CRANFIELD UNIVERSITY

MUHAMMAD SHARJEEL KHAN

THE CONSTRUCTION OF A MODEL FOR LEAN PRODUCT DEVELOPMENT

SCHOOL OF APPLIED SCIENCES

PhD Thesis
Academic Year: 2009 - 2012

Academic Supervisors: Dr. Ahmed Al-Ashaab & Dr. Essam Shehab
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This thesis is submitted in partial fulfilment of the requirements for the degree of PhD

ABSTRACT

'Lean' or 'lean thinking' refers to an improvement philosophy which focuses on the fulfilment of customer value and the reduction of waste. This philosophy is credited with the extraordinary rise of Toyota, one of the largest and most profitable automotive companies in the world. This thesis presents a pioneering study investigating how lean thinking should be applied to product development (PD).

The aim of the research was to construct an innovative model which supports the implementation of lean thinking in PD. This was achieved through progressive collaboration with practitioners from European manufacturing companies. The model provides a process for the conceptual development of an engineering project, and is composed of phases and activities for which methodologies have been defined.

The construction of the lean PD model was preceded by a systematic literature review and an industrial field study, wherein 36 semi-structured interviews were conducted in five manufacturing companies in Europe. The constructed model was later implemented on two real-life case studies via action research. The two conducted case studies involved the product architecture design for a car audio head unit and the development of a helicopter engine.

It was concluded that the lean PD model addresses various industrial challenges including customer value, communication, and innovation. Furthermore, by focusing on conceptual design, the lean PD model is expected to reduce design rework. As a result of the positive effects of the model, one of the companies involved intends to implement the lean PD model further, and wishes to extend the model to the rest of the organisation.

This research makes four main contributions: (1) a novel lean PD model; (2) a number of tools developed to support the model; (3) a framework for lean PD enablers; and (4) a categorisation of challenges faced by PD in industry used to verify the relevance of the lean PD model.

Keywords:

Innovation; set-based; engineering; design; knowledge-based; Toyota

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LIST OF PUBLICATIONS

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Cabello, A., Flores, K., Flores, M., Khan, M. S. and Al-Ashaab, A. (2012), "An analysis of methods to achieve conceptual robustness for lean product development", *18th International ICE Conference on Engineering, Technology and Innovation,* 18 - 20 June 2012, Munich.

Kerga, E. T., Blázquez, A. and Khan, M. S. (2012), "Advanced process planning in lean product and process development", *18th International ICE Conference on Engineering, Technology and Innovation,* 18-20 June, Munich.

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LIST OF ABBREVIATIONS

Abbreviation	**Full name/title**
ANC	Active noise cancellation
Ac	Additional capability
AHU	Audio head unit
Bn	Billion
Co.	Company
CAD	Computer-aided design
CAE	Computer-aided engineering
CAM	Computer-aided manufacturing
CU	Cranfield University
DFA	Design for assembly
DFM	Design for manufacturability
DAB	Digital audio broadcasting
DSP	Digital signal processor
PhD	Doctor of Philosophy
EQ	Equaliser
ESE	Euro Styles East
FMEA	Failure modes and effects analysis
FP7	Framework 7 project
GM	General Motors (Company)
HVAC	Heating, Ventilation and Air-Conditioning
HD	High definition
IMVP	International Motor Vehicle Program
KB	Knowledge-based
KBE	Knowledge-based engineering
LeanPPD	Lean product and process development
Lean PD	Lean product development
LAMDA	Look-ask-model-discuss-act
MIT	Massachusetts Institute of Technology
MBA	Master of Business Administration
MS	Microsoft
NPD	New product development

NUMMI	New United Motor Manufacturing Inc.
NTCP	Novelty, technological uncertainty, complexity and pace
OEM	Original equipment manufacturer
PDCA	Plan-do-check-act
PBD	Point-based design
PSU	Power supply unit
PCB	Printed circuit board
PD	Product development
QFD	Quality function deployment
R&D	Research and development
ROI	Return on investment
R-R	Rolls-Royce Plc.
SBCE	Set-based concurrent engineering
SBD	Set-based design
SBM	Set-based method
SRS	Sound retrieval system
SFC	Specific fuel consumption
SoW	Statement of work
SWOT	Strengths, weaknesses, opportunities, and threats
TRL	Technology readiness level
TRIZ	The theory of inventive problem solving
TPDS	Toyota product development system
TPS	Toyota production system
Tn	Trillion
UK	United Kingdom of Great Britain and Northern Ireland
USA	United States of America
UM	University of Michigan
VSM	Value-stream mapping
VES	Visteon Engineering Services
VW	Volkswagen
WIP	Work-in-progress

1 INTRODUCTION

1.1 Research Background

The challenges faced by engineering companies are fierce, and many find themselves struggling for mere survival. The entire engineering enterprise is being compelled to improve; some of the pressures include economic crises, evolving market demands, stiff global competition, and the need to improve time-to market (Yelkur and Herbig, 1996; Murman et al., 2000; Molina et al., 2005; De Brentani, 2010). Lean thinking – an improvement philosophy which focuses on the creation of value and the elimination of waste – is a potential weapon in this struggle (Womack and Jones, 2003).

After the cold war, engineering companies were forced to shift their engineering paradigm from ‘anything to enhance capability’ to ‘better, faster and cheaper’ (Murman et al., 2000). As a result, the following two decades were subject to considerable improvement, with companies focusing on incremental enhancement and innovation to their products, as well as shorter project lead times, and improved cost effectiveness. However, with all the progress made, there was still substantial opposition to the ‘better, faster and cheaper’ paradigm. Reduced research and development (R&D) investment led to a reduction in innovation. Faster lead times were impeded by the incorporation of advanced hardware and software tools, new methods, rapid changes to customer requirements (often due to technological advances), and the adherence to new standards and regulations. Cost effectiveness was obstructed by the push for higher employee salaries, inflation rates and increased global competition.

The automotive industry is one of the most competitive, and amidst this competition Toyota Motor Co. has in recent years dominated the industry, and is seen by many to be the epitome of ‘better, faster and cheaper’ (Womack et al., 1990).

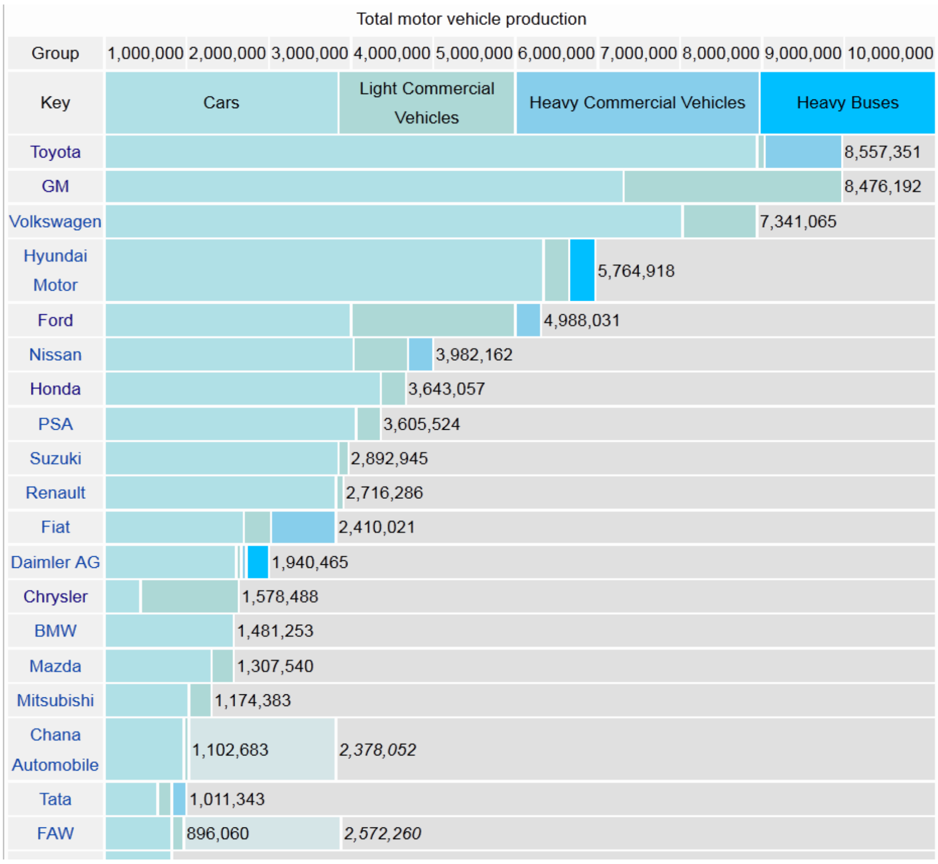

Figure 1.1 Top motor vehicle manufacturing companies by volume 2010 (World ranking of manufacturers, 2010)

Toyota overtook General Motors (GM) to become the world's largest automobile manufacturer in 2009 and 2010 (as shown in Figure 1.1), after GM had dominated the position for 77 years. Although Toyota was severely affected by vehicle recalls in 2009 and 2010, and a catastrophic earthquake and tsunami in 2011, revenues of ¥18.583tn ($232.385bn) and profits of ¥283.6bn (US$3.5bn) were reported in May 2012 (see A.1, Appendix A). During the same period GM filed for bankruptcy protection and required a $50bn USA government bailout. As a result GM reclaimed their previous position of the world's largest automobile manufacturer in 2011 and annual profits have since increased (see A.2, Appendix A). It is the accelerated climb, profit margins, and entrance into world markets that is key here, and this is what led researchers and practitioners to study Toyota and in turn establish lean thinking as an improvement philosophy (Womack et al., 1990).

Lean thinking has been a subject of research for more than two decades, the focus of which has been on improving manufacturing processes (Khalil and Stockton, 2010), as well as administration, management and the supply chain. There has however, been comparatively less research done to apply 'lean' to product development (PD): the transformation of a market opportunity and a set of assumptions about product technology into a product available for sale (Krishnan and Ulrich, 2001). This is rather strange, as PD has the greatest influence on the profitability of any product (Duverlie and Castelain, 1999). One possible reason for this is the 'room for creativity' and subsequent unstructured and iterative approach in traditional product design. Research undertaken to improve PD with lean thinking may prove instrumental in the progress of engineering.

A preliminary literature review and ensuing extensive review both confirmed the scarcity of academic research related to the application of lean thinking to PD. The opportunities for research in this field are countless and include defining the vernacular, proposing theory, developing methodologies, as well as analytical and experimental research.

1.2 Research Aim and Objectives

The primary aim of this research is to construct an innovative model which supports the implementation of lean thinking in PD. This aim is in response to the overall research question: how should lean thinking be applied to PD?

The model which has been constructed, combines lean PD principles and practices, and provides a unique process for the conceptual phase of PD. The model is expected to help an organisation to develop new products that are more customer-focused and innovative, while reducing project risk and late design changes.

From the onset of this research, project objectives were defined based on the research questions shown in Table 1.1. The five objectives are to:

1. Review lean product development (PD) approaches and examine the current state of literature on the subject of lean PD

2. Explore whether or not lean PD has a presence in industry and identify current PD challenges faced
3. Extract Lean PD principles and enablers from literature and define a framework that combines them
4. Develop a process model through which lean thinking can be implemented in PD
5. Test the model through industrial application

Table 1.1 Research questions aligned with objectives

Primary research question	Research objective	Supplementary questions
What does lean product development (PD) mean?	Review lean PD approaches and examine the current state of literature on the subject of lean PD	How have different researchers approached lean PD and how do they compare? Have any case studies of aspects of lean PD been conducted, if so what has been done? What are the constituents of lean PD, and is there any consensus among researchers?
Does lean PD have a presence in industry?	Explore whether or not lean PD has a presence in industry and identify current PD challenges faced	What are the challenges being faced by PD in industry?
How should lean PD be structured and represented?	Extract Lean PD principles and enablers from literature and define a framework that combines them	What are the core enablers for lean PD? Which tools and methods support lean PD?
How can lean PD principles and practices be implemented in a PD project?	Develop a process model through which lean thinking can be implemented in PD	Which tools can be used to support the implementation of lean PD?
How do lean PD principles and practices interact with the PD environment?	Test the model through industrial application	Is the lean PD model effective in addressing PD challenges?

1.3 Overview of the LeanPPD FP-7 project

This PhD project forms part of a European project titled ‘Lean Product and Process Development (LeanPPD)’. The European project is addressing the need of European manufacturing companies for a new paradigm that goes beyond lean manufacturing to ensure the lean transformation of PD in an engineering enterprise (LeanPPD website). This is a response to evolving market demands for products with greater customisation, higher quality, sustainability, quicker lead times and reduced cost. Models, methodologies and tools have been developed as part of the on-going research project to support the implementation of lean thinking in PD. An industry-focused approach has been ensured throughout the project by basing the research on business cases from different industry sectors in the European project consortium: aerospace, automotive and home appliances. These business cases helped to derive requirements for and test tools, methodologies and models developed as part of this research project. The multi-sector approach adopted supports the generalisation of research deliverables and findings. A list of consortium members is presented in Table 1.2.

Table 1.2 Members of the LeanPPD FP-7 project consortium

Consortium member name	Short name	Country
1. Tecnalia Corporación Tecnológica	Tecnalia	Spain
2. Cranfield University	CU	UK
3. Rolls-Royce	R-R	UK
4. University of Warwick	WARWICK	UK
5. Institut für angewandte Systemtechnik Bremen	ATB	Germany
6. VolksWagen A.G.	VW	Germany
7. Ecole Polytechnique Fédérale de Lausanne	EPFL	Switzerland
8. Visteon Engineering Services Ltd	VES	UK
9. SISTEPLANT	SIS	Spain
10. Politécnico of Milano	POLIMI	Italy
11. Indesit	INDESIT	Italy
12. SITECH Sp. So. o.	SITECH	Poland

1.4 Industrial collaborators

This section provides an overview of the companies that have collaborated with the researcher in order to conduct the research presented in this thesis.

1.4.1 Rolls-Royce Plc.

Rolls-Royce (R-R) is a world-leading provider of power systems and services for use on land, at sea and in the air. The company has established a strong position in civil aerospace, defence aerospace, marine, energy and nuclear global markets. In 2011, R-R performed well in difficult market conditions and continued to invest for future growth, including £908 million in R&D. R-R have a £62.2bn order book, underlying revenue has grown to £11.3bn ($18.153bn) and underlying profit has increased 21 per cent to £1.2bn ($1.928bn). Over 40,000 employees work for R-R in offices, manufacturing and service facilities in 50 countries around the world (R-R website).

