industry. This case study was validated for two aims, i.e. comparison of alternative materials and comparison of alternative designs in the conceptual design stage. The results indicate an improvement in the decision making, customer involvement in the decision making and a reduction in cost.

The system was also validated by eight experts belonging to different fields, i.e. experts in the field of cost estimation, lean product and process development experts and industrial experts. These experts evaluated the system on the basis of questionnaires provided to them.

The following chapter provides a discussion, offers conclusions and proposes future work following this thesis.

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CHAPTER 7

7 DISCUSSION, CONCLUSIONS AND FUTURE WORK

7.1 Introduction

In Chapter 5, the development of a cost modelling system to support lean product and process development was presented. The development was based on the observations which emerged from Chapter 2 (literature review) and Chapter 4 (current industrial practices). The developed system was validated in Chapter 6 (validation of developed system) through two industrial case studies and experts' opinions.

The purpose of this chapter is to present a discussion on the key themes considered throughout this thesis. Additionally, the conclusions drawn from this thesis are presented in this chapter.

7.2 Discussion of Key Research Findings

This section discusses the key findings achieved from this research. The discussion follows the sequence in which the thesis has been presented.

7.2.1 Literature review

The literature review covered the lean product and process development and cost estimation for lean product and process development. With regard to the former, the literature review revealed that the research into this topic is growing, and that companies are striving to adopt lean thinking in their product development process. The lean product and process development principles are available; however, there is a lack of tools and techniques that companies may implement in their product development process.

From the literature review carried out on set-based concurrent engineering, it can be seen that it is a process which considers a set of alternative solutions and narrows them down gradually to identify a final feasible solution. However, it is identified that there is no clear direction for defining a set of designs and methods for narrowing down the feasible design region by eliminating the weak design solutions.

Value is an important element of lean product and process development, which also helps designers in defining a set of designs in set-based concurrent engineering. It has been identified that the value definition at the beginning of product development is mostly ignored by product development team members. The literature stresses the need to define values with respect to company and customers, to realise the needs of all the stakeholders. A knowledge-based continuous improvement environment helps the lean product development team to survive and grow faster. In knowledge-based engineering, there is a need to capture and reuse the knowledge of cost dynamically. In the area of mistake-proofing, there is also a need to identify all types of mistakes that may occur in product development and eliminate them before the design is finalised in order to develop customer-acceptable mistake-proof products.

The literature review also was carried out in the area of cost estimation for lean product and process development. It was identified that a number of cost estimation methods are available. The selection of a particular method is entirely dependent on available estimation time, required precision of estimate, and degree of product innovation. Moreover, it was identified that cost is an important decision making element for the selection of alternative designs in lean product and process development. However, little or no effort has been made in this regard. Previously developed cost estimation systems and models mostly provide the information of cost but provide limited support to designers in terms of taking the right decisions. There is a need to enhance the capability of these systems. Although knowledge-based cost estimation systems have been developed in the past, these systems inadequately support the concepts of knowledge-based engineering, set-based concurrent engineering and mistake-proofing. Therefore, an extraordinary effort is required in this area.

7.2.2 Research methodology

As explained in Chapter 3, a qualitative research methodology was followed. The main weaknesses of qualitative research are potential bias from the participants and from the researcher as well. This bias nature can affect the validity and reliability of results. To mitigate these weaknesses, the researcher took a number of actions. One of the measures was the data collection from a number of sources. The researcher collected data from face to face interviews via semi-structured questionnaire, and a case study from within industry. The questionnaire used in this research was developed in consultation with three other PhD researchers involved in the LeanPPD project. Moreover, analysis of the interviews was sent to the participating industries for validation and feedback.

During the system development, the researcher utilised the documents provided by the industrial collaborator in the research. In addition, regular meetings with the industrial collaborator reduced the possibility of bias.

7.2.3 Current industrial practices

The researcher, after conducting face to face interviews and case study analysis, managed to capture the current industrial practices. It was identified that the objective of cost estimation is not fully recognised by the product development teams. Companies mostly employ cost estimation to target and reduce the overall product development cost, whereas, it is not utilised frequently as a decision making tool. Cost is considered to be a critical criterion during product development and companies mostly employ design to cost as an aid during product development; however, the product development team does not consider design to cost as an effective product development tool.

It was realised from the literature review that the technical leader/chief engineer should be responsible for managing the resources. However, the field survey showed that multiple departments are involved in cost estimation. In terms of cost estimation methods employed by the companies, it was identified that companies mostly employ case-based reasoning, analogical and feature/

activity-based costing in the design stage. In addition, since the commercial softwares require a huge investment, most of the companies prefer to use in-house developed cost estimation softwares.

In term of initiatives taken for the data storage and utilisation, a large number of companies claimed that they have already initiated projects for capturing the cost of previous projects. However, in real practice the data are stored in different media such as paper format, PDM database, ERP and in a share drive. These different cost data storage media require a substantial amount of time to retrieve the cost of previous projects. In terms of challenges faced by the development teams, it has been identified that they mostly face challenges regarding cost overrun issues.

European companies wish to develop the lean tools required for whole product development. In order to develop a cost modelling system to support lean product and process development, the participants would like to integrate three lean product enablers: set-based concurrent engineering, knowledge-based engineering and mistake-proofing, as these enablers have an enormous potential to improve the product development. However, the designers showed concerns about the tool, such as value stream mapping, as it creates hurdles for designers and restricts their innovation.

7.2.4 Cost modelling system to support lean product and process development

A new process for cost estimation has been proposed in this research. The new process employs target costing methodology to identify and eliminate the designs that do not fulfil the targets. It also supports the decision making through identification of alternative designs which greatly suit the requirements. In addition, the proposed process eliminates the design mistakes occurring by designers.

The foundations of the proposed cost modelling system to support lean product and process development are based on three lean product and process development enablers: set-based concurrent engineering, poka-yoke (mistake-proofing) and knowledge-based engineering, as explained below.