R-R has a broad customer base comprising 600 airlines, 4,000 corporate and utility aircraft and helicopter operators, 160 armed forces, more than 2,000 marine customers including 70 navies, and energy customers in 120 countries. The company now has a total of 54,000 gas turbines in service worldwide and they generate a demand for high-value services throughout their operational lives.

R-R continues to invest in core technologies, products, people and capabilities with the objective of broadening and strengthening the product portfolio, improving efficiency and enhancing the environmental performance of its products. The company seeks to add value for its customers with aftermarket services that will enhance the performance and reliability of its products. This approach is fundamental to developing and sustaining collaborative long-term relationships in all its markets (LeanPPD website).

1.4.2 Visteon Engineering Services Ltd.

Visteon Engineering Services (VES) is a global automotive supplier with locations in 26 countries around the world. VES employs approximately 25,000 employees and had revenues of $8.05bn in 2011 (VES website). Aside from a strong global footprint, VES's foundation is its portfolio of winning products – climate, interiors and electronics (including lighting). VES is a leading designer and manufacturer of vehicle interior systems, integrating the highest levels of craftsmanship and functionality, focused on enhancing the driving experience. VES has a full range of electronic products that control critical vehicle systems and connect people to their vehicles and the world around them. The portfolio consists of cockpit electronics, containing audio and infotainment, instrumentation and displays, control panels, power train electronics, and a lighting portfolio including front and rear lighting. The third-core area of the business is climate. VES is a global leader in the designing and manufacturing components, modules and systems that help keep vehicle cabin temperatures at desired comfort levels and engines cool. Key product lines in this area include: HVAC systems, power-train cooling, compressors, fluid transport and engine induction. Customers include all the major global vehicle manufacturers such as Ford, GM, Chrysler [and Daimler], Renault, Nissan, Hyundai, Honda, BMW and VW (VES overview presentation, 2009).

1.4.3 Volkswagen AG

With production facilities in 15 countries and a broad product range stretching from the high-efficient "blue motion" passenger car to luxury and sports cars, light & heavy duty trucks and commercial vehicles, the Volkswagen Group (VW) has grown to be one of the largest globally active automotive manufacturers with world-wide sales of over eight million units in 2011. The VW comprises 12 active automotive and motorcycle companies. VW's annual revenues exceeded €159bn (over $205bn) in 2011. The average number of employees worldwide is approximately 400,000 (Volkswagen website).

Volkswagen's aim is to produce vehicles with ever increasing quality, safety and technology standards and at the same time reduce fuel consumption and emission levels. VW is interested in the application of new developments in all automotive areas not only to meet all relevant technical and legal requirements but also to satisfy customer demands on a consistently high level (LeanPPD website).

1.4.4 Indesit

Indesit is one of Europe's leading manufacturers and distributors of major domestic appliances, including washing machines, dryers, dishwashers, fridges, freezers, cookers, hoods, ovens and hobs. It is the undisputed leader in major markets such as Italy, the UK and Russia. Founded in 1975 and listed on the Milan stock exchange since 1987, the Group posted revenues of over €2.8bn (over $3.61bn) in 2011. Indesit Company has 14 production facilities (in Italy, Poland, the UK, Russia and Turkey) and 16,000 employees. The Group's main brands are Indesit, Hotpoint and Scholtès (Indesit website).

The company takes advantage of over 100 years of cumulative engineering experience, a highly motivated, qualified and inventive staff and an extensive network of partnerships with major companies and universities (LeanPPD website). The R&D division of the Indesit company owns all the patents on home automation, energy management, and electronic controls. (Indesit website).

1.4.5 Sitech Sp. z o.o.

The Sitech Group is a globally active subsidiary of Volkswagen AG with production companies in Germany, Poland and China. In Germany, Sitech GmbH has production facilities at Wolfsburg, Emden and Hanover. In Poland, the parent company of Sitech GmbH, Sitech Sp. z o.o., has one production facility, at Polkowice. The Sitech Group is also active in a joint venture in Shanghai (Sitech website).

The Sitech Group has positioned itself as a development supplier to Volkswagen with its own seat development team, supplying steel seat structures and complete seats to VW brands (LeanPPD website). Sitech also produces components such as central consoles and instrument panels that are fitted to many VW models. In 2010, Sitech produced and delivered to customers a total of 9.83 million complete seating sets (car seats). Sitech's customers are not only VW passenger cars (including AUDI, Skoda and Porsche), but also other car manufacturers in international market. The Sitech Group currently employs about 3,980 people, including 2,100 with Sitech GmbH in Germany (Wolfsburg: 1,400, Emden: 400, Hanover: 300), 1,500 employees at Polkowice (Poland) and about 380 in Shanghai (Sitech website).

1.5 Thesis Structure

This thesis is arranged as a monograph, comprising seven chapters that are structured according to the progression of the research conducted. An overview of the contents of the chapters is provided in Table 1.3. Each chapter starts with an introduction intended to help the reader understand the rationale behind the chapter organisation. Summaries are provided at the end of chapters 2-6 to help recap chapter contents and sum up any salient points.

Table 1.3 Thesis organisation: by chapter

Chapter 1	Introduction	• Research background • Aim and objectives • Overview of the wider LeanPPD European project • Overview of industrial collaborator companies
Chapter 2	Research Methodology	• Research context description • Research typology overview • Three-phase research design • Research methods employed • Approach towards data analysis • Research considerations
Chapter 3	Literature Review	• Review strategy • The historical foundation of lean PD • Research trends • Lean PD representations • Case study applications of lean PD • Research gaps
Chapter 4	Industrial Context	• Industrial field study description • Interview results • Discussion of field study results

Chapter 5	Model Construction	• The development of a framework for lean PD enablers • A summative review of research regarding the application of lean PD to conceptual design via set-based concurrent engineering • A synopsis of how the lean PD model was constructed • Methodological recommendations for lean PD model activities • Tools recommended to support the lean PD model • Implementation process for the lean PD model
Chapter 6	Industrial Applications	• An overview of the action research approach adopted during case studies • Results from a case study involving the product architecture design for a car audio head unit • Results from a case study involving the development of a helicopter engine
Chapter 7	Discussion and Conclusions	• Discussion of case study results and the articulation of findings • An evaluation of the research, including: the lean PD model itself, the research methodology, research limitations, and the fulfilment of research objectives • Key research contributions • Implications for practitioners who wish to implement the lean PD model, or lean PD in general • Suggestions for future research • Conclusions based on the research conducted
Appendices	A - E	• Automotive industry articles referred to in the introduction chapter • A table illustrating the numbers of practitioners involved in the research referred to in the research methodology chapter • An illustration of the stage-gate model referred to in the literature review chapter • An example of a PD model referred to in the literature review chapter • The interview instrument referred to in the industrial context chapter

2 RESEARCH METHODOLOGY

This chapter presents background information about the research design as well as the adopted research methodology.

This chapter is divided into seven sections:

Section 2.1 provides some contextual information about the research. Section 2.2 clarifies the research type by addressing both epistemological stances and research strategies related to the research in this thesis. In section 2.3 the research design is described and related to the research objectives presented in section 1.2. The research design draws on a number of research methods which are reviewed in section 2.4. This style of having research methods reviewed after describing the research design is somewhat unconventional, however, it was deemed appropriate in order to focus on research methods relevant to the described research design. Some key points regarding data analysis are discussed in section 2.5. Ethical considerations and threats to research trustworthiness are explained in section 2.6. A summary of the chapter is provided in section 2.7.

2.1 Research Context

It is important to clarify the context of research in order to develop an appropriate research methodology. This research focuses on contributing to the new product development (NPD) research area. NPD is the complete process of transforming conceptual ideas into tangible, marketable, and profitable products (Hart, 1996; Brethauer, 2002; Trott, 2008). This research may also fall under a number of other research areas including engineering design, systems engineering[1], and concurrent engineering[2].

The research reported in this thesis was conducted primarily in the United Kingdom between the summers of 2009 and 2012. A substantial proportion of

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[1] ‘Systems engineering’ is defined as “a methodical, disciplined approach for the design, realisation, technical management, operations, and retirement of a system.” (Kapurch, 2008)

[2] Concurrent engineering has been defined as “the consideration of the factors associated with the life cycle of the product during the design phase” (Abdalla, 1999)

the research was also conducted in a number of countries in Europe, including Germany, Italy, Poland, Spain and Switzerland.

The research presented was carried out by the author with the support of a consortium of industrial and research partners (see Table 1.2). Over 300 practitioners were involved over the duration of the project (see Appendix B). Due to the scale of the research conducted over a short timescale, a number of students also supported mainly for the purpose of data collection.

The research was applied during the concept development phase of real industrial projects at two different UK-based engineering companies.

2.2 Research Type

As the fundamental goal of this research is to contribute to knowledge, a philosophical stance and justification of what may be regarded as knowledge is important. Epistemology is the branch of philosophy concerned with the nature and limitations of human knowledge. It is recommended to discuss the epistemological standpoint before describing the actual design of research (Sayer, 1992). Research paradigms, strategies, types, and styles are all dependent on the research objectives or questions.

This research involves the study of human beings in social settings and is therefore under the umbrella of social science or social research. As the research involves the development of theory for a real world setting, it would be considered to be applied research as opposed to pure research. Kumar (2010) proposes four central purposes and subsequent types of research: descriptive, correlational, explanatory and exploratory. It can be concluded based on the research objectives that exploratory and descriptive are both suitable in this case. Research objectives 1 and 2 mainly involve exploratory research, while the remaining objectives require descriptive research.

In order to develop and communicate a rich understanding of the social setting and the impact of the research on it, a predominantly flexible and qualitative approach was adopted. This is especially significant where the research may need to draw on multiple perspectives and be responsive to both primary and secondary data. It is worth mentioning a point raised by Hood (2006) that 'most researchers will not fit neatly into the categories of any given typology'; the research presented in this thesis combines both epistemological standpoints and also research types. The standpoint that has been adopted is a hybrid of social constructivism and pragmatism. Social constructivism suggests that knowledge is created as a result of social interaction, while pragmatism suggests that knowledge is created as a result of practice. Moreover Robson (2011) commented that 'pragmatism provides a highly compatible theoretical underpinning to mixing two types of method in the same project'. It is envisaged that the contribution to knowledge will be both a result of the interaction between social phenomena and also what the researcher will develop as a result of what is learnt from practice.

Grounded theory, ethnography and case study research are three research strategies in qualitative research (Robson, 2011). Table 2.1 provides an overview of these three research strategies.

Table 2.1 Overview of three qualitative design strategies (adapted from Robson, 2011)

Research Strategy	Overview
Grounded Theory	The focus of research is on developing a theory of the particular social situation forming the basis of the study. The theory is 'grounded' in the sense of being derived from the study itself. Interviews are commonly used, but other methods are not excluded.
Ethnography	The focus of research is on the description and interpretation of the culture and social structure of a social group. Typically involves the longitudinal observation of participants, but other methods may also be used.
Case Study	The focus of research is on a case in its own right, and taking its context into account. Typically employs multiple data collection methods.

Robson (2011) describes mixed methods research as a new research paradigm where pragmatism is the social underpinning for the research. In this research it was envisaged that grounded theory would be employed for theoretical and methodological development, and case study research would be conducted for testing purposes. As the research involves a considerable amount of collaboration with industrial partner companies, it may also have some resemblance to ethnographic studies. Potential benefits of multi-strategy designs have been described by Robson (2011) and Bryman (2006), and include:

1. Triangulation due to different data types and methods
2. Completeness and comprehensiveness of the research setting
3. Ability to answer different research questions
4. Ability to deal with complex phenomena and situations
5. Explaining findings based on further investigation
6. Refining research questions based on qualitative data
7. Instrument development and testing

To further elaborate on the adopted approach, the research ties in very well with action research. Cohen et al. (2007) define action research as "a small scale intervention in the functioning of the real world and a close examination of the effects of such an intervention". Action research was employed to test the constructed lean PD model via case study research. The aspiration to develop a rich understanding of the social setting in question has already been mentioned, therefore a case study approach is deemed highly suitable. A case study can be used to describe what is learnt about a particular phenomenon within a contextual boundary, or propose some generalisations for similar contexts which may be tested in future case studies. Another advantage of adopting a case study approach is that it may benefit from prior development of theoretical propositions to guide data collection and analysis.

Having explained the typology of the research, the actual research design and selected methods will be discussed in the following sections.

2.3 Research Design Adopted

The research carried out as part of this study may be divided into three chronological phases (as illustrated in Figure 2.1). The first phase is the exploratory phase wherein the initial two objectives were addressed. This was followed by the development phase, in which a model and methodology was developed thus satisfying objectives 3 and 4. The third and final phase is the implementation phase through which the final objective was addressed.

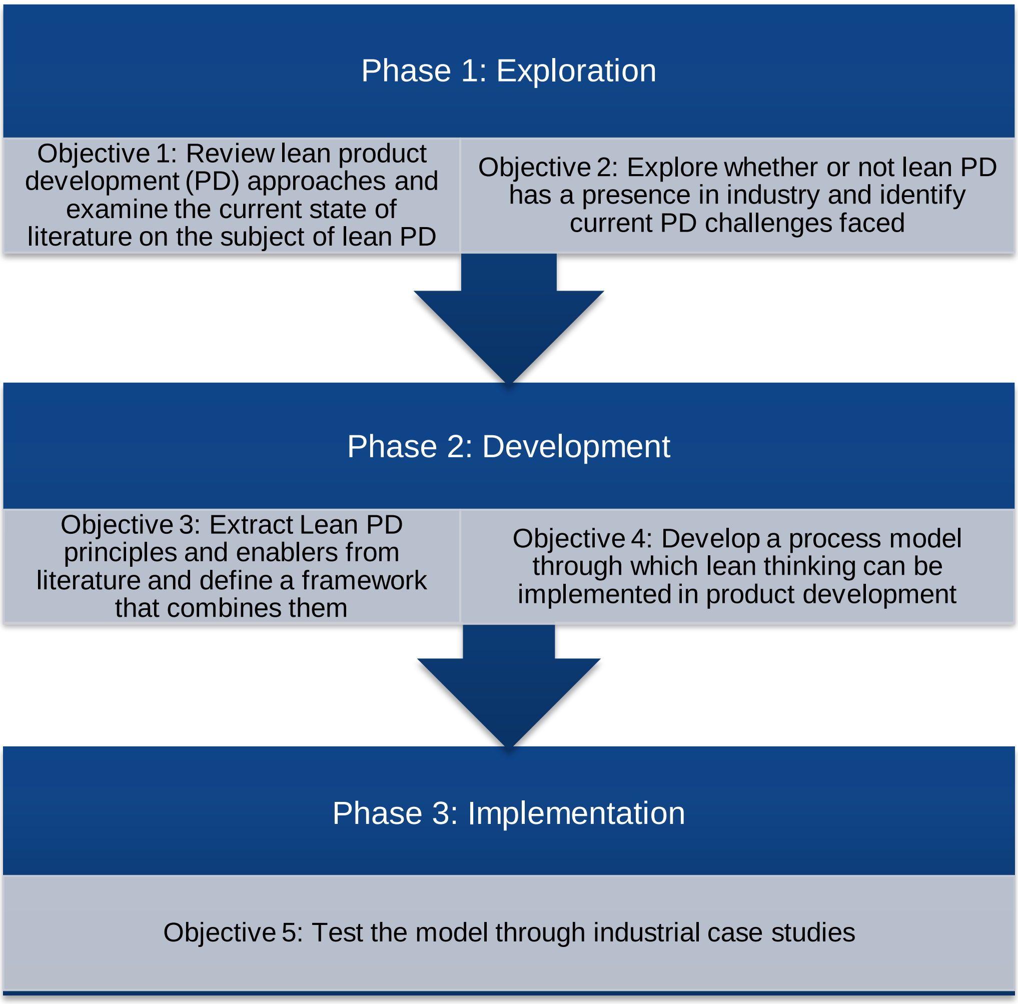

Figure 2.1 Phases of the research project

2.3.1 Phase 1: Exploration

The exploratory phase involved an extensive analysis of literature related to the research topic as well as an investigation of five industrial partner companies. An audit of the literature review was kept in the form of a spreadsheet which captured the summary and analysis of each source. Through the literature review research trends and gaps were identified. Research trends were critiqued and a preferred direction for the research was determined.

Initial interaction with industry involved various discussions through virtual web-based meetings, and face-to-face meetings at a number of European locations: UK, Germany, Italy, and Poland. Meetings were held in order to understand industrial needs and to ensure an industrial-driven approach to the research. Regular virtual web-based meetings were held in order to discuss research progress and other specific issues. Face-to-face meetings were deemed infeasible as they would have obliged participants to rendezvous at a single location, and may not have ensured the participation of all parties. Some face-to-face meetings were however, occasionally held. Minutes of each meeting were documented by the researcher as well as other attendees using notebooks.

The author visited the five industrial partner companies in order to develop an initial understanding of the context and also to discuss the research topic. This involved over 100 hours of interaction. It was deemed necessary to visit the companies in order to observe and experience the actual setting of both PD and production activities. The observations and contextual notes for each visit were documented separately. Observations were informal and not pre-structured. Corporate PowerPoint presentations and other PD documentation were also provided for analysis.

Further data was required in order to understand whether or not Lean PD had a presence in industry as well as the challenges that are currently faced. This was important in order to ascertain the relevance of Lean PD amidst the current challenges. Although observation and surveys could have been used, the researcher deemed semi-structured face-to-face interviews as the preferred method in order to gain a deeper understanding of participant views, opinions and non-verbal cues. Another key differentiator was the opportunity to change the line of enquiry and discuss tertiary points that surround the question, as opposed to simply obtaining answers to a restricted number of questions.

Based on the understanding gained from literature and initial interaction with industrial partner companies, a number of questions were developed. The questions were designed to probe discussions that would allow a qualitative analysis of a wider spectrum of lean PD enablers[3] based on interview transcripts. A semi-structured questionnaire was thus developed to guide the interview process. A group of designers, engineers and managers were interviewed face-to-face at each company, and were selected on a representative basis by the responsible parties at each company. Interviews were carried out in company meeting rooms with multiple researchers present in order to ensure accuracy of transcription. Recording was avoided to ensure that participants were not fearful of potential repercussions for their answers. Prior to each interview, participants were briefed about the purpose of the study; the anonymity of responses was also communicated. Each interview ranged from 90 to 120 minutes depending on the responses from the interviewees. Multiple choice questions were designed to allow the interviewees to objectively characterise their company's PD practice. Where respondents felt that the choices provided did not adequately represent their company or views, additional comments were captured. The questions did not use terms such as Toyota or Lean in order to remain impartial. Participants were given the option not to answer a question when they were unsure of the answer.

The results from the interviews were compiled in a report along with their analysis, and sent to industrial collaborator representatives via email for verification. Data collected via the interviews also helped to:

- Develop an understanding of how lean PD ideas and approaches are perceived and responded to by practitioners

[3] Lean PD enablers were extracted from literature, and are presented in section 3.5

- Develop a richer appreciation of the research context
- Improve understanding of nuances in the research context
- Provide expert opinion and guidance for the research
- Highlight gaps in the research and areas that required further attention
- Provide fresh stimuli for the research

2.3.2 Phase 2: Development

The first phase of research highlighted both research gaps and the relevance of the undertaken research. During the second phase of research a framework and methodology were developed to support the implementation of lean thinking in PD. This involved further analysis of literature and the identification of principles, methods and tools that previous research has used to describe lean PD. Principles, methods and tools were categorised to provide a framework of enablers for lean PD. This step was necessary in order to systematically perform a gap analysis between theoretical lean PD, and PD practice at the companies involved in phase 1 of the research. One of the key findings from this analysis was that the concept phase of PD is where lean PD was most unique.

Further analysis of the literature revealed additional principles for the application of lean thinking to the conceptual phase of PD via set-based concurrent engineering (SBCE). The combined principles for lean PD were organised in chronological order in line with the process of PD. The focus was on concept development as opposed to the latter stages of PD. Based on this analysis the lean PD model was divided into five stages composed of activities that are based on the identified principles of lean PD. The model was reviewed by research and industrial partners and iteratively improved over the duration of its development. The lean PD model was also associated with methods and tools extracted from literature related to lean PD (refer to table Table 3.2). Other tools were also included based on recommendations from industrial experts over a series of workshops.

2.3.3 Phase 3: Implementation

The developed lean PD model was applied to two case study projects during the implementation phase. The main purpose of this phase was to observe the effects of the model on the context of study.

Conducting multiple case studies in each of the two (or even more) companies would have been ideal; however this was infeasible due to budget and time restrictions. Multiple cases in a single context could also have been carried out, however generalisability would have been jeopardised and the results are likely not to be as rich as multiple case studies from different contexts (companies).

Multiple case studies were conducted as opposed to a single case study due to the analytical benefits that could be gained. Another reason for the selection of multiple case studies was the potential generalisability that could result if the findings in multiple cases are common[4]. The two case studies were conducted in parallel so that a single methodology could be tested in two different companies.

The researcher played a participatory role during the concept development of each case and thus this phase would be described as action research. The purpose of action research is to influence or improve a practice of some kind, the understanding of the practice, and the situation in which the practice takes place (Robson 2011). Action research was conducted in order to influence or change the concept development process employed on real PD projects, which may not have been possible otherwise. This approach also allowed the researcher to play an explanatory role for the duration of phase 3. Due to the extent of the task involved, a number of students assisted during this phase for data collection purposes. Data was collected in the form of documentation, archival records, observation, and a questionnaire. The questionnaire was used to collect data about the concept development process employed on a historic case. This was followed by a number of meetings to discuss the research implementation further. A gap analysis was conducted between the developed

[4] Common findings from the case studies are presented in section 7.1.3.1

lean PD model and the concept development process employed on the historic case. It may be suggested that comparing against company process documentation would be easier and more logical than the questionnaire approach adopted, however, one of the findings from phase 1 was that company process documentation is often idealistic. The gap analysis assisted in identifying potential changes from the current concept development processes employed, to the new approach proposed. These changes were proposed to PD representatives and the agreed changes were implemented. This resulted in bespoke versions of the methodology tailored for the specific application. Every effort was made to ensure that tailored versions were representative of the lean PD model and were harmonious with the case study objectives. The researcher participated in project meetings and guided the project to follow the new methodology. Once the implementation was complete, the changes were evaluated collaboratively with PD representatives at each company.

2.4 Methods Employed for Data Collection

Several methods were used for the purpose of data collection in this research. The research methods were selected based on the information required to achieve research objectives (Figure 2.2). As the selection of methods has already been discussed, this section will provide an overview of the methods employed.

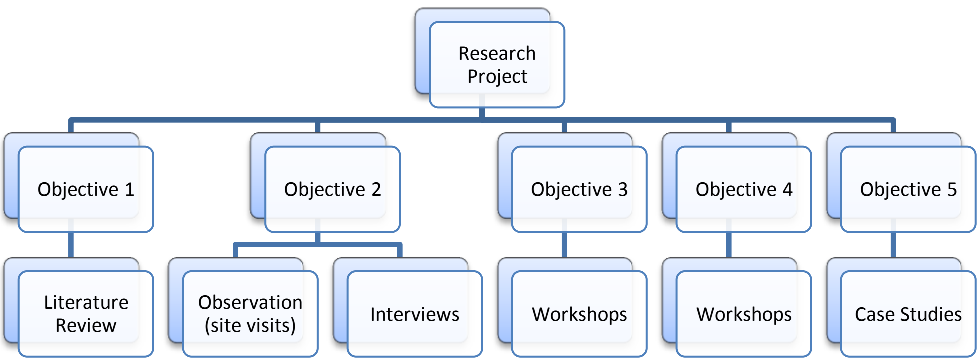

Figure 2.2 Employed data collection methods linked with research objectives

2.4.1 Literature Review

‘The literature is what is already known, and written down relevant to your research project’ (Robson, 2011). Multiple purposes for conducting a literature review have been proposed beyond the traditional review which comprises of the systematic identification, location, and analysis of documents containing information related to a research problem or aim. Some other purposes or advantages of a literature review adapted from Robson (2011) are that it:

1. Exposes relevant gaps in literature or knowledge, and identifies principal areas of dispute and uncertainty requiring further study
2. Helps identify general patterns to research and research findings by analysing multiple examples of research in the same area
3. Juxtaposes studies with apparently conflicting findings to help explore explanations for discrepancies
4. Helps to define terminology and identify variations in the definitions used by researchers or practitioners
5. Helps to identify appropriate research methodologies and instruments for data collection
6. Develops the researchers knowledge and understanding of the research topic
7. Helps to prevent duplicating research and avoid pitfalls and errors experienced in previous research

The types of literature that are included in an academic review may vary depending on its purposes. Furthermore there is also variation in the kinds of information that would be considered to be contributions to knowledge. Original research may be published in the form of articles, books, and reports. Each of these three publications may be subject to peer-review and academic rigour; however it is important to be aware of the strengths and weaknesses of each type. An evaluation of different types of publication is provided in Table 2.2.

Table 2.2 Strengths and weaknesses of different types of publication

Type of publication	Strengths	Weaknesses
Book	Unconstrained length allows room for elaboration	Peer-review process is often unstructured and may not be robust
Journal article	Academic rigour and originality are the main criteria	Readability may be compromised
Conference article	Succinct communication of original research	Academic rigour varies from one conference to another
Academic report (thesis)	Comprehensive representation of research	Quality varies depending on the researcher and research institution
Research project report	Flexible structure and representation	Stakeholder influence may affect the research results

Other sources may also be considered when conducting a literature review and may prove highly insightful. The internet is increasingly becoming a considerable source for research. Academic databases and portals, government and legal publications, and a myriad of websites for research dissemination are additional sources that have been considered.

2.4.2 Observation

Actions and behaviour of people are a central aspect of research involving the real world. Observation is an obvious technique that may be employed to gain both a preliminary and even detailed understanding of phenomenon or social contexts. Practitioners often view researchers as too theoretical and even unaware of the reality for which they conduct research. A researcher’s presence in the field of study can therefore be instrumental to their appreciation of the research setting.

Observational methods differ depending on the purpose of their use. The degree of pre-structure, formality, and the role of the observer are perhaps the main variables that influence the choice of approach. A formal approach imposes structure and direction on the research, while an informal approach allows the researcher considerable freedom in what information is gathered and how it is recorded, normally in the form of notes and any additional documentation. The researcher may play the role of a pure observer or a participant, the basic difference being that the former requires an observation instrument, whereas in the latter the researcher is in effect the instrument. A key feature of participant observation is that the observer seeks to become some kind of member of the observed group. This involves physical presence, interaction, learning and sharing social conventions etc.

Observation may be used for several purposes in a study. It is common to use observation in the exploratory phase of research, typically in an unstructured form, to gain insight into a situation as a precursor to subsequent research (Robson, 2011). Observation may be especially useful in multi-strategy research designs and may prove critical to achieving triangulation. Some of the dimensions that could be captured during observation include (adapted from Spradley, 1980):

1. Location: physical setting; rooms, outdoor spaces, etc.
2. Actors: the names and relevant details of the people involved
3. Activities: the various activities of the actors
4. Objects: physical elements
5. Acts: specific individual actions
6. Events: particular occasions e.g. meetings
7. Time: when the observation took place
8. Goals: what were the purposes of events
9. Feelings: emotions expressed and their particular contexts

2.4.3 Interviews

The interview is a survey approach which allows the researcher to explore a topic of study from a sampled population. Table 2.3 compares different survey approaches.

Table 2.3 Evaluation of survey approaches (adapted from Walsh, 2001)

Survey type	Advantages	Limitations
Postal survey	Saves on interviewing time Can reach a large number of people easily Respondents can think carefully about their answers	Response rates are often low You cannot be sure who actually filled in the questionnaire Can be expensive due to postage costs
Email survey/interview	Most convenient and quick approach Can reach a large number of people very easily Respondents can think carefully about their answers	Response rates are often low You cannot be sure who actually filled in the questionnaire Responses are often rushed
Telephone survey	Convenient and quick The interviewer can clarify questions and probe answers	Can be expensive if calling overseas You cannot see the respondent Can be difficult to explain verbally
Virtual interview	The interviewer can control the survey The interviewer can clarify questions and probe answers Non-verbal information can be gained	Subject to audio/visual quality The interviewer is likely to bias or influence the answers
Face-to-face interview	Response rate are likely to be high The interviewer has maximum control over the survey The interviewer can clarify questions and probe answers A wealth of non-verbal information can be gained	Most time-consuming approach The interviewer is likely to bias or influence the answers

Researchers who conduct surveys take a broad, systematic view of a topic at a specific moment in time and collect empirical data on it (Walsh, 2001). Out of the different survey approaches face-to-face interviews are preferred when the research focus is exploratory and rich qualitative data is sought.

Three common interview types are structured, semi-structured, and unstructured. Table 2.4 compares the three interview types.