A five steps set-based concurrent engineering process was employed in the developed system to reduce the number of designs. The five steps process is as follows: (i) Explore customer and company values and give them preferences; (ii) Identify the target of each value through experts' judgement, past experience, analysis, experimentation/testing; (iii) Develop multiple alternative solutions concurrently; (iv) apply minimum constraints to find the compatibility of alternatives; and (v) narrow down the alternatives gradually to reach the final solution. To represent the output of multiple solutions, a matrix for communicating alternatives has been employed in the system. A quantification method has also been explored and employed within the system, which helps to identify and eliminate the weaker design solution. The trade-off values embedded into the system is also a helpful tool to identify the weakest solution.

Poka-yoke (mistake-proofing) in the developed system performs three objectives of mistakes elimination. The first is in manufacturability identification, where the mistakes during materials and machines selections are eliminated. Therefore, only a suitable design is selected for the cost estimation, which helps to minimise the cost estimation time and reliability of cost estimates. The second objective is in the product design, where the design mistakes created by designers during the detailed design of product are eliminated. Therefore only the right design is forwarded to the downstream manufacturing department, which helps to minimise the cost of rework. The third objective is in the process parameters selection. In this objective, the correct process parameters are forwarded to the manufacturing department which helps to eliminate the rework requirements. Rules have been embedded into the developed system to achieve these three mistakes elimination objectives.

In the developed system, a seven stages lean knowledge life cycle was employed to capture and reuse the knowledge. The seven stages are: (i) Knowledge identification; (ii) Previous product and domain knowledge capture;

(iii) Knowledge representation; (iv) Knowledge sharing; (v) Knowledge-based Engineering; (vi) Dynamic knowledge use and provision; and (vii) Dynamic knowledge capturing. In (i), interviews were conducted with product development team members to identify the required knowledge. Since the research is related to cost estimation, therefore, necessary cost estimation components such as machines' information, machines' availability, materials' information, and product design rules were identified as suitable knowledge for capturing. During (ii), the knowledge highlighted in the previous stage was collected with the help of product development team members. Once the knowledge was captured, it was transformed into suitable rules for demonstration in stage (iii). In (iv), the developed rules were shared with all stakeholders to view or modify them whenever changes occur in the product. The cost modelling system to support lean product and process development was developed in (v). This application was developed in C# 3.0 within a .NET Framework and Microsoft SQL Server 2008 to design and build rules. A CAD-Excel-SQL server interface was developed for reading and transferring the CAD data information into the SQL server for quick cost estimation. In (vi), the knowledge of both the previous and the new product was used concurrently to estimate the cost of the new product; and, the cost of the on-going project was proposed to capture and store in knowledge repository for the dynamic capturing (vii) of the cost of future projects.

Six modules, namely (i) value identification; (ii) manufacturing process/machines selection; (iii) material selection; (iv) geometric features specification; (v) geometric features and manufacturability assessment; and (vi) manufacturing time and cost estimation, have been integrated into the system. These modules have been developed in a particular sequence to follow the cost estimation process for lean product and process development. The backbone of the developed system is the knowledge database. Six separate groups of database namely (i) geometric features database; (ii) material database; (iii) machine database; (iv) geometric features assessment database; (v) manufacturability assessment database; and (vi) previous projects cost database, have been developed in the system. This database is linked with system modules to follow the cost estimation process for lean product and process development.

The system has been developed to support both the conceptual and detailed design stage. In the former, the system facilitates three options namely: (i) compare alternative materials; (ii) compare alternative manufacturing processes; and (iii) compare alternative designs. In the latter, the system facilitates only one option, i.e. assess the design and estimate the manufacturing and total cost of product along with other values.

A feature-based cost estimation method has been applied in the developed system. This method is mostly applicable for the companies motivated towards incremental innovation or really new innovation. The system supports the cost estimation of resistance spot welding, laser welding and, limited, number of machining processes. The cost model of these processes has been illustrated in Section 5.7.

7.2.5 Validation of the developed system

The system has been validated through two industrial case studies. One of the purposes of these case studies was to demonstrate the applicability of research in different industrial sectors. Therefore, the case studies from different industrial sectors fulfilled this purpose. These case studies are validated through the automotive and petroleum industries. Another purpose of the case studies was to prove the benefits achieved by the concerned industries through the application of the developed system. It was identified that the companies achieved the benefits as improvements in decision making, and reduction in design mistakes, cost estimation time, internal meetings to finalise the design, and quotation response time. Other associated benefits include: the development of a formalised cost estimation process, involvement of suppliers and customers in decision making, and negotiation of the selling price with suppliers.

In addition to the validation through case studies, the system was also validated through eight experts from different disciplines. Experts belonging to different fields evaluated the system on the basis of questionnaires provided to them. All the experts confirmed that the logic of the developed system is truly valid, the system is generalisable in other business sectors, the system is flexible and easy to use, and it has been developed for three lean product and process development enablers as per their true principles.

7.3 Main Contribution to Knowledge

This research has contributed to a better understanding of the cost estimation for lean product and process development. It has introduced a novel cost estimation process and system which enables designers to take the right decisions and eliminate mistakes in a knowledge-based, continuous improvement environment.

The key contributions of the research are summarised as follows:

- A quantification method has been explored which guides designers to eliminate the weaker design solutions. This method has been established on the basis of the fact that the selected design needs to satisfy the target cost, as well as meeting the customer and company values for a successful lean product and process development.
- A new cost estimation process for lean product and process development has been developed. The developed process is applicable in both the conceptual and detailed design stage. By following the process, designers can overcome the issues of lengthy revisions, cost overruns and mistakes in both the conceptual and detailed design stage. In addition, the capability of optimum design solution selection minimises the difference between experienced and inexperienced product development team members.
- A novel cost estimation method of the manufacturing process in the joining and machining domain, e.g. resistance spot welding, laser welding and machining processes, has been investigated and integrated into the developed system.
- Three lean product and process development enablers have been incorporated into the system. These enablers are knowledge-based engineering, set-based concurrent engineering and poka-yoke (mistake-proofing).They enable designers to take the right decisions at an early

design phase, validate the design before manufacturing, satisfy the targets and minimise the rework requirements.

7.4 Limitations of Research

This section presents the limitations of this research. These limitations are related to the research methodology, followed by the cost modelling system development and validation.

7.4.1 Research Methodology

Since the research is qualitative in nature, there was the possibility of bias and problems with validity, reliability and replication of the results due to the human aspect of the qualitative research method.

To counteract the probability of bias and associated problems, the data were collected through multiple sources i.e. interviews and a case study. The interviews with the experts from different fields within a number of organisations supported reducing the possibility of bias. The interviews were well documented and analysed in the light of the research theme. The analysis of results in the form of reports was sent back to the participants for their review, feedback and validation. In addition, the research-relevant case study was conducted carefully. In this process, the selected expert had wide experience in the organisation. It was ensured that the participant fully understood the case study and the requirements of the research.

7.4.2 Cost modelling system development

At the time of the project initiation, limited knowledge of lean product and process development was an issue. Moreover the lean tools and techniques were not clear to the industries who are motivated to adopt lean product and process development. Therefore, only three lean product and process development enablers could be identified at that stage. At present, the working of the proposed lean enablers is clear; therefore, the capability of the developed system could be improved by identifying and incorporating more lean product and process development enablers, such as supplier involvement strategy, lessons learnt and A3 problem solving.

In this research, the cost models of only manufacturing processes, namely joining and machining processes, were considered in the developed system. These limited numbers of processes restrict the application of the system in a wider number of industrial sectors.

The feature-based cost estimation method has been employed in the developed system which has limitations in terms of complete product information requirement. Therefore, only the companies motivated towards the incremental innovation or really new innovation can take advantage of the developed system. This limitation can be minimised by developing the system using other cost estimation methods and following the developed cost estimation process.

The CAD-Excel-SQL server interface has been proposed in the developed system, to read the CAD data and the estimation of cost. In addition, the cost targets have been proposed to be input by the user directly. Since the designers mostly avoid the cost estimation process due to the high number of inputs required to provide accurate cost estimation, these limitations need to be removed by providing a customised package which may tackle these problems.

7.4.3 Validation of the developed system

The system has been validated through two case studies. The researcher identified the case studies from two different sectors to describe the application of the developed system in different industrial sectors. Although validation through only two industries appears to be a small quantity, the researcher managed to validate the system through a number of options in each industry and therefore was able to minimise the consequences.

The system has also been validated by experts' opinions. To address the issue of bias, the researcher validated the system through experts belonging to different fields of expertise including academia and industry. Their collaborative validation reduced any bias of both the researcher's and the experts' opinions. In addition, the purpose of contacting different experts was to identify the advantages of the system. However, one limitation that occurred at this stage is that, from the eight experts who participated in the validation of the developed system, three also participated in its development and refinement stage. This could cause bias since their views were already taken into account at the development stage. However, the other five experts who were not involved at the development stage reduced the issues of bias.

7.5 Fulfilment of research aim and objectives

This section states how the four objectives of this thesis were achieved.

The first objective was to identify and analyse cost estimation, and lean product and process development best practices through an extensive literature review and industrial field study. In order to achieve this objective, the author conducted a literature review, followed by an industrial field study through semi-structured interviews and case study analysis. Based on the analyses, the researcher concluded the following:

- Lean product and process development is a growing research area at the present time. To go beyond lean manufacturing, the industry desires to develop the lean tools, techniques and principles for whole product development. However, it was identified that there is a lack of clarity in terms of lean enablers and adoption for European companies.
- European companies are highly supportive for initiating the necessary steps for the adoption of lean in the entire product development exercise; however, they are not willing to accept that Toyota is the leader in lean product development. Furthermore, they want to avoid the lean tools which create hurdles and decrease the creativity or innovation of their development team members.
- The product development team members are not clear about the importance of cost estimation. They employ it to reduce the cost of product and to achieve financial benefits. However, the most important factor of cost estimation (i.e. decision making) is unknown by most of the organisations.

- The product development team members employ a number of tools during product design and development but consider these tools (especially the design to cost tool) as less effective in terms of their performance.
- The product development team members mostly rely on in-house cost estimation tools as compared to commercially available softwares.

The second objective was to determine the lean product and process development enablers which will be incorporated into the cost modelling system. After the analysis of the literature review and interviews with the product development team members, the researcher identified that:

- Set-based concurrent engineering, knowledge-based engineering, and poka-yoke (mistake-proofing) are significant lean enablers. The incorporation of these enablers into the cost modelling system has the potential to improve the performance of product development.
- Set-based concurrent engineering improves the decisions, provides a number of solutions for backup support, enhances the product value and keeps the cost in the target range.
- The incorporation of knowledge-based engineering promotes the cost estimation, and captures and reuses the cost estimation knowledge for the improvement of future product.
- The incorporation of poka-yoke eliminates the mistakes related to product design, cost estimation and process parameters selection.

The third objective was to develop a cost modelling system to support lean product and process development. The researcher has achieved the following:

- A cost modelling system to support lean product and process development has been developed.
- This system application has been developed in C# 3.0 within .NET Framework and Microsoft SQL Server 2008.
- The system incorporates three lean product and process development enablers namely; set-based concurrent engineering, poka-yoke (mistake-proofing) and knowledge-based engineering.

- The data from the CAD file is transferred in the SQL server through a CAD-Excel-SQL server interface.
- Six modules namely: value identification module, manufacturing process/machines selection module, material selection module, geometric features specification module, geometric features and manufacturability assessment module, and manufacturing time and cost estimation module, have been embedded into the system. These modules have been developed in a sequence to follow the cost estimation process for lean product and process development.
- In addition, the system incorporates six separate groups of database namely: geometric features database, material database, machine database, geometric features assessment database, manufacturability assessment database, and previous projects cost database.

The fourth objective was to validate the system through industrial case studies and experts' opinions. To achieve this objective, the following activities were carried out:

- The system was validated through two industrial case studies within the automotive and petroleum industries.
- Validation through case studies demonstrated the applicability of the research to different industrial sectors. In addition, the benefits achieved by the application of the system further validated the system.
- The system was also validated through eight experts from different disciplines. Their views were collected to validate and improve the system.
- The experts validated the system in terms of logic, the generalisability for other business sectors, benefits and limitations, flexibility and ease of use, and system development for three lean product and process development enablers as per their true principles.
- The analysis of experts' opinions has been explained in Section 6.3.2, which validates the purpose of the system development.