Table 2.4 Evaluation of interview types (adapted from Robson, 2011)

Interview type	Overview	Advantages	Limitations
Fully structured	Has predetermined questions with fixed wording, usually in a pre-set order; the use of open response questions is the only essential difference from a survey questionnaire	Interviews can be quick Analysis of results is not complex	Does not fit easily into flexible research designs Interviewer does not have the flexibility to explore issues that arise during the interview
Semi-structured	The interviewer has an interview guide that serves as a checklist of topics to be covered and a default wording and order for the questions, but the wording and order are often substantially modified based on the flow of the interview, and additional unplanned questions are asked to follow up on what the interviewee says	Used in flexible and multi-strategy research designs Allows the interviewer to explore motives	May be the most time-consuming There may be inconsistencies between respondent answers and what the interviewer believes to be the case
Unstructured	The interviewer has a general area of interest and concern but lets the conversation develop within this area; it can be completely informal	Interview time can be constrained Interviewer has maximum control over data collection	Difficult to analyse results Lack of structure may lead to unsatisfactory results

The suitability of different interview types is dependent on the research objectives (or questions). The biggest challenge is to conduct interviews in a professional manner while avoiding influence and bias on the results. Interviews can be captured via a prepared template, by transcribing notes, and may also be recorded, subject to consent.

2.4.4 Workshops

Historically a workshop was a room or building in which mechanical products were manufactured or repaired. The term workshop is now also used to refer to an extended conference room meeting in which the sequence of items on the agenda leads to a clear deliverable. Researchers can control a workshop by maintaining the focus of discussion on the agenda and the end deliverable. Although workshops are not considered to be a fundamental data collection technique and are rarely found in research methodology literature, their merit is evident especially in industrial research. Key stakeholders can be brought together to discuss pressing research deliverables at the research setting or at another suitable and prudent location.

The involvement of key stakeholders and experts in this manner can be seen to provide a considerable level of validation to research. Consensus that is reached through workshops may be very supportive to research, while disagreement implies that further investigation is required in a particular issue. Workshops are highly suitable in flexible research design as they can be scheduled as and when required.

2.4.5 Case Studies

Yin (2003) describes the case study as “an empirical enquiry that investigates a contemporary phenomenon within its real life context, especially when the boundaries between phenomenon and context are not clearly evident”. He also suggests that case studies are preferred when “how” and “why” questions are posed, and when the focus is on contemporary phenomenon within a real life context. Conducting action research using a case study may be considered among the most challenging social science research endeavours due to the need to combine and balance between research development, participation, influence, description and evaluation. Early development of theory is very important in case study research, whether the purpose of the case study is to develop or test theory. The goal of theory development is to have a sufficient blueprint for your study, which requires theoretical propositions that assist in guiding case study data collection (Yin, 2003).

Assuming that through case study research statistical generalisation can be achieved is farfetched. Cases tend not to be sampling units, and should be considered to be experiments of some kind. Multiple cases are similar to multiple experiments and allow researchers to propose analytical generalisations based on their experimentation.

2.4.6 Other Methods

Additional research methods that were employed for data collection include: document analysis, reviewing archival records, and observing physical artefacts. These methods were employed in an unstructured fashion when they were deemed appropriate by the researcher and when the data became available. Additional techniques used for data collection and collaboration include face-to-face and web-based virtual meetings (via Cisco WebEx video conference software), telephone conversations, emails, and informal discussions. These methods will be discussed further throughout the subsequent chapters.

2.5 Data Analysis

In qualitative research it is important to consider the analysis of data before data collection. Walliman (2005) highlights that 'by immersing him/herself in the data and then searching out patterns, surprising phenomena and inconsistencies, the researcher can generate new concepts and theory, or uncover further instances of those already in existence'. Repetition of words, incidents, emotions, and irregularities are particularly insightful in qualitative analysis.

Preliminary analysis was conducted while applying each of the data collection methods and researcher comments were also captured. This process is quite natural as the researcher adopts an analytical attitude towards the type and amount of data being captured. The second stage of analysis is the codification and collation of data. Quantitative analysis was conducted with data extracted from the literature review and interviews. Spreadsheets were used to support data analysis where possible, primarily to visualise data in the form of tables and charts. Once data was processed, qualitative analysis was performed in order to help generate theory based on the data extracted.

Data from other methods were not analysed quantitatively, but were compiled in the form of reports. Reports were produced throughout the research providing analysis of data at the end of each research phase. Miles and Huberman (1994) propose three components of data analysis: data reduction, data display, and conclusion drawing and verification. Using suitable methods to display the data (in the form of matrices, graphs, charts and networks) aids in reducing data and its analysis (Walliman, 2005).

2.6 Research Considerations

In order to ensure the quality of research, ethics and trustworthiness have been given special attention.

2.6.1 Ethics

As social research is predominantly concerned with people, ethics requires careful consideration. The integrity of research depends on both its scientific rigour and also its ethical adequacy (Oxford Brookes University, Ethical Standards for Research Involving Human Participants: Code of Practice, 2003). The purpose of this research was to gain greater knowledge and understanding of a phenomenon and not to assist in any unethical cause. This research involved extensive communication with both researchers and practitioners, and care was taken to avoid any potential harm to those involved. An example of this is the anonymity of interviewee responses during interviews. In some cases the research was expected to benefit the participant and thus serve as a mutually beneficial activity.

Parties involved in the research did so with consent and were briefed about the research prior to their involvement. Honesty and integrity were central considerations in this research, especially between the researcher and participants. Participants were provided summaries of research results and consent was sought prior to any public dissemination activities. As this research involved company specific data, confidentiality agreements were signed and every effort was made to protect the confidentiality of data and information.

2.6.2 Research Trustworthiness

Validity and generalisability are considered to be central concepts to fixed research designs. Validity is concerned with whether the findings are really about what they appear to be about, while generalisability refers to the extent to which the findings of the enquiry are more generally applicable outside the specifics of the situation studied (Robson, 2011). However, Robson (2011) brings to light the considerable debate about the applicability of validity and generalisability to flexible research designs. This point is exacerbated in the case of multi strategy designs, as the different strategies are combined to neutralise weaknesses and enhance strengths in order to achieve stronger inferences.

In order to ensure research trustworthiness the following tactics (adapted from Robson, 2011) have been applied to address researcher bias, respondent bias and reactivity:

1. Prolonged involvement: research was conducted over three years with regular involvement of practitioners and other researchers
2. Data triangulation: by employing different research methods to capture data from different sources
3. Member checking: involved presenting results and analysis to participants in order to get feedback
4. Peer debriefing and support: debriefing sessions with other researchers after data collection helped to reduce researcher bias

5. Negative case analysis: searching for instances which will disconfirm your theory helps to identify limitations and boundaries, as well as refine the theory
6. Audit trail: a record of activities was kept for the duration of study
7. Research dissemination: activities through which research was publicised resulted in the refinement of research due to criticism and feedback

It is important to distinguish between internal and external generalisability (Maxwell, 1992). Internal generalisability refers to the generalisability of conclusions within the particular research setting, while external generalisability is beyond that setting. This point is exceptionally pertinent in flexible research design which is not reflective of random sampling. Internal generalisability may be claimed respective of the research settings, but external generalisability cannot. However, this is not to say that external generalisability cannot be commented on, or hypothesised based on even a single case (Yin, 2003). Another point raised with regards to generalisability is that the research should be repeatable. If theoretically a later investigator conducts the same research all over again using the same procedures they should arrive at the same conclusions. Research procedures, data collected, and analysis must all be carefully documented in order to warrant reliability.

2.7 Summary

In this chapter background information about the research design and the adopted research methodology were described.

The research presented in this thesis contributes to knowledge related to NPD. Research conducted is predominantly flexible and qualitative, and falls under the umbrella of social science. The research paradigm is a hybrid of social constructivism and pragmatism, and a multi-strategy design is employed. The research has been structured into three stages: (1) exploration; (2) development; and (3) implementation. Research methods used in the first phase include a literature review, observation, and semi-structured interviews. Workshops with practitioners and other researchers were the primary method used in phase 2. In phase 3 case studies were conducted to test the constructed lean PD model through action research. A variety of considerations were aforethought in order to mitigate research threats and biases, including ethical guidelines, prolonged involvement, and triangulation.

The next chapter presents the literature review conducted in phase 1 of the research project.

3 LITERATURE REVIEW

This chapter presents a systematic review of literature related to lean PD. The literature review addresses the first research objective: review lean PD approaches and examine the current state of literature on the subject of lean PD.

The chapter is divided into 8 sections:

In section 3.1 the strategy adopted for the literature search and review is explained. In section 3.2 the historical foundation of lean PD is presented. Research trends are presented and evaluated in section 3.3, followed by a synopsis of lean PD representations found in prior research in section 3.4. Enablers for lean PD were extracted from literature via content analysis and are presented in section 3.5. Case studies in which lean PD is suggested to have been implemented are reviewed in section 3.6. Identified research gaps are articulated in section 3.7, and a summary of the chapter is provided in section 3.8.

3.1 Literature Review Strategy

A fair amount of research has been conducted on the subject of lean PD. It was thus necessary to review and appreciate the various research contributions made to the subject, and in turn identify where and how this research could contribute further. As the subject of research is relatively new, this review covered all publications related to lean PD found in the English language. The literature review sought to determine the history and state-of-the-art of the research area, including research trends, representations, and empirical research. A list of enablers was also extracted from the literature, which includes all techniques, methods, tools and mechanisms proposed to support lean PD.

In order to identify and analyse the published body of knowledge on the subject, a systematic literature search was carried out (Robson, 2011). In the first stage, a foundational understanding of the subject was gained through textbooks and other books which tend to address a wider audience and present ideas in a simpler fashion. Library catalogues, internet booksellers, and electronic book (e-book) databases were the main sources for the first stage. In the second stage, the focus was on understanding the contributions made by researchers through academic research publications. A mixture of databases was used to locate journal and conference papers, including but not limited to: Scopus, ProQuest, EBSCO, Springerlink, IEEE Xplore, Emerald, and Science Direct. A number of research reports and other documentation were also reviewed; these were found primarily through internet searches. The third stage involved backtracking through references found in the literature considered to be key, in an attempt to ensure that important contributions were not overlooked. This stage was considered to be important due to the limitations of relying on keyword searches. Additional and new contributions were found using automated Zetoc alert emails which list the table of contents from particular journals and articles that match searches for keywords or authors' names.

Terms that define the research subject were selected as keywords. Keywords also included similar terms that may be used interchangeably. The main keywords that were used in searches were: 'lean product development', 'lean engineering', 'lean design', and 'lean model'. Logical terms were also used to identify literature such as 'lean AND product development', and 'lean OR Toyota AND design'. Truncating terms were also used in searches such as 'engineer$' or 'develop*'. Publications were limited to the social and physical sciences research areas and were initially filtered by title and abstract. Publications that were not relevant to PD such as those that focus on manufacturing process improvement, operations management of the supply chain, or software development were not reviewed. All relevant literature was reviewed and critically analysed, a synopsis of which is provided in the ensuing sections of this chapter.

3.2 The Foundation of Lean Product Development

Lean has become one of the most popular words in engineering improvement initiatives. In the foundation book 'The Machine that Changed the World (Womack et al., 1991), the term 'lean' was explained as a combination of principles and ideas developed by Toyota, many of which were described earlier by Taichi Ohno (Ohno, 1988) while outlining the Toyota production system (TPS). Another publication in 1996 promoted the philosophy of 'Lean Thinking', which focuses on enhancing value and eliminating waste through the application of five core lean principles: (1) specify value; (2) identify the value stream; (3) flow; (4) pull; and (5) perfection (Womack and Jones, 2003).

The term lean was initially used in reference to manufacturing operations; lean is now being used across a spectrum of sectors (Baines et al., 2006). The term lean has become confusing as some label Toyota practice as lean (Womack et al., 1991), while others label good practice as lean (Mynott, 2000). Lean thinking is no doubt based on Toyota unique approach, and much of the lean literature describes Toyota practices. Baines et al. (2006) identified a difference between earlier works where the focus was on waste elimination and latter works that focus on value creation. One reason for this may be that earlier works focused on manufacturing operations whereas latter works attempted to apply the same principles to different settings. Browning (2003) draws a similarity between engineering and an athlete, and argues that simply losing weight will not allow you to win a race. He quotes a number of cases where companies have over-emphasised on waste reduction and efficiency which resulted in lost production and sales. Such a causative relationship is however, not easy to prove. Lean manufacturing has evolved as its own discipline, and many have tried to adapt lean manufacturing principles to other parts of the engineering enterprise.

The term 'lean production' was first interjected by John Krafcik in a Sloan Management Review article in 1988 (Krafcik, 1988), based on his master's thesis at the Massachusetts Institute of Technology (MIT). Krafcik had been a quality engineer in the Toyota-GM New United Motor Manufacturing Inc.

(NUMMI) joint venture in California before his MBA studies at MIT. Krafcik's research was part of the International Motor Vehicle Program (IMVP) at MIT, which resulted in the aforementioned book ‘The Machine That Changed the World’ (Womack et al., 1991). Prior to the term 'lean', TPS was considered to be ‘fragile’ perhaps due to scepticism from the USA researchers who initiated the case study. The IMVP program actually had two initial phases, both led by Professor Daniel Roos; the founding director of MIT’s engineering systems division. The first 5-year research program began in 1979, aimed at understanding the future role of the automobile, while the second 5-year program began in 1985, aimed at measuring and describing the gap between the Western World and Japan (Holweg, 2007).

While the focus of research at MIT was on TPS, Allen Ward, a professor of mechanical engineering at the University of Michigan (UM) was more concerned with PD. Allen had initially completed his PhD at MIT - at the same time as the IMVP - in artificial intelligence for automating engineering design. Through his studies he realised that conventional PD was fundamentally flawed and stumbled upon what he coined set-based concurrent engineering (SBCE): a unique PD process (Sobek et al., 1999; Ward, 2007).

Allen Ward after joining UM continued in this research area. He began a case study of Toyota PD with a number of PhD students and later Jeffrey Liker, a professor of industrial and operations engineering. Allen was considered to be the leading USA authority on Toyota's PD process, and was the technical expert for a two-year collaborative project with the National Centre for Manufacturing Sciences in Michigan. The project (initiated by GM/Delphi) titled ‘Product Development Process - Methodology and Performance Measures’, aimed to understand how to make substantial PD improvements by studying world class companies that had distinguished themselves with a combination of high quality products and fast time to market (Kennedy, 2003).