In summary, the thesis has achieved the stated aim and objectives by demonstrating that the cost modelling system to support lean product and process development is a novel tool which enables designers and other product development team members to assess the design and provides decision support at an early product development stage.

7.6 Conclusions

In conclusion, it may be asserted that this research study has achieved the main aim and its set objectives of developing a cost modelling system to support lean product design and development. Moreover, this thesis has conducted the following:

- The thesis has presented a review of techniques, tools and methodologies of lean product and process development and cost estimation to support lean product and process development.
- The literature review and industrial field study exercise identified a number of research gaps. Significantly, the exercise generated a need for further work in the area of cost modelling to support lean product and process development.
- The developed cost modelling system to support lean product and process development contains three lean product and process development enablers, namely set-based concurrent engineering, knowledge-based engineering, and mistake-proofing (poka-yoke). This system application has been developed in C# 3.0 within .NET Framework and Microsoft SQL Server 2008.
- The developed cost modelling system has the capability to estimates product cost and associated values concurrently. Therefore, the designers may be enabled to estimate and utilise the product cost and associated values effectively in their daily jobs. In addition, the system helps the designers to eliminate mistakes during the design stage, and to incorporate the ‘customer voice’ during a critical decision making stage.
- The developed cost modelling system was validated through two industrial case studies within the automotive and petroleum industries. The validation demonstrated that the system has wide applicability in number of industrial sectors. The developed cost modelling system can

be used for the estimation of manufacturing costs in the design phase, specifically in the conceptual and detailed design phases. The cost modelling system can also be used to develop cost quotations. In addition, since the cost estimations of manufacturing processes (i.e. joining processes and machining processes) are embedded into the system, the companies having the capability of these manufacturing processes can therefore use the system directly, with any necessary adjustments according to their manufacturing capabilities.

7.7 Future Research

The literature review showed that lean product and process development is a key research area. The current research focused on three lean product and process development enablers which are set-based concurrent engineering, knowledge-based engineering, and mistake-proofing (poka-yoke). In the future, more lean product and process development enablers may be identified to improve the cost estimation process.

This research supports only two manufacturing domains, namely the machining and joining processes. More manufacturing processes need to be investigated and incorporated into the developed system to provide a full package for those organisations having a multiple process capability in their manufacturing facilities. In addition, the developed system has been validated through the automotive and petroleum industries only. In future, the cost estimation needs to be customised for other industrial sectors.

In the developed system, a strong solution selection has been proposed through the quantification method and trade-off value; however, other optimisation tools have not been considered in this research. In future, it will be necessary to compare the proposed methods with other multi-objective optimisation tools to improve the decision making capability.

Three mistake-proofing types namely: (i) mistakes elimination in manufacturability identification; (ii) mistakes elimination in product design; and (iii) mistakes elimination in process parameters selection have been incorporated in the developed system. In future, more mistakes need to be eliminated for developing high value products.

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APPENDIX A: SEMI STRUCTURED QUESTIONNAIRE FOR LEANPPD FIELD STUDY

Researcher: Wasim Ahmad

Supervisors: Dr. Essam Shehab, Prof. Hassan Abdalla

INTERVIEWEE DETAILS

Name	
Job Title	
Role in organisation	
Years of Experience in current role	
Previous Role(s)	
Years of experience in previous role(s)	
Tel	
Email	

1. Product Development Process

1.1. Do you have a formal product development (PD) model (visual representation of the PD process, including the various stages, activities, mechanisms and supporting tools) and is it effective in guiding the PD operations? (select one option)

Options		Effectiveness		
		Not Effective	*Somewhat Effective*	*Very Effective*
○	There is currently no PD model	○	○	○
○	The current PD model is developed by a central organisation that administers its implementation, but it is not followed	○	○	○
○	The current PD model is developed by a central organisation that administers its implementation, and it is followed	○	○	○
○	The current PD model is developed, and maintained by decentralised groups that administer its implementation in their respective areas	○	○	○

1.2. Do you have flexibility in how you do your job? (Or is it mandatory to comply to a process, that you do not have ownership of?) (select one option)

Options	
○	Engineers must complete defined tasks in the order of process documentation
○	Engineers must complete defined tasks in process documentation but the order is flexible
○	Engineers understand their responsibilities and are provided with company best practice information and complete key deliverables in accordance with project deadlines, but process documentation is not imposed on them

1.3. Is there a technical leader who is responsible for the entire development of a product from concept to launch? (select one option)

Options		Effectiveness		
		Not Effective	*Somewhat Effective*	*Very Effective*
☐	No technical supervisor has responsibility for the entire development of a product	○	○	○
☐	A project manager (non-technical) has responsibility for the entire development of a product while an engineer or a group of engineers share some responsibility	○	○	○
☐	A chief engineer with a team of engineers have responsibility for the entire development of a product	○	○	○

1.4. Every specification is a compromise between what customers want and what can be provided. How is a product specification stabilised in your product development process? (select one option)

Options	
○	Specification provided early on by customer or central organisation and must be adhered to
○	Specification provided early on, but subject to engineering alterations
○	Specification grows through continuous interactions along the stages of PD as the product understanding matures

1.5. How do you select the design solution that will be developed? (select one option)

	Options
○	We only produce one design solution for each product
○	We identify multiple solutions and select the one that most closely matches the design specification
○	We identify multiple solutions and select the solution that has the lowest development costs
○	We design multiple solutions for each product/component, and rule them out as more information becomes available (due to prototyping, testing, integration etc.)

1.6. How are your current processes and work methods reviewed/improved? (select one option)

	Options
○	Processes are not regularly reviewed
○	Processes are reviewed at regular intervals by experienced company members or a central organisation, but improvement suggestions are rarely incorporated
○	Processes are reviewed at regular intervals by experienced company members or a central organisation and there is a formal mechanism to capture improvement suggestions
○	Engineers are encouraged to make improvement suggestions at any time and there is a formal mechanism to capture suggestions, but engineers are not confident that good ideas will be incorporated
○	Engineers are encouraged to make improvement suggestions at any time and there is a formal mechanism to capture suggestions, and there is evidence that good ideas are regularly incorporated

1.7. Do manufacturing (production) engineers play an active role in each stage of product development? (select one option)

	Options
○	Once the design is complete, it is communicated to the manufacturing engineers
○	Once the detailed design is prepared, the manufacturing engineers are involved
○	Once the final concept is selected, the manufacturing engineers are involved
○	Manufacturing engineers are involved in the concept selection
○	Manufacturing engineers provide design constraints to design engineers before design solutions are prepared and they are also involved and referred to throughout the development process

1.8. Do your suppliers provide you with multiple alternatives for a single part (component)? (select one option)

	Options
◯	Suppliers provide one part (solution) based on a detailed design specification that we provide
◯	Suppliers have flexibility to provide one (solution) based on a rough design specification that we provide
◯	Suppliers provide multiple solutions for most parts and we work with them to develop the solution
◯	Suppliers inform us on developments in what they can provide and we together develop multiple solutions and progressively eliminate weak solutions as the product design solution matures

1.9. How are projects currently initiated, and does the product development process flow? (select one option)

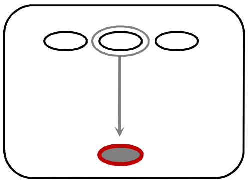
	Options
◯	Project initiation is dependent on customer requests and projects often run late
◯	Project initiation is dependent on customer requests, but projects rarely run late
◯	Projects start at regular intervals, but do not have consistent standard durations
◯	Projects start at regular intervals, have consistent standard durations, and are composed of multiple project types (e.g. facelifts, major mods, redesign/breakthrough), but projects do run late
◯	Projects start at regular intervals, have consistent standard durations, and are composed of multiple project types (e.g. facelifts, major mods, redesign/breakthrough), but projects are always on time

2. Product Design

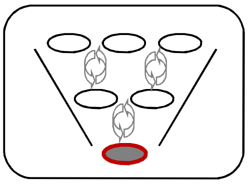
2.1 Which of the following tool/techniques have you formally implemented and utilised as an aid during the design of the product?

Tools/Techniques	Frequency of use			Effectiveness		
	Never	*Sometimes*	*Always*	*Not Effective*	*Somewhat Effective*	*Very Effective*
Design for Manufacture Assembly	○	○	○	○	○	○
FMEA *(Failure Modes Effective Analysis)*	○	○	○	○	○	○
TRIZ *(Theory of Inventive Problem Solving)*	○	○	○	○	○	○
Value Analysis /Value Engineering	○	○	○	○	○	○
Design to Cost	○	○	○	○	○	○
Design for Recyclability	○	○	○	○	○	○
Design for Modularity	○	○	○	○	○	○
Design for Sustainability	○	○	○	○	○	○
Design for Ergonomics	○	○	○	○	○	○
Design for Maintainability	○	○	○	○	○	○
Design for Aesthetics	○	○	○	○	○	○
Design for Six Sigma	○	○	○	○	○	○
Design for Reliability	○	○	○	○	○	○
Design for Usability *(user-friendliness)*	○	○	○	○	○	○
Design for Serviceability	○	○	○	○	○	○
Design for Minimum Risk	○	○	○	○	○	○
Other:	○	○	○	○	○	○

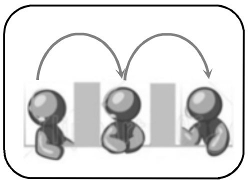
2.2 From the diagrams below can you indicate what method(s) of product development do you currently follow and rate its effectiveness?



Concurrent Eng



Set-Based Concurrent Eng



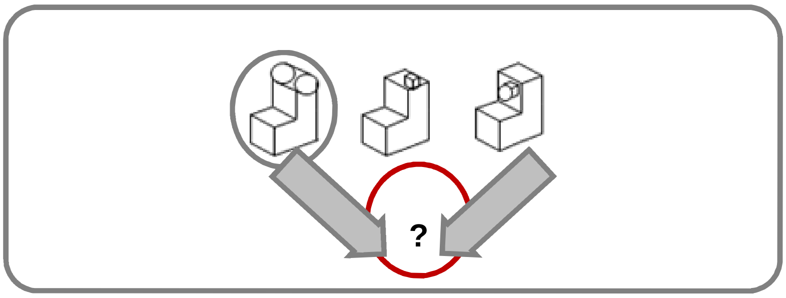
Sequential Manner

Method	Frequency of use			Effectiveness		
	Never	*Sometimes*	*Always*	*Not Effective*	*Somewhat Effective*	*Very Effective*
Concurrent Eng						
Set-based Concurrent Eng						
Sequential Manner						

2.3 During the design do you consider incorporating error/mistake-proofing (features/elements/mechanisms) for the following:

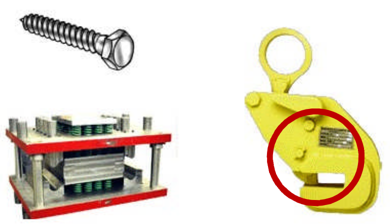
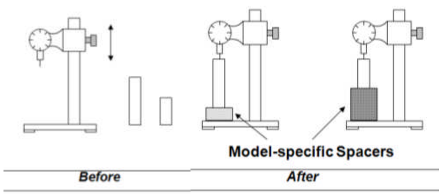
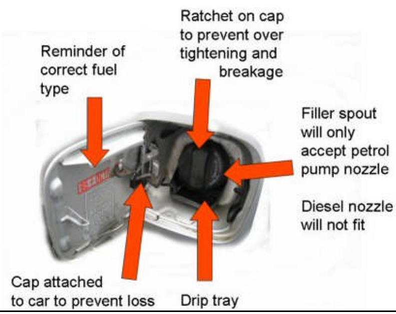
User	Incorporation		
	Never	*Sometimes*	*Always*
End User			
Prototyping			
Manufacture			
Assembly			
Testing			
Packaging			
Storage			
Distribution/sales			
Delivery			
Disposal			

2.4 During concept selection which of the following criteria do you consider in reaching a final solution? *(select applicable)*