3.3 Research Trends in Applying Lean Thinking to Product Development

Researchers and practitioners took different journeys once they realised the potential benefit that PD could gain by becoming 'Lean' (Khan et al., 2011). These approaches may be divided into five categories, presented in Table 3.1:

(1) Those who rebranded concurrent engineering as Lean PD

(2) Those who viewed 'Lean' as lean manufacturing - as described in the various texts analysing TPS – and tried to adapt the various constituents to make sense to PD; in some cases lean manufacturing was mixed with other theories and approaches in order to ensure the proposed Lean PD approach was relevant to PD

(3) Those who appreciated the foundation of Lean PD to be the Toyota PD system (TPDS), but - probably due to the lack of literature on the topic – incorporated some elements of TPDS into the five lean principles, combined with other ideas from lean manufacturing and tried to apply this combination to PD

(4) A fourth group that identified the foundation of 'lean' to be Toyota and went to great extents to study TPDS from the Toyota Motor Company and identified a more comprehensive set of principles and mechanisms directly related to PD that were argued to be theoretically superior to conventional PD theory

(5) A fifth group has recently emerged where researchers and practitioners have applied Toyota PD principles and practices in industrial companies; this group is reliant on group 4 for their principles and mechanisms

All of these groups used Toyota's success to support their approaches; however, Toyota's success was not achieved by the approaches described by groups 1-3. Rather Toyota's success was due to the approach and principles that they themselves adopted, and their PD practices may have contributed significantly. This means that only the researchers that focused purely on TPDS can substantiate such a claim (groups 4-5).

Table 3.1 Approaches/trends in applying lean thinking to product development

Approach	Author	Year	Title	Source/Publisher
1. Rebranding concurrent engineering as Lean PD	Karlsson and Ahlstrom	1996	The Difficult Path to Lean Product Development	Journal of Product Innovation Management
2. Adapting ideas from Lean Manufacture to PD in combination with other theories	Mynott	2000	Lean Product Development	American Technical Publishers
	Fiore	2003	Lean Strategies for Product Development	Quality Press
	Cooper and Edgett	2005	Lean, Rapid and Profitable New Product Development	Product Development Institute
	Anand and Kodali	2008	A Conceptual Framework for Lean New Product Development	International Journal of Product Development
	Gautam and Singh	2008	Lean product development: Maximizing the customer perceived value through design change (redesign)	International Journal of Production Economics
	Reinertsen	2009	The Principles of Product Development Flow	Celeritas Publishing
	Yadav and Allada	2009	Developing a Lean Value Model for Product Development	Proceedings of the ASME 2009 International Design Engineering Technical Conferences
	Kumar et al.	2009	Optimization of Lean New Product Development process using Advanced Dual Stage Performance Phase method	International Journal of Recent Trends in Engineering
	Beauregard, Bhuiyan	2011	Post-Certification Engineering	Engineering Management

Approach	Author	Year	Title	Source/Publisher
	and Thomas		Taxonomy and Task Value Optimization in the Aerospace Industry	Journal: Special Issue on Lean PD
	Nepal, Yadav and Solanki	2011	Improving the NPD Process by Applying Lean Principles: A Case Study	Engineering Management Journal: Special Issue on Lean PD
	Wang et al.	2012	Focus on Implementation: A Framework for Lean Product Development	Journal of Manufacturing Technology Management
3. Integrating elements of TPDS with Lean Manufacturing principles and methods, and applying them to PD	Haque and James-Moore	2004	Applying Lean Thinking to New Product Introduction	Journal of Engineering Design
	Oppenheim	2004	Lean Product Development Flow	Systems Engineering
	McManus	2005	Lean Engineering: Doing the Right Things Right	1st International Conference on Innovation and Integration in Aerospace Sciences
	Hines, Francis and Found	2006	Towards Lean Product Lifecycle Management	Journal of Manufacturing Technology Management
	Mascitelli	2006	The Lean Product Development Guidebook	Technology Perspectives
	Hines and Packham	2008	Implementing Lean New Product Development	Proceedings of the 2008 Industrial Engineering Research Conference
	Schuh, Lenders and Hieber	2008	Lean Innovation: Introducing Value Systems to Product Development	Proceedings to Portland International Conference 2008 on Management of Engineering & Technology

Approach	Author	Year	Title	Source/Publisher
	Oppenheim, Murman and Secor	2011	Lean Enablers for Systems Engineering	Systems Engineering
	Letens, Faris and Aken	2011	A Multilevel Framework for Lean Product Development System Design	Engineering Management Journal: Special Issue on Lean PD
4. Describing Toyota principles and practices based on a case study of TPDS	Ward, Liker, Cristiano and Sobek	1995	The Second Toyota Paradox: How Delaying Decisions Can Make Better Cars Faster	Sloan Management Review
	Sobek, Liker and Ward	1998	Another Look at How Toyota Integrates Product Development	Harvard Business Review
	Sobek, Ward and Liker	1999	Toyota's Principles of Set-Based Concurrent Engineering	Sloan Management Review
	Kennedy	2003	Product Development for the Lean Enterprise	The Oaklea Press
	Morgan and Liker	2006	The Toyota Product Development System: Integrating People, Process, and Technology	Productivity Press
	Ward	2007	Lean Product and Process Development	Lean Enterprise Institute
	Kennedy, Harmon and Minnock	2008	Ready, Set, Dominate: Implement Toyota's Set-based Learning for Developing Products and Nobody Can Catch You	Oaklea Press
5. Applying TPDS principles and practices in industry	Panchak	2009	Teledyne Benthos Adapts the Toyota Product Development System	Association of Manufacturing Excellence (Target)
	Oosterwal	2010	The Lean Machine: How Harley-Davidson Drove Top-Line Growth and	AMACOM

Approach	Author	Year	Title	Source/Publisher
			Profitability with Revolutionary Lean Product Development	
	Schipper and Swets	2009	Innovative Lean Development: How to Create, Implement and Maintain a Learning Culture Using Fast Learning Cycles	CRC Press
	Radeka	2011	Lean product development provides manufacturing value	Association of Manufacturing Excellence (Target)
	Liker and Morgan	2011	Lean Product Development as a System: A Case Study of Body and Stamping Development at Ford	Engineering Management Journal: Special Issue on Lean PD

Benchmarking is not a new practice. Its origin is often quoted as the measurement of feet on a bench by cobblers, while later it was re-contextualised to company performance measurement (Cooper and Kleinschmidt, 1995). The Japanese - while initiating their automobile industry - used benchmarking when they visited the USA automobile giants, as well as other European companies (Ohno, 1988). The USA used benchmarking in the International Motor Vehicle Program (IMVP) and the UM Toyota PD case study to evaluate and learn from Toyota and other Japanese companies. The global community develops as a whole and learns from each other to achieve excellence. This does not mean that one company will not outperform its competitors, nor does it mean that a company will disclose its advanced capabilities. Benchmarking however, must be done properly, and once complete, should not be generalised as an all-encompassing solution. Those who adopted lean manufacturing principles in PD may have witnessed some short term benefits. However, lean manufacturing was extracted from TPS and not TPDS.

When manufacturing principles and mechanisms are applied to PD there are a number of inconsistencies: the output is not a physical product received by a customer, eliminating waste does not identify poor quality, and value stream mapping (VSM) is based on the assumption that all the required value-adding steps are already present in a process. Another assumption is that five principles are sufficient for PD as they were for manufacturing, however, Morgan and Liker (2006) - who based their work on a case study of Toyota PD – developed 13 principles which were specific to PD.

Based on the analysis that has been described, the author believes that Lean PD should refer to PD theory that is based on Toyota PD principles and practices, and not lean manufacturing[5]. Once lean PD is established - based on TPDS - then it may evolve into a discipline in its own right. This was indeed the case with lean manufacturing. Similarly, lean PD must not be constrained to Toyota practices. Lean PD must be a dynamic system that is always improving and responding to the challenges that PD faces. Currently research conducted in this area is limited and it must be steered in the right direction to avoid mistakes in theory and practice.

In a review of Lean PD research, Leon and Farris (2011) categorised the research in this area into a number of knowledge domains including: performance, decisions, process, and strategy. Despite the difference in categorisation, their work is not contrary to the classification provided in this section. Through their analysis, the authors found that the Lean PD literature (to date) has focused on what types of things should be done (e.g. principles) in order to improve PD processes, rather than methodological recommendations for implementation (Leon and Farris, 2011).

3.4 Representations of Lean Product Development

Three models have been put forward to represent lean PD based on TPDS. These models will be discussed in this section.

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[5] As a result of this conclusion, lean PD and Toyota PD have been used interchangeably throughout the thesis

3.4.1 The Lean Product Development System Model

Morgan and Liker (2006) put forward what they refer to as a 'socio-technical systems model' to describe TPDS. The model summarises 13 principles organised around three central 'sub-systems': (1) process, (2) skilled people, and (3) tools and technology (Figure 3.1).

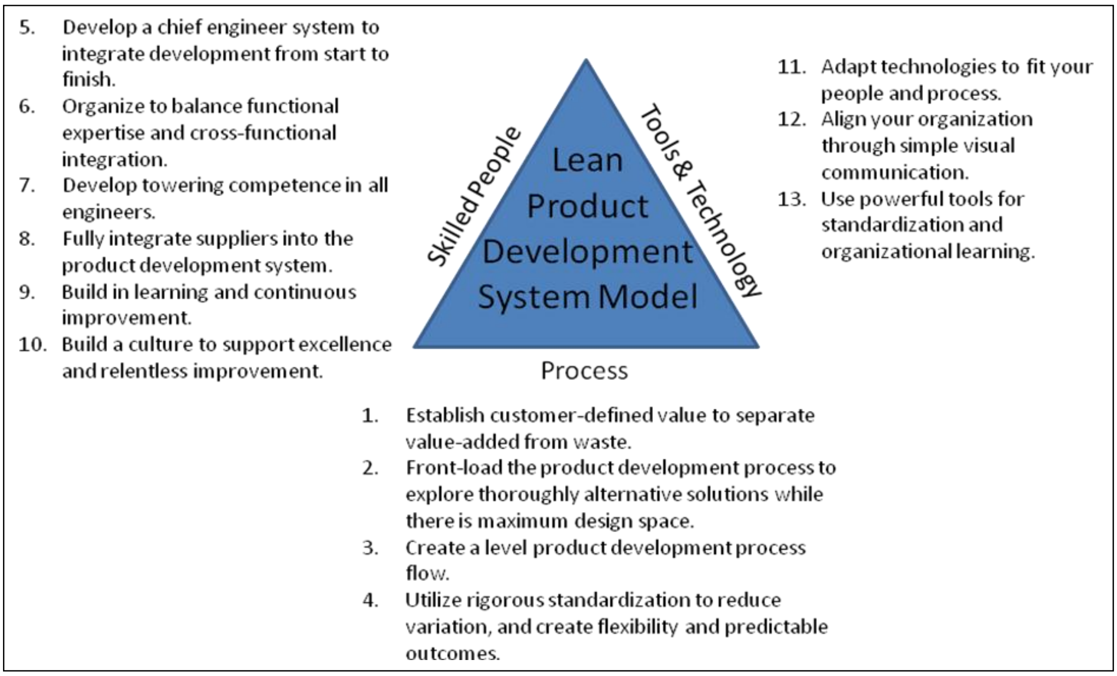

Figure 3.1 The lean product development system model (Morgan and Liker, 2006)

Each principle has been described with convincing rationale and illustrative anecdotes from Toyota. Various methods, tools and mechanisms have also been described providing the research community with arguably the most comprehensive overview of TPDS. The authors also foster the idea that TPDS is an integrated evolving system which has developed over time. Although elements of their system have been described in isolation, albeit organised around three sub-systems, this is by no means what industrialists would describe as a PD model that can be used to guide a project team through the

PD process[6]. The model is however, based upon empirical evidence and provides a wealth of insight into TPDS.

3.4.2 The Lean Development Model

Ward (2007) contributes another representation of lean PD, which has also been referred to as the emergent learning model. The author states that the secret to lean PD is "learning fast how to make good products" and maintains this focus on learning, creating 'usable' knowledge, and producing consistently profitable operational value streams throughout. Operational value streams are described as "the output of development, and run from suppliers through plants into product features and out to customers" (Ward, 2007). In order to achieve these goals, four cornerstones are described, and despite the term model not being used by the author, it is discussed here as a significant contribution in the field of research (Figure 3.2).

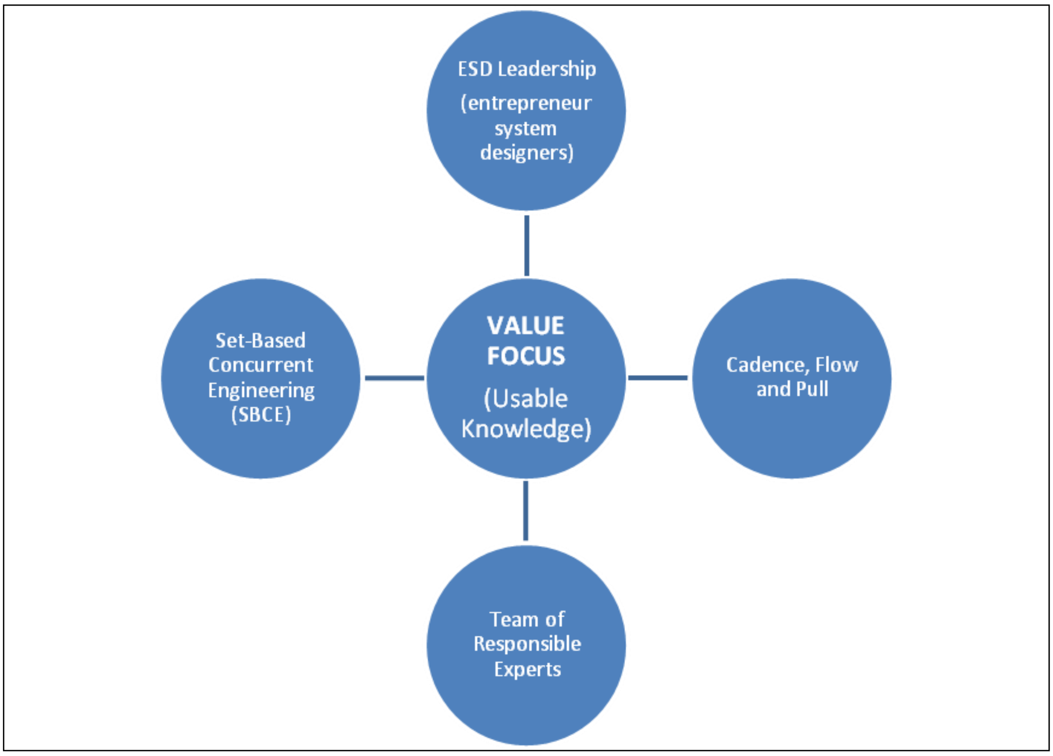

Figure 3.2 The lean development model (Ward, 2007)

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[6] A stage-gate PD model illustration and an PD model example are provided in Appendix C and Appendix D respectively

Although this work was intended to be a textbook and a culmination of research conducted on the Toyota PD process (Ward et al., 1995), SBCE (Sobek et al., 1999), and Toyota's management of PD (Sobek et al., 1998), it was published posthumously based on an incomplete manuscript. Nevertheless, this contribution provides further insight into SBCE, portfolio management, and a number of other lean PD principles and practices.