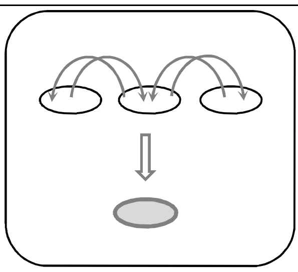


Criteria	Considerations			Criteria	Considerations		
	Sometimes	*Always*	*Never*		*Sometimes*	*Always*	*Never*
Function				Safety			
Critical to quality				Sustainability			
Durability				Ease of Manufacture			
Technology				Portability			
Cost				Enhanced Capability			
Performance				Usability			
Featurability				Reliability			
Ergonomics				Recyclability			
Customisation				Innovation			
Maintainability							

2.5 Have you considered adopting lean manufacturing techniques as a sense of inspiration during the conceptual design?

Example		Consideration Yes	Consideration No
<u>Single Minute Exchange Die (SMED)</u> Replace 4 bolts that require 32 turns before the die is secure, with a clip-on attachment.		☐	☐
<u>Quick Change Over (QCO)</u> Measuring different product models requires manual adjustment of the dial. By using model-specific spacers, adjustment time is reduced – allowing for quick change over.		☐	☐
<u>Poka-Yoke (Mistake-proofing)</u> Apply mistake-proofing mechanisms and features to prevent the loss of the fuel cap and remind the user to use the correct type of fuel		☐	☐

2.6 What approaches do you use in assuring optimal values (as assigned in the design specification) are achieved in your final design?

		Mathematical approaches		None Mathematical approaches
 	☐	Regression analysis	☐	Personal experience/understanding
	☐	Multi-objective optimisation	☐	Design Matrix
	☐	*Other:*	☐	*Other:*

2.7 What sources do you use to ensure the following are considered your design? *(Select applicable)*

sources / Factors	Rules	Design Standards	Inspiration	Innovation	Personal Intuition	Personal Experience	Design text books
Mistake-proofing	☐	☐	☐	☐	☐	☐	☐
Manufacturability	☐	☐	☐	☐	☐	☐	☐
Assembly	☐	☐	☐	☐	☐	☐	☐
Critical to quality	☐	☐	☐	☐	☐	☐	☐
Reliability	☐	☐	☐	☐	☐	☐	☐
Performance	☐	☐	☐	☐	☐	☐	☐
Sustainability	☐	☐	☐	☐	☐	☐	☐
Recyclability	☐	☐	☐	☐	☐	☐	☐
Innovation	☐	☐	☐	☐	☐	☐	☐
Ergonomics	☐	☐	☐	☐	☐	☐	☐
Cost	☐	☐	☐	☐	☐	☐	☐
	☐	☐	☐	☐	☐	☐	☐

3. Knowledge-Based Engineering

Introduction:

Efficient usage of product life cycle knowledge can only be accomplished if the knowledge is captured and structured in a way that it can be formally represented and reused within an organisation to support engineering decisions in product design and development. These procedures are defined as the Knowledge Life Cycle.

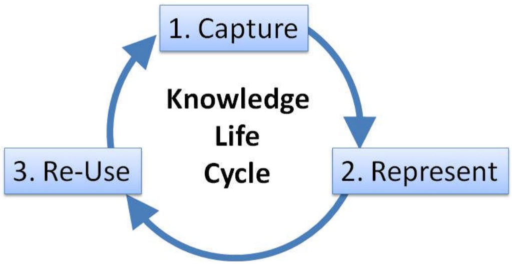


Figure: Knowledge Life Cycle

Knowledge Capturing

3.1 From your personal experience, how important do you assess the following sources of Knowledge? (Select one each)

Sources of Knowledge	Importance				Comments
	Not important	*Important*	*Very Important*	*Essential for Competitive Advantage*	
Design Rules:	◯	◯	◯	◯	
• Heuristic Rules – Company own design rules	◯	◯	◯	◯	
• Published Rules e.g. from Books	◯	◯	◯	◯	
• Rules from supplier e.g. from Material Provider	◯	◯	◯	◯	
Design Standards	◯	◯	◯	◯	
Capability of current resources	◯	◯	◯	◯	
Capability of current process	◯	◯	◯	◯	
Previous Projects	◯	◯	◯	◯	
Tacit Knowledge (Expertise of Engineers)	◯	◯	◯	◯	
Other	◯	◯	◯	◯	

3.2 Do you have formal initiatives or software(s) for capturing previous projects in a common database to provide a source of information and knowledge to support new product development? (Select one each)

Initiatives	Ratings				
	No Initiative & Not Interested	*Desired*	*Initiated*	*In Progress*	*Fully Established*
Lessons Learned	◌	◌	◌	◌	◌
CAD Files	◌	◌	◌	◌	◌
CAE Files	◌	◌	◌	◌	◌
Test Data	◌	◌	◌	◌	◌
BOM	◌	◌	◌	◌	◌
Technical Issues	◌	◌	◌	◌	◌
Cost Data	◌	◌	◌	◌	◌
Product Specifications	◌	◌	◌	◌	◌
Engineering Requirements	◌	◌	◌	◌	◌
Other	◌	◌	◌	◌	◌

3.3 Currently what are the implemented mechanisms to capture knowledge in your organisation and how efficient do you assess them? (Select one each)

Mechanisms	Usage			Effectiveness		
	Never	*Sometimes*	*Always*	*Not Effective*	*Somewhat Effective*	*Very Effective*
Verbal communication	◌	◌	◌	◌	◌	◌
Questionnaires	◌	◌	◌	◌	◌	◌
Document Templates	◌	◌	◌	◌	◌	◌
Web-Blogs/ Notice Boards	◌	◌	◌	◌	◌	◌
Other	◌	◌	◌	◌	◌	◌

Knowledge Representation and Reuse

3.4 What technologies or functions are used in your company to realize that captured knowledge is reused and shared during the product development process and how frequently it is used? In addition, do you think the knowledge content of the provided technologies is adequate in supporting decision taking in an efficient way? (Select one for usage and one for efficiency if applicable)

Technologies and Functions		Usage			Efficiency		
		Never	*Some times*	*Always*	*Not Supportive*	*Some Content is Adequate and Supportive*	*All Content is Adequate and Essential for decision taking*
☐	Knowledge-Based Engineering System	○	○	○	○	○	○
☐	Check Lists	○	○	○	○	○	○
☐	Design Templates	○	○	○	○	○	○
☐	Design & Development Handbook or Manual	○	○	○	○	○	○
☐	Quality Gates	○	○	○	○	○	○
☐	Assessment and Judgement from Experts in your Organisation	○	○	○	○	○	○
☐	Wikis	○	○	○	○	○	○
☐	Web Servers / Intranet	○	○	○	○	○	○
☐	E-Books	○	○	○	○	○	○
☐	Reports	○	○	○	○	○	○
☐	*Other*	○	○	○	○	○	○

3.5 How do you assess the importance of proven knowledge (e.g. test results) to support decision taking in product design and development? (Select one)

Not Important	Important	Very Important	Essential for any decision
○	○	○	○

3.6 In general any product development task consists of two key elements; routine tasks and innovative tasks.

- Routine tasks are standard and done for all products; as most of the products are not developed from scratch rather they are successive from previous designs
- Innovative tasks distinguish the new product from previous ones and have not been considered before.

The following picture represents a common distribution:

Please estimate as a percentage how much of your work is related to routine or innovative tasks? *(Select one)*

○	100% routine - 0% innovative
○	80% routine - 20% innovative
○	60% routine - 40% innovative
○	50% routine - 50% innovative
○	40% routine - 60% innovative
○	20% routine - 80% innovative
○	0% routine - 100% innovative

3.7 Please estimate how much, as a percentage, do you rely on knowledge from previous projects when designing a new product? (Select one)

○	100%
○	80%
○	60%
○	50%
○	40%
○	20%
○	0%

3.8 What specific knowledge domain do you need for your regular engineering activities? (Select one each)

	Importance		
Domain	*Not Important*	*Important*	*Very Important*
Injection Moulding	○	○	○
Stamping	○	○	○
Machining	○	○	○
Casting	○	○	○
Other	○	○	○

3.9 From your personal experience, which of the following activities would you consider to be important for engineering decision taking? (Select one each)

Activities	Importance: Not Important	Importance: Important	Importance: Very Important
Definition of Product Specifications	○	○	○
Design for Manufacture and Assembly	○	○	○
Poka-Yoke(Mistake-Proofing)	○	○	○
Tooling Design	○	○	○
Cost Calculation	○	○	○
Production Planning and Scheduling	○	○	○
Testing and Simulations	○	○	○
Other	○	○	○

3.10 Which commercial software do you use to support product development?

Software for:	*Commercial Software (e.g. Catia V5)*	*Release (e.g. R14)*
Product Lifecycle Management (PLM)		
Computer Aided Design (CAD)		
Product Data Management (PDM)		
Enterprise Resource Planning (ERP)		
Knowledge-Based Engineering (KBE)		
Computer Aided Engineering (CAE), e.g. CFD, FEA etc.		
Computer Aided Manufacturing (CAM)		
Cost Calculations		
Quality Management		
Other		

3.11 What is your experience in using the following acclaimed commercial Knowledge-Based Engineering systems? (If used select one and rate experience)

Used	Knowledge Based System	Experience			
		Bad – Not Useful	Occasionally Beneficial	Very Good – Recommended	Comments
☐	AML - TechnoSoft Inc	○	○	○	
☐	DriveWorks - SolidWorks	○	○	○	
☐	Knowledge Fusion - UG	○	○	○	
☐	Knowledgeware - Catia	○	○	○	
☐	Expert Framework - ProEng	○	○	○	
☐	Siemens Teamcenter - Enterprise Knowledge Foundation	○	○	○	
☐	PACE KBE Platform	○	○	○	
☐	*Other*	○	○	○	
☐	*I have not used any Knowledge-Based Engineering system before*				

3.12 How and which of the following data are stored at your company for a specific product during the entire product life cycle? (If used select one or multiples for storage)

No.	Used	Data	Storage Form				
			Paper Form	PDM Database	ERP	Share Drive	*Other*
1	☐	QfD	☐	☐	☐	☐	
2	☐	BOM	☐	☐	☐	☐	
3	☐	Cost Calculations	☐	☐	☐	☐	
4	☐	Make or Buy	☐	☐	☐	☐	
5	☐	RfQ	☐	☐	☐	☐	
6	☐	Specifications Documents	☐	☐	☐	☐	

7	☐	CAD Models	☐	☐	☐	☐	
8	☐	CAD Drawings	☐	☐	☐	☐	
9	☐	CAE Files	☐	☐	☐	☐	
10	☐	DFMEA	☐	☐	☐	☐	
11	☐	Test Reports	☐	☐	☐	☐	
12	☐	Design Validation Reports	☐	☐	☐	☐	
13	☐	Capacity Planning	☐	☐	☐	☐	
14	☐	PFMEA	☐	☐	☐	☐	
15	☐	PSW	☐	☐	☐	☐	
16	☐	PPAP Documents	☐	☐	☐	☐	
17	☐	Process Capability	☐	☐	☐	☐	
18	☐	Resource Capability	☐	☐	☐	☐	
19	☐	Change Requests	☐	☐	☐	☐	
20	☐	Customer Satisfaction Reports	☐	☐	☐	☐	
21	☐		☐	☐	☐	☐	

4. Cost Estimation

4.1. What is the role of cost estimation in product development?

(You may select multiple options)

☐	To target and reduce the overall development cost
☐	To compare the cost of product/component alternatives
☐	To support decision taking through cost visualisation
☐	Others (please explain)

4.2. Please assess the following product development cost drivers

Cost Drivers		Impact		N/A
		Major	*Minor*	
1	Product complexity and size	○	○	○
2	Technical difficulty	○	○	○
3	Development team experience, skill level and attitude	○	○	○
4	Method of communication among team members	○	○	○
5	Tools used for design (computer assisted tools)	○	○	○
6	Reuse factor	○	○	○
7	Design partners' involvement	○	○	○
8	Pressure to complete the job	○	○	○
9	Out of sequence work	○	○	○
10	Initial vendor specifications	○	○	○
11	Availability of customer-furnished information and /or equipments	○	○	○
12	Drawing types (Basic, assembly, manufacturing)	○	○	○
13	Formal process (Phase review or stage gate process)	○	○	○
14	*Other*	○	○	○