3.4.3 The Learning First Product Development Model

Kennedy et al. (2008) elaborate upon a previous fictional business novel to describe the transformation of a PD model by practitioners. It may be argued that this publication does not warrant referencing in an academic report; however the authors must be credited with their endeavour to develop a model for lean PD (Figure 3.3).

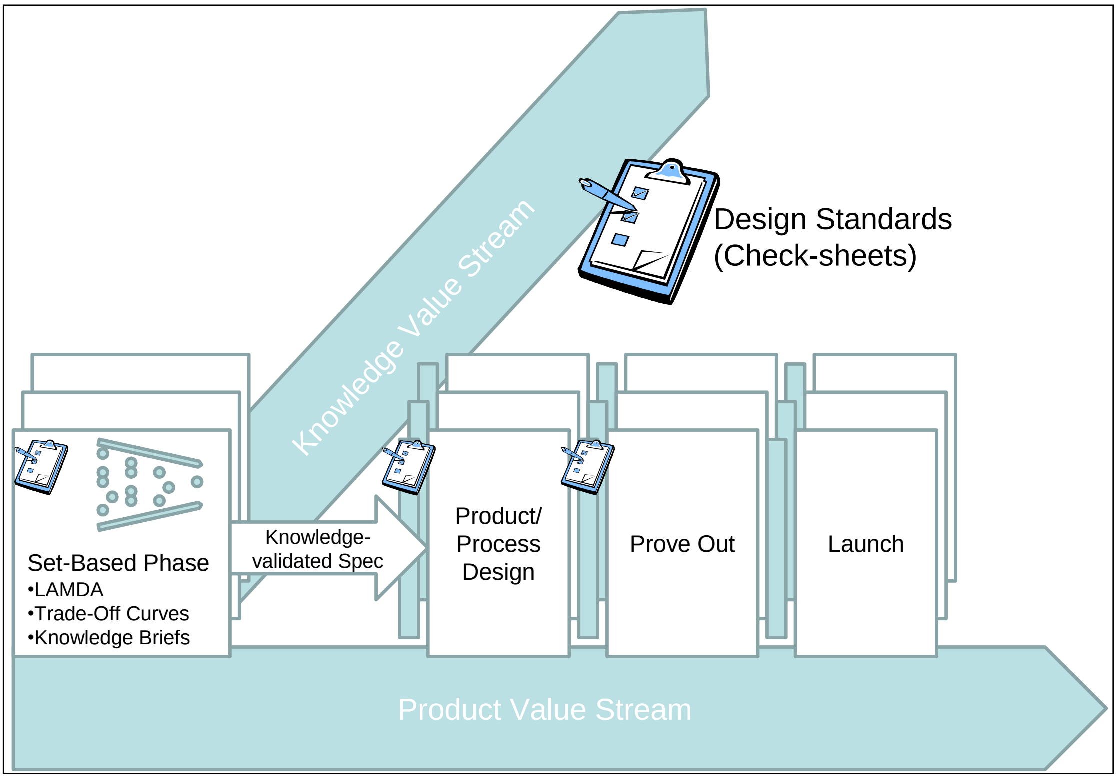

Figure 3.3 The learning first product development model (Kennedy et al., 2008)

Although this work does not contribute much to the theory, a number of methods, tools, and mechanisms are uniquely described. The authors are also credited with dividing PD value into two value streams: product and knowledge.

3.5 Enablers for Lean Product Development

This section introduces lean PD principles and practices - referred to here as enablers - advocated by researchers who focused on TPDS (group 4; see Table 3.1). Citations for the different enablers are provided in Table 3.2. An overview of TPDS enablers follows.

Table 3.2 Lean product development enablers: content analysis

#	Lean product development enablers	Ward et al. 1995	Sobek et al. 1998	Sobek et al. 1999	Ward 2007	Morgan & Liker 2006	Kennedy 2006	Kennedy et al. 2008	Tally
1	Checklists	x	x	x	x	x	x	x	7
2	Chief engineer (technical leadership)	x	x	x	x	x	x	x	7
3	Set-based concurrent engineering (SBCE)	x		x	x	x	x	x	6
4	Integrating/target events	x		x	x	x	x	x	6
5	Extensive prototyping/partial prototypes	x	x	x	x	x	x		6
6	Trade-off curves			x	x	x	x	x	5
7	Learning cycles: LAMDA/PDCA			x	x	x	x	x	5
8	Employee empowerment/individual responsibility		x		x	x	x	x	5
9	Expert workforce development		x		x	x	x	x	5
10	Technical design standards /rules			x		x	x	x	4
11	Knowledge-based environment / organisational learning				x	x	x	x	4
12	Knowledge flow/cadence				x	x	x	x	4
13	Minimum constraint (delaying specification, which is the results)	x		x	x		x		4
14	PD value-focus				x	x	x	x	4
15	Knowledge/information pull (right place at right time)				x	x	x	x	4
16	A3 /problem & action report		x		x	x		x	4
17	Mentoring (Genchi Gunbutsu)		x		x	x	x		4
18	Obeya (Collaboration) team rooms				x	x	x	x	4
19	Standardisation (skills, process, design)		x		x	x	x		4

#	Lean product development enablers	Ward et al. 1995	Sobek et al. 1998	Sobek et al. 1999	Ward 2007	Morgan & Liker 2006	Kennedy 2006	Kennedy et al. 2008	Tally
20	Value-stream mapping (VSM)				x	x		x	3
21	Vision: shared company/product vision (Hoshin management)				x	x	x		3
22	Culture (learning organisation; contribution focus-society/technical)				x	x		x	3
23	Rapid learning / comprehension				x	x		x	3
24	Knowledge focus (creation-capture-representation)				x		x	x	3
25	Digital engineering: simulation & analysis tools (CAD/CAE/CAM)	x				x		x	3
26	Multiple full-scale models	x		x		x			3
27	Supplier SBCE	x			x	x			3
28	Keiretsu (interlocking suppliers/reduced supplier tracking/communication)	x				x	x		3
29	Design structures functional plan (K4)	x		x		x			3
30	Knowledge reuse				x	x	x		3
31	Customer focus (needs & interests defined by customer)				x	x		x	3
32	Multi-project management/categorisation/ portfolio/families		x		x	x			3
33	Design in quality, mistake proofing (poke yoke)/early problem solving	x	x			x			3
34	QFD/quality matrices	x	x			x			3
35	Concept paper/blueprint	x	x			x			3
36	Visual management/control					x	x		2
37	Staggered design release/product launch				x	x			2
38	Systems thinking				x	x			2
39	Knowledge databases (searchable know-how database)					x	x		2
40	Nemawashi (consensus decision making/counsel - problem sharing)			x		x			2
41	5 why's/root-cause analysis					x		x	2
42	Kaizen (continuous improvement)					x	x		2

#	Lean product development enablers	Ward et al. 1995	Sobek et al. 1998	Sobek et al. 1999	Ward 2007	Morgan & Liker 2006	Kennedy 2006	Kennedy et al. 2008	Tally
43	Design (concepts) matrix			x		x			2
44	Cross-functional/module development teams	x				x			2
45	Lessons learnt/reflection (hansei)					x		x	2
46	Test-then-design				x			x	2
47	Separating research from development (advanced technology planning)				x	x			2
48	Standard architectures/ common parts		x			x			2
49	Limit curves/test to failure (Ijiwara)					x			1
50	Levelled workload					x			1
51	Competitor benchmark reports & teardown analysis					x			1
52	Ringi process (formal decision making process for significant decisions)					x			1
53	Process sheets (manufacturing process per part)					x			1
54	Simultaneous engineering					x			1
55	Digital Assembly					x			1
56	Design Autonomation (Jidoka)					x			1
57	Jikigata designs	x							1
58	Product Lifecycle Plan (Strategy)		x						1

SBCE is a unique PD process, and is considered the main enabler for Lean PD by some researchers (Ward, 2007). Other enablers that have been described in the literature are either embodied within or support this process. Design participants practise SBCE by reasoning, developing, and communicating about sets of solutions in parallel. As the design progresses, they gradually narrow their respective sets of solutions based on the knowledge gained. As they narrow, they commit to staying within the sets so that others can rely on their communication (Sobek et al., 1999). The theory of SBCE is illustrated in Figure 3.4. SBCE comprises of a number of principles, including: explore multiple alternatives, delay specification, a minimal constraint or 'delayed commitment' policy, extensive prototyping (or simulation), and convergence upon the optimum design (Ward et al., 1995). PD integration/target events are another important enabler (Kennedy et al., 2008). These events are unique design reviews used to guide the set-based process. Supplier strategy also resonates through the research, with the focus being on inter-locking key suppliers (keiretsu). Empowering suppliers to develop their own set-based approach can enable reduced supplier tracking and provide more room for innovation (Liker et al., 1998).

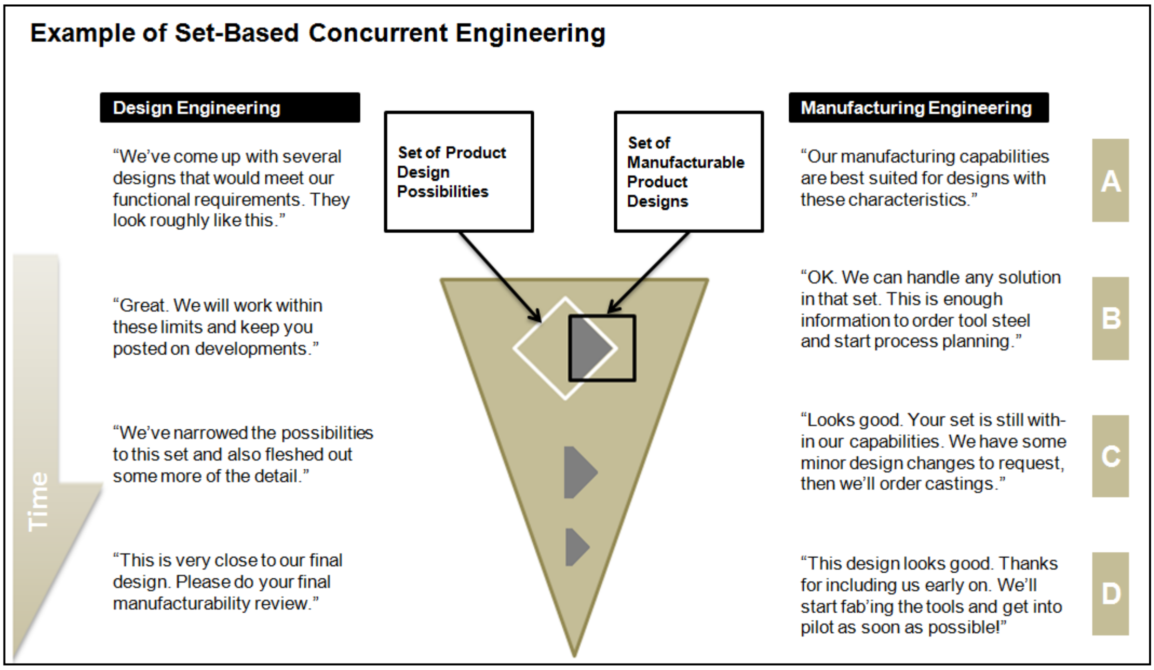

Figure 3.4 Set-based concurrent engineering process illustration (Sobek et al., 1999)

A number of additional design techniques are employed early in the design process, such as mistake proofing (Poke Yoke) and early problem solving, considering potential action scenarios to ensure conceptual robustness, and designing in quality (Morgan and Liker, 2006). A design structures plan is also developed by each functional department to work out the main features of the design.

Another design technique that can support lean PD, is 'test-to-failure' (Ijiwara in Japanese), wherein prototypes are tested to the breaking point (Morgan and

Liker, 2006). The aim of this technique is to learn more about designs and their thresholds, and produce 'limit curves' which capture the results (Oosterwal, 2010). This technique forms part of the 'test-then-design' approach, wherein decisions are made after designs have been tested and objective knowledge (evidence) is provided (Ward, 2007). Matrices for comparing design concepts and ensuring quality (e.g. quality function deployment) are also employed to aid in decision making (Sobek et al., 1999).

The concept of value-focus is mentioned by all researchers, and the differentiation between product/customer value and process/enterprise value is also echoed. This principle is shared with lean manufacturing alongside value stream mapping which has been mentioned briskly by a number of researchers. This may be indicative of its limited application in PD or lack of clarity as to how it should be applied. A strategic approach to PD is employed by Toyota which allows projects to be used to enhance the knowledge value-stream (Kennedy et al., 2008). Ward (2007) proposes a product portfolio, categorised into a number of project types: tailoring, strategic breakthrough, limited innovation and reintegration, and research. Each category has a standard duration and follows a regular drumbeat with standard intervals. These development projects extract mature technologies from advanced technology teams that focus on R&D. Once a design is sufficiently mature for launch its release may be staggered to align with a multi-project plan that ensures the strategic launch of new products (Ward, 2007). This process is symbolic of the holistic systems thinking that Toyota applies to PD.

The Chief Engineer technical leadership is another enabler in which a technical leader is involved prior to conception and remains at the helm throughout the entire PD process (Morgan and Liker, 2006). The chief engineer follows a shared company vision and is responsible for the generation of a design concept document, which is used to communicate the vision for the product system. Cross-functional module development teams also play a role in the chief engineer system (Morgan and Liker, 2006).

Another major enabler is a knowledge-based (KB) environment in which learning more about the design alternatives is the focus of PD activities (Ward, 2007). Ensuring knowledge is pulled by upstream processes as opposed to pushed by downstream processes is another important factor which ensures that knowledge flows and is received in the right place at the right time (Morgan and Liker, 2006). Mechanisms for capturing, representing and communicating knowledge support the KB environment. These include: trade-off curves, check sheets, technical design standards and rules, and A3 single-sheet knowledge representations, which are primarily used for problem solving (Ward, 2007). These methods collectively provide a means for rapid communication and comprehension. Digital engineering including CAD, CAM, CAE, and other simulation software also support the KB environment (Morgan and Liker, 2006). A learning organisation culture wherein employees are rewarded and appreciated for their technical contribution is another echoed enabler. Junior employees are mentored by senior employees who train their students how to approach technical problems in addition to passing on a wealth of tacit knowledge. Learning cycles such as PDCA (plan-do-check-act), and LAMDA (look-ask-model-discuss-act) represent the general problem solving approach. This collaboration sustains an expert workforce which is empowered to make decisions and do their own responsibility-based planning. Another enabler is a knowledge-based (KB) engineering system, also referred to as a 'know-how' database (Morgan and Liker, 2006). The KB engineering system captures knowledge in a centralised database, with the capability to locate and extract required information easily. Another frequently mentioned technique is a lessons learnt process wherein experiences are reflected upon (Hansei in Japanese) and captured in the KB engineering system. Lessons learnt may also be published in books and provided to employees.

A culture for continuous improvement (Kaizen) in addition to formal methods to incorporate improvements, have been suggested by researchers to be a key part of lean PD (Sobek et al., 1998). This enabler is also shared with lean manufacturing. Standardisation of processes, skills, and design methods allows continuous improvement to be regularly considered during meetings and reviews (Morgan and Liker, 2006). The Toyota approach to problem solving (Obeya in Japanese) is a pertinent example, where an A3-single sheet problem report is prepared and then used as the focal-point of collaborative meetings in team rooms. The aim is to share the problem, take counsel and arrive at a consensus for decisions. This often includes some root-cause analysis and an investigation known as '5 whys' where the source of a problem is identified.

A number of other enablers have been mentioned by a single researcher or group, and may be relevant enablers for lean PD. However due to the unilateral mention and based on the critical analysis conducted, it is likely that they are not fundamental lean PD enablers.

Oppenheim et al. (2011) offer a comprehensive checklist of what they term 'lean enablers for systems engineering' to the research field. The checklist is an amalgamation of recommendations for systems engineering organised around 6 principles: (1) capture value defined by the customer; (2) map the value stream and eliminate waste; (3) flow the work through the planned and streamlined value-adding steps and processes; (4) let the customers pull value; (5) pursue perfection of all processes; and (6) respect people. Although a substantial contribution to the field, this framework is based on lean manufacturing principles merged with TPDS enablers and aerospace engineering best practices without distinction in many cases.

Hopperman et al. (2011) developed a framework for organising lean PD enablers. The authors performed content analysis of literature that both addresses lean PD and provides a systems perspective in their recommendations for PD. This approach resulted in 11 'components' of lean PD under which other 'elements' can be structured, 10 of these components have been included in Table 2 as enablers: strong project manager (chief engineer), workload levelling, responsibility-based planning and control, cross-project knowledge transfer, simultaneous engineering, supplier integration, product variety management (multi-project management), rapid prototyping, simulation and testing, process standardisation, and set-based engineering. The authors include 'specialist career path' as a 'component', which is debatable. A similar framework was developed in this research and is presented in section 5.1.

3.6 Lean Product Development Case Studies

Until recently there were no published case studies on the implementation of Toyota PD principles and practices. There were however a number of cases of value-stream mapping (VSM) and similar process transformations where a number of improvements, including reduction in PD cycle time were achieved (McManus et al., 2005; Morgan and Liker, 2006; Hines and Packham, 2008; Kumar et al., 2009; Nepal et al., 2011). A case study was also put forward by Gautam and Singh (2008) in which they analysed the effect of making incremental design changes on the fulfilment of customer value for an unnamed automotive company.

Panchak (2007) reported on the positive interim response that Teledyne Benthos provided upon their adoption of various Toyota PD practices. Teledyne Benthos is a provider of underwater equipment and quality control instrumentation. Test-then-design, A3 reports, trade-off curves, learning cycles, and checklists were all alleged to have been implemented; however, minimal empirical evidence was provided.

Oosterwal (2010) provides an account of applying Toyota PD principles and practices at the Harley Davidson motorcycle company. The application of various TPDS enablers is claimed to have resulted in an increase to new product output (see Figure 3.5), and a decrease in launch issues and problems late in the development cycle. The author describes various problems that his company faced before their implementation of Toyota PD principles and practices supported by statistical data and graphs. The author also describes the various principles and practices adopted and outlines how the company benefitted. One mechanism that was unique in this work was limit curves, which depict feasible and infeasible design regions. This case study however, having been authored by a PD consultant, may be subject to bias and requires academic analysis and peer review.

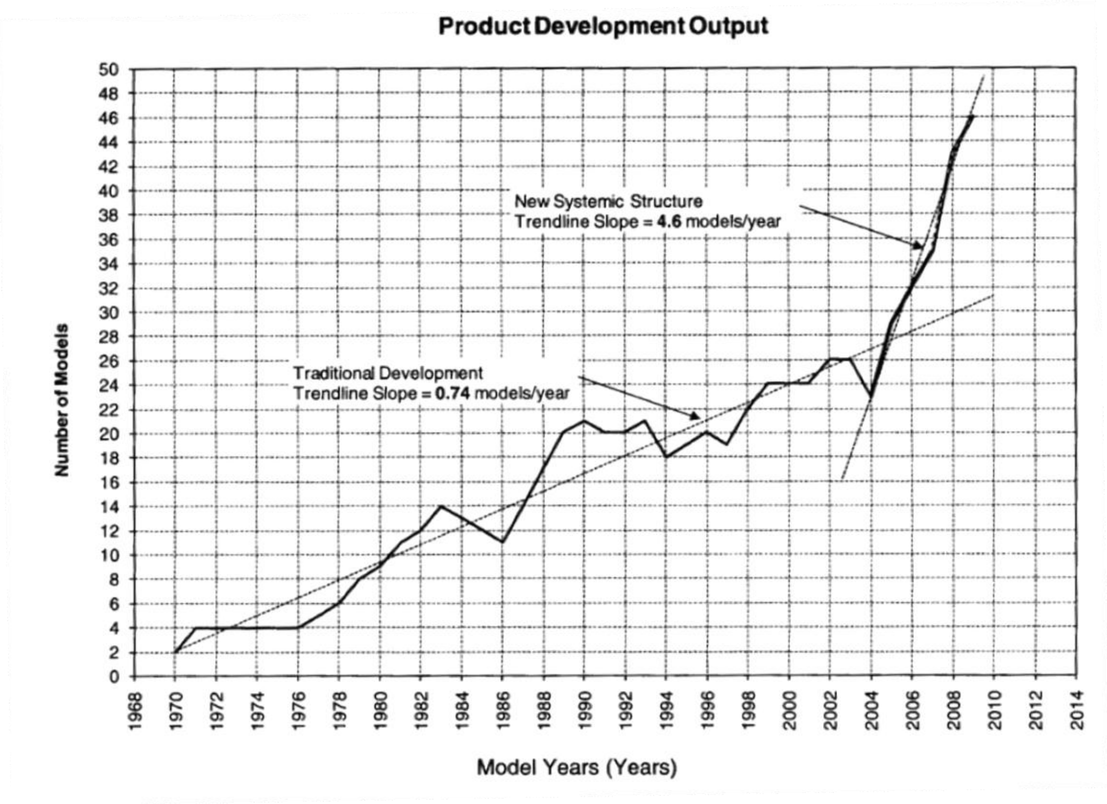

Figure 3.5 Harley Davidson product development output from 1970 to 2009 (Oosterwal, 2010)

Similarly Radeka (2011) reported on the positive results that Playworld Systems Inc. experienced after trialling a number of Toyota PD practices. Playworld makes commercial playground equipment for schools, new housing developments, and parks. A3 reports, learning focus, and the pursuit of multiple alternatives were all alleged to have been implemented; again with minimal empirical evidence. Playworld are suggested to have seen a 29% increase in new products in 2011, compared to the previous year, a reduction in the number of late projects by 29%, and only 1% of its new products were delayed more than 60 days from the scheduled introduction date.

The Teledyne Benthos, Harley Davidson, and Playworld cases were conducted by practitioners and there is no evidence of research motivation or methodology. The cases are no doubt encouraging, and highlight the positive enhancements that implementation of lean PD research can result in. In spite of this, without the substantiation of due protocol the cases lack academic integrity, and thus cannot be used as the basis for academic theory.

Letens et al. (2011) evaluated a multi-level framework for lean PD through which they addressed the portfolio, project, and functional levels of PD. A number of Toyota PD principles and practices were applied in the three-year case study, including value-focus, generating and evaluating multiple alternative designs to obtain an increased understanding of trade-offs, and guidelines for standardisation and design re-use. The case study was conducted with the technical studies and installations department of the Belgian armed forces. The department is said to have experienced breakthrough improvements in a number of key performance measures: project throughput doubled, project work in progress (WIP) reduced from 82 to 20 live projects, the percentage of projects completed within their target lead times increased from 25% to 80%, and a coefficient for value-added time (effort/lead time) increased from 5% to 20% (Letens et al., 2011). Through this research the authors noted the need to define interim deliverables for lean PD.

Morgan and Liker (2006) provide a comprehensive system's view of lean PD through their 13 principles of TPDS. These principles were drawn on in the transformation of body development at the Ford motor company between 2004 and 2009. Automotive body development has historically been a major bottleneck to launching products on time, at target cost, and with high quality (Liker and Morgan, 2011). The authors conducted a reflective case study in which live experiences were reflected on to develop lessons learnt (Kotnour and Landaeta, 2004). The research began with a gap analysis between Mazda and Toyota, (which the authors believe shared all 13 principles) and Ford. Based on this analysis, opportunities for improvement were uncovered and a number of organisations and processes were established within the company to apply the 13 principles. The case study involved the application of various Toyota PD practices as well as principles. The improvements to body development at Ford have been linked to a reduced average overall lead time of 40%, reduced internal tool and die construction time by an average of 50%, reduced internal tool investment costs by an average of 45%, an increase in die production productivity of 400%, enhanced quality, and also improved employee morale (Liker and Morgan, 2011). Five key lessons gained from the case study are highlighted: (1) Lean processes can be effective in driving high quality, low cost, and short lead times in PD, (2) the transformation requires a long-term commitment and a staging of the transformation process, (3) Driven, accountable team members transform lean PD from static tools to a living high-performance system, (4) The main role of lean tools is to make problems visible and provide a method of solving them at the root cause, and (5) Lean implementation is a social, cultural, and political transformation. This case study provides a strong case for both the portability of Toyota PD principles and practices, as well as the potential benefits that can be gained.

3.7 Identified Research Gaps

Lean PD is an emerging area of research that is currently growing. Conflicting approaches provide plenty of room for debate which can no doubt benefit from both theoretical and empirical research. It has been concluded based on this review that the Toyota PD system (TPDS) should be used as the basis for lean PD, and there is a considerable body of knowledge available to support the formulation of theory based on TPDS. This includes an array of principles and practices presented in Table 3.2. Research is required to differentiate between the most critical enablers and those which can be substituted with other equivalents. Field research may also be required to determine whether or not these enablers have a presence in industry.

A number of principle-based representations have been published in order to support PD transformations, however they focus on what types of things should be considered for improvement (e.g. principles), rather than methodological recommendations for implementation. No integrated framework of the identified lean PD enablers has been put forward in the surveyed literature, nor has a methodological guide been formulated to support the application of lean thinking on an engineering project.

Sobek et al. (1999) went to great lengths to study and document Toyota's SBCE approach, however, research is still required to construct a methodology for SBCE. In the model proposed by Morgan and Liker (2006) SBCE is given little attention. It is evident that other researchers consider SBCE to be a core enabler for lean PD (Ward et al., 1995; Sobek et al., 1999; Ward, 2007). A comprehensive model that combines all of the core lean PD enablers was not found.

It may be that by focusing on PD as a system, insufficient attention is given to the most critical parts. Conceptual design appears to be where Toyota is most unique through SBCE. It may be that this stage provides a window of opportunities for structure and enhancement. Liker and Morgan (2011) highlighted this gap in their recommendation for future research on front-end loading and innovation. Process-related factors have been downplayed by some academics who consider organizational strategies to be the key to success (Cusumano, 1994; Cusumano and Nobeoka, 1998). Although the importance of organizational strategy is not disputed, it is vital to translate organizational strategy into processes in order to achieve enterprise success.

Case studies conducted in the area of lean PD are scarce. The two case studies that have tested theories for lean PD based on TPDS, have taken an organisation-wide approach (Letens et al., 2011; Liker and Morgan, 2011). Although both studies have demonstrated the impact of their research on organisational departments through metrics, neither has provided an in-depth account of the development of an engineering component, sub-assembly, or system. This research is vital for the research community to learn about and understand how Toyota PD principles and practices - as phenomena - interact with the local environment in which they are applied.

Some additional voids in the research area include: the interaction between lean PD and other PD approaches (e.g. systems engineering), the suitability and impact of TPDS enablers, and cultural implications of the various Toyota PD principles and practices. These gaps amongst others have been noted, but are not the focus of this research.

3.8 Summary

In this chapter a systematic review of literature related to lean PD is presented. Historically, the term 'lean' has been used in reference to case studies of the Toyota Motor Company, such as in the case of lean manufacturing. It is argued that lean PD should similarly refer to PD theory based on Toyota PD principles and practices. A number of representations of lean PD (based on Toyota PD) have been put forward in literature, however they focus on what types of things should be considered rather than implementation, and none of the representations constitutes a PD model. Enablers for lean PD were extracted from research publications which focus on Toyota PD principles and practices; the list of enablers is integral to the construction of the lean PD model. A few case studies have been conducted to test Toyota PD principles and practices, most of which are by practitioners and lack academic integrity.

Through the literature review the following key research gaps were identified:

1. Research is required to differentiate between the most critical lean PD enablers and those which can be substituted with other equivalents
2. Field research is required to determine whether or not lean PD enablers have a presence in industry
3. No integrated framework of lean PD enablers has been put forward in the surveyed literature
4. No methodological guide has been formulated to support the application of lean thinking on an engineering project
5. Conceptual design appears to be where Toyota is unique through set-based concurrent engineering for which no step-by-step methodology was found
6. No in-depth case study was found where an engineering component, sub-assembly, or system was developed using lean PD

The next chapter addresses the second research gap above, and focuses on exploring the industrial context for this research.

4 THE INDUSTRIAL CONTEXT

This chapter presents an industrial field study carried out to better understand the industrial context for this research. This activity addressed the second research objective: to explore whether or not lean PD principles and practices have a presence in industry and identify current PD challenges faced. The findings from this study helped to provide direction for the construction of the lean PD model.

The chapter is divided into 4 sections:

In section 4.1 the development of the industrial field study is described, including the interview strategy and questionnaire design. This is followed by section 4.2 where the results from the interviews are presented, regarding both PD practice and challenges in industry. The results are subsequently discussed in section 4.3. A summary of the chapter is provided in section 4.4.