4.3. What methods do you use to analyse the cost of design?

Methods	Effectiveness		
	Not Effective	*Somewhat Effective*	*Very Effective*
Previous projects are analysed to generate the cost of a new product	◯	◯	◯
Expert system for cost estimation	◯	◯	◯
Historical cost data to predict the future cost	◯	◯	◯
Parametric approach to estimate the cost	◯	◯	◯
Activity / feature-based cost analysis	◯	◯	◯
Commercial software	◯	◯	◯
In-house developed software / technique	◯	◯	◯

4.4. Who is responsible for cost estimation in product design?

Finance personnel	☐
Design engineers	☐
Cost engineers	☐
Other	☐

5. Additional Questions

5.1 What are the main problems with your current PD model? (you may select more than one option)

	Options
☐	Too many sign-offs required (bureaucracy)
☐	Needs to be updated to meet changing demands
☐	Causes work to be delayed due to unnecessary tasks/activities
☐	Engineers are forced to spend time on lengthy documentation (reports)
☐	The model hasn't been well communicated to employees
☐	

5.2 What are the main challenges that you face in product development? (you may select more than one option)

	Options
☐	Products are not innovative enough
☐	We normally face cost overruns
☐	We are always overburdened with the quantity of work
☐	Downstream engineers pass optimised designs that require significant modification or redesign
☐	

5.3 What challenges do you face with regard to knowledge capture and representation? (you may select more than one option)

Options	
☐	Often very time-consuming
☐	Incompatibility of knowledge formats between different softwares
☐	Unnecessary knowledge capture and overcrowded documents/figures/posters/databases etc.
☐	Designers find it difficult to extract knowledge from previous projects
☐	

5.4 Do you think that mistakes in previous designs could have been prevented by the correct knowledge being provided at the right time? (select one option)

none ○ ○ ○ ○ ○ all

5.5 How are design problems currently resolved in your company (A3)? (please explain)

5.6 What is your idea of lean in design; do you consider it useful in your product design and development?

5.7 In future, what is your ambition towards LeanPPD, (1) lean principles or (2) lean tools?

5.8 LeanPPD is composed of a number of enablers; which enablers do you propose for developing a cost modelling system to support lean product and process development?

APPENDIX B: QUESTIONNAIRE, VALIDATION OF COST MODELLING SYSTEM TO SUPPORT LEAN PRODUCT AND PROCESS DEVELOPMENT

Researcher: Wasim Ahmad

Supervisors: Dr. Essam Shehab, Prof. Hassan Abdalla

A. General

1. Name: ..……………………………………………………………………………………...
2. Organization: …...……………………………………………………………….…………….
3. Role: ……………………………………………………………………………...……………..
4. Years of experience (in cost estimation OR Lean product and process development: …….

B. **Logic**

5. How logical is the cost modelling system to support lean product and process development?

1	2	3	4	5	6	7	8	9	10
Totally Unsuitable	Suitable with major deficiencies				Suitable with minor deficiencies				Totally suitable

If there are deficiencies, please describe them:

………
………
……………………………………………………………………………....………………………

6. Is the system suitable for the conceptual and detailed design stages?

1	2	3	4	5	6	7	8	9	10
Totally Unsuitable	Suitable with major deficiencies				Suitable with minor deficiencies				Totally suitable

If there are deficiencies, please describe them:

………
………
…………………………………………………….………………………………………………

Do you have any improvement suggestions?

………
………
………

7. Can the system be applied in an alternative product development stage? Yes No

If yes, please specify which stages

……

……

C. Generalisability

8. Do you think that the system can be generalisable and easily integrated into your business (or any business)?

1	2	3	4	5	6	7	8	9	10
Strongly disagree	Disagree		Slightly disagree		Slightly agree		Agree		Strongly agree

Explain the reason for your choice:

……

……

……

D. Benefits of using the system

9. How does the development team get benefit from the system?

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……

……

10. What are the benefits of Set-based concurrent engineering considerations in the developed system?

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11. What are the benefits of Poka-yoke considerations in the developed system?

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……

……

12. What are the benefits of Knowledge-based engineering considerations in the developed system?

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E. Limitations of the system

13. What are the potential limitations and challenges that arise in using the system?

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………………………………………………………………...

14. What are the potential organisational limitations and challenges that arise in applying the system?

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…………………………………………………………………...

F. Usability of the system

15. Assessment of usability of system in terms of features

a. What are the strongest features?

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………………………………………………………………...

b. What are the weakest features?

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…………………………………………………………………...

16. The terminologies and concepts used in the developed system are consistent? Yes No

17. Does the system provide a sufficient amount of information to guide the user? Yes No

18. Assess the time required to provide information for cost estimation

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……………………………………………………………………...

19. Please assess the following aspects in the system
    a. Layout
    b. Ease of navigation
    c. Information input into the system

20. Is the system flexible enough to be applied to different levels of information availability?

21. This system has been developed to generate the cost for conceptual and detailed design stages. Do you think that stages defined in the system are valid?

G. Assessment of the system

22. Please assess the completeness/suitability of the system for the following questions

a. The process of cost estimation for lean product and process development is aligned with the developed system

1	2	3	4	5	6	7	8	9	10
Totally misaligned	Aligned with major deficiencies				Aligned with minor deficiencies				Totally aligned

If it is not totally aligned, please explain the reason:

……
……
……

b. The set-based concurrent engineering application in the developed system

1	2	3	4	5	6	7	8	9	10
Totally incomprehensive	Suitable with major deficiencies				Suitable with minor deficiencies				Totally comprehensive

If it is not totally comprehensive, please explain the reason:

……
……
……

c. The poka-yoke application in the developed system

1	2	3	4	5	6	7	8	9	10
Totally incomprehensive	Suitable with major deficiencies				Suitable with minor deficiencies				Totally comprehensive

If it is not totally comprehensive, please explain the reason:

……
……
……

d. The knowledge-based engineering application in the developed system

1	2	3	4	5	6	7	8	9	10
Totally incomprehensive	Suitable with major deficiencies				Suitable with minor deficiencies				Totally comprehensive

If it is not totally comprehensive, please explain the reason:

……
……