4.1 Description of the Study

Initial interaction with industry involved various discussions through virtual web-based meetings, and face-to-face meetings at a number of European locations: UK, Germany, Italy, and Poland. Meetings were held in order to understand industrial needs and to ensure an industrial-driven approach to the research. One of the main topics of discussion was the enablers for lean PD. Especial interest was directed towards SBCE and the following anticipated benefits were put forward by key stakeholders from the five industrial collaborators (see section 1.4 for company details):

- The SBCE methodology is the most important benefit
- Decision support, decision reliability, minimising risk in PD, and supporting the selection of manufacturing technology (depending on production volume)
- Allowing for different approaches, and supporting new creative solutions
- Addressing innovation

- Reducing the gap between perceived quality and designed quality in order to improve customer responses to the designed and produced product
- It should improve the efficiency of the whole PD (process) as it increases time savings and reduces design iterations

4.1.1 Initial Interaction with Industry

The five industrial partner companies were visited in order to develop an initial understanding of the context and also to discuss the research topic with key stakeholders. This involved both observation of design and manufacturing practice, and also discussions with engineers and managers.

Four out of the five industrial partner companies have manufacturing systems (factories and workshops) in close proximity to the PD teams who design the products, each having implemented lean manufacturing principles and practices. Two of the companies have both PD teams and manufacturing systems collocated within the same building for a number of components. All of the companies have globally distributed supply chains and take advantage of cheaper labour and material costs. Although many similarities were observed, both the design and manufacturing at each company was unique and differed due to the type of product, design and manufacturing complexity, size of product, scale of production, and quality assurance, amongst other factors. Design work in all companies was predominantly computer-based, utilising a variety of CAD software and MS Office for the most part. The use of CAM, CAE, and other modelling and simulation software was witnessed in three of the companies.

The site visits were important for a number of reasons: (1) they provided an early appreciation of the research context, including the variation in language, culture, and behaviour; (2) they helped to establish rapport with stakeholders and facilitated a better understanding of their views and concerns; and (3) they helped to define the scope of the research and discuss expectations.

4.1.2 Interview Strategy

Further data was required in order to understand the presence of Lean PD in industry and also to identify the main challenges that are currently being faced. This was indeed an arduous task for a number of reasons. A logical approach would be to determine which of the lean PD enablers (identified in the literature review) were being formally implemented at each company using a checklist of some sort. Through initial interaction however, it was noted that the terminology that lean PD researchers had used was somewhat unconventional albeit intentionally. In addition, it was found that some terms were being used to different effect. The term chief engineer for example was being used at a number of companies; however the role and responsibilities of the chief engineer varied considerably from one company to another. This meant that enablers would have to be objectively described which would no doubt be more time-consuming.

Another issue that arose was that merely determining whether or not each of the lean PD enablers was being implemented would not help to understand the different approaches that were being implemented. This was important because it was presumed that alternative approaches could be uncovered which were equivalent or superior to some of the lean PD enablers. With the aim of this research being to construct a new model, it would be nonsensical to overlook the advanced approaches that have been established in companies over time. With the above in mind a rather shrewd approach was devised. A restricted set of questions were developed which focused on what was viewed at the time to be the main lean PD enablers[7], but each question would also be related to a number of additional enablers. Each question would also offer alternative descriptions in order to help characterise the approach of each company. This proved very tricky as it was impossible to pre-characterise all possible approaches in a short checklist. One of the questions is exhibited in Table 4.1.

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[7] As the research evolved, the author's understanding improved and a framework of enablers was developed which categorise the lean PD enablers; the framework is presented in section 5.1

In this question the main lean PD enabler of enquiry was ‘delaying specification’ however; the question also addresses ‘minimal constraint’ and SBCE, while at the same time characterising the company approach. In some cases additional lean PD enablers were not addressed by the question itself, but by the ensuing discussion. This information was captured in the form of interview transcription notes.

Table 4.1 Semi-structured interview question example

How is a product specification stabilised in your product development process? (Select one option)	
❑	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 and we try to finalise the specification as early as possible
❑	Specification grows through continuous interactions along the stages of PD as the product understanding matures and we intentionally delay the final specification

A series of review meetings with academic supervisors and other researchers helped to arrive at an agreed list of scenarios for each question, and it was concluded that in case the approach differed from what was described, comments and amendments to the descriptions would be noted. Had the focus of this study been quantitative, this would have proved a problem, however in the case of qualitative research it would only add to the richness of data.

The questions were thus used to guide the explorative study through face-to-face interviews with managers and engineers. It was important for these interviews to be face-to-face so that the behaviours and expressions of interviewees could be analysed and evidence could be requested by the interviewer for the answers provided. Thirty six candidates have been interviewed from the five companies. Each interview ranged from 90 to 120 minutes depending on the responses from the interviewees. Multiple interviews were conducted in the same company in order to gain a better overall picture, without losing the individual views and opinions. It was requested for interviews to be conducted individually (i.e. with a single interviewee), however this was not possible in all companies due to company policies for data collection and the availability of participants. The interviews were conducted between March and July of the year 2010. Table 4.2 provides an overview of the interviews that were conducted. Company names have been removed to ensure the confidentiality of responses, and replaced with letters (A-E). Company/interview numbers (#) have been used to separate interview sessions (some interviews involved multiple participants).

Table 4.2 Profile of interviewees

Company/ interview#	Role in organisation	Industrial experience (years)
A1	Design engineer	21
	Design engineer	10
	Corporate specialist in design methods	24
	Corporate specialist in design methods	9
A2	Corporate specialist in cost methods	26
	Head of design systems engineering	33
	Corporate specialist in design methods	27
	Head of quality systems	32
A3	Chief of design	14
	Chief of manufacturing production	13
	Corporate specialist in design methods	21
A4	Engineering senior manager 1	28
	Engineering senior manager 2	22
	Corporate specialist in knowledge based	14
B1	Systems/Requirements manager	16
B2	Software sub-systems manager	18
B3	Mechanical technical fellow	29
B4	Electronics technical fellow	9
B5	Software validation senior engineer	19
B6	Optical design engineer	12
B7	Hardware validation engineer	11

Company/ interview#	Role in organisation	Industrial experience (years)
C1	Project manager	9
C2	Hardware design manager	10
C3	Corporate specialist in noise and vibration	11
C4	Virtual reality lab technician	9
C5	Corporate specialist in materials	0
D1	Director of technical development	15
D2	Design manager	13
D3	Stamping design engineer	7
D4	Design team leader	8
D5	Design engineer	8
D6	Logistics manager 1	10
D7	Logistics manager 2	5
E1	Component development leader	18
	Product unit engineer	21
	Design engineer	0

4.1.3 Qualitative Analysis Approach

Results from the interviews were analysed qualitatively. The following considerations were made during the analysis of results in order to ensure the results represent PD at each of the studied companies, without neglecting individual opinions and perceptions:

- Role in organisation: Responses from managers were weighted higher for questions that were related to organisational processes, while responses from engineers were weighted higher for design methods and tools employed in PD
- Years of experience: Responses from interviewees who have been working for the organisation for a longer duration were generally weighted high, as they often had a better understanding of PD at their organisation
- Consensus: Where there was a consensus or majority of responses, it was quite certain that the answer was representative of the organisation, whereas if the answers varied then further analysis was required to

provide a single representative result or a combined result representing different opinions or views

- Incorrect responses: Some interviewees guessed, or answered without the required knowledge, such answers generally became apparent to the interviewer and were logged during the interview, and in some cases became apparent when comparing results
- Transcripts: Notes taken during the interviews were consulted while analysing results to ensure the context of each answer was understood, and in some cases the behaviour of the interviewees

The five companies that have been studied represent the aerospace, automotive and home appliances sectors as well as different tiers of the supply chain: OEM, first tier, and second tier suppliers. The companies were selected for participation in this project due to the complex nature of their products and their reputation for high quality engineering. Although it may be argued that the companies were not selected at random and thus results cannot be generalised to manufacturing companies in Europe, statistical sampling and population representation was not intended. The results are however likely to be indicative of the adoption of lean PD principles and practices by manufacturing companies in Europe, in addition to the challenges being faced[8].

4.1.4 Questionnaire Design

This section describes the synthesis of questions that formed the basis of the semi-structured interviews. With the aim of this research being to develop a novel model, it was sensible to understand whether or not the companies being studied actually had representations of the PD process. Eppinger et al. (1994) advocated the organisation of PD tasks by means of illustration, and proposed that the first step to improving a PD process is to model it. Iansiti (1995) divides PD models into two categories: (1) traditional models for PD that have emerged from observation, where the emphasis is on efficient execution of a sequentially

[8] It is important to note that this study has been extended to a number of additional companies in Europe, and the overall findings were not dissimilar.

phased process and avoiding unnecessary change; and (2) flexible models that have been architected to gather and rapidly respond to new knowledge regarding technology and product markets, where the focus is on managing the development of a system, technological choices, and concept decisions. Finger and Dixon (1989) refer to the two types as descriptive and prescriptive. It is also known that the stage-gate model has pervaded engineering practice and has been adopted by many best practice companies (Cooper et al., 2002)[9]. This leads to the first question.

Question 1.1a: Do you have a formal product development (PD) model (visual representation of the PD process, including the various stages, activities, mechanisms and supporting tools)?

In this question three pieces of information were collected: the presence of a PD model, who developed it, and the level of adherence.

The construction of a PD model may be a praiseworthy effort, but without supporting the personnel who are responsible for implementing its content, the benefit of a PD model is questionable. It could be the case that a mandated model provides nothing more than hurdles for PD teams to overcome. This gave rise to the second question.

Question 1.1b: Is your PD Model effective in guiding PD operations?

The issue of mandate is also quite interesting. In the case where a mandate exists, an engineer or manager who identifies that the most appropriate cause of action is to go against the mandate is left in a difficult situation. Their options are: (1) to seek approval to go against the mandate; (2) to go against the mandate and explain later why they did so; or (3) to submit to the mandate and absolve themselves of responsibility for any ramifications. The idea of engineers and managers having the authority and taking responsibility for decisions is one that is highlighted in various accounts of TPDS. This prompted the following question.

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[9] Refer to Appendix C for an illustration of the stage-gate model

Question 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?)

The issue of authority and responsibility in engineering is closely intertwined with leadership. Heavyweight project managers, chief engineers, and entrepreneurial system designers are all terms used to describe project leaders at Toyota (Karlsson and Ahlstrom, 1996, Morgan and Liker, 2006, and Ward, 2007). Sobek et al., (1998) suggested that companies in the USA were moving towards a heavyweight project-management structure. However, the leadership approach, structure and style can vary considerably. This gave rise to the next question.

Question 1.3a: Is there a technical leader who is responsible for the entire development of a product from concept to launch?

A discussion around the subject of leadership is likely to bring out opinions when discussed, it being a contentious subject. Thus a further question was included regarding leadership.

Question 1.3b: How effective is your PD leadership?

Another lean PD enabler considered to be a cornerstone of lean PD by Ward (2007) is set-based concurrent engineering. Constituents of SBCE include delaying specification, minimal constraint, extensive prototyping, convergence on an optimum solution, a KB environment, and KB decision making. These enablers were addressed in the subsequent two questions.

Question 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?

Question 1.5: How do you select the design solution that will be developed?

Toyota prides itself with an effective system for continuous improvement, or what they refer to as Kaizen. They promote improvement ideas and cultivate an environment receptive to change with the necessary procedures in place (Shingo, 2007). Although heralded as the fifth principle for lean manufacturing, continuous improvement has also been associated with PD (Morgan and Liker, 2006). The issue of interest is not whether or not companies want to improve their PD processes and practices; rather it is how they facilitate improvement. This gives rise to the next question.

Question 1.6: How are your current processes and work methods reviewed/improved?

Up until now production or manufacturing and its involvement in PD has not been addressed. However, with the 'lean researchers'[10] referring to Toyota as their underpinning, there must be a strong link between the design and manufacture of products. Sobek et al. (1999) highlights this interaction rather dramatically, as though the two are in continuous conversation throughout PD (refer to Figure 3.4). With the proliferation of simultaneous engineering, concurrent engineering, and agile manufacture the relationship between design and manufacturing groups has improved (Ribbens, 2000; Büyüközkan et al., 2004). However, it is expected that companies vary in their integration of the two disciplines, and of particular interest is the stages of PD where manufacturing engineers are involved as well as the level of involvement. This leads to the next question.

Question 1.7: Do manufacturing (production) engineers play an active role in each stage of product development?

With the changing dynamics of engineering corporations, outsourcing both the manufacture of components and sub-assemblies as well as their designs has become all too common (Arnold, 2000; Hätönen and Eriksson, 2009). However, the approach that suppliers use to support the design of systems can vary considerably. In a study in the USA Liker et al. (1996) found that set-based design communication was more prevalent in Japanese parts suppliers as compared to USA suppliers. Through the next question this issue was addressed.

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[10] The term 'lean researchers' has been used here in reference to researchers in the fields of lean production/manufacturing and lean product development

Question 1.8: Do your suppliers provide you with multiple alternatives for a single part (component)?

Effective management of development projects is key to the success of a manufacturing organisation (Cooper et al., 2002). Morgan and Liker (2006) refer to this as creating a levelled PD process flow. Oosterwal (2010) suggested that a key factor in achieving process flow was project initiation and that it would be wise to stagger project initiation in some cases. Honda's ability to leverage key subsystems or platforms into new products has been highlighted as it can lead to rapid market responses and lower development costs (Meyer, 2008). Cusumano and Nobeoka (1997) associated this idea of multi-project management with Toyota over a decade earlier. This in turn led to the following question.

Question 1.9: How are projects currently initiated, and does the product development process flow?

These questions formed the primary section of a questionnaire that was used as the main research instrument. The questionnaire included additional sections that focused on specific details regarding product design; KB engineering, and cost estimation[11]. Reference to results from these sections was however, useful in the analysis of results in general. A section for additional questions was also included that addressed challenges in PD[12]. The full interview instrument can be found in Appendix E.

Although the vast majority of lean PD enablers were addressed, some were excluded from the study (see Table 4.6). Enablers were excluded for a number of reasons: (1) some enablers are difficult to measure or determine their presence; (2) constraints on the interviews; priority was given to enablers that were considered to be more important; and (3) some enablers are standard elements of PD in all companies.

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[11] It is important to note that these 3 sections were designed by other researchers
[12] This section was composed by the author

4.2 Results

4.2.1 Product Development Practice in Industry

This section presents the questionnaire results related to the PD processes at the five manufacturing companies studied. The section is organised according to the sequence of questions that were asked.

All of the companies have developed PD models. As indicated in Figure 4.1, models tend to be developed by central organisations that are responsible for implementation. Multiple models existed in some companies which led to some initial confusion amongst the respondents.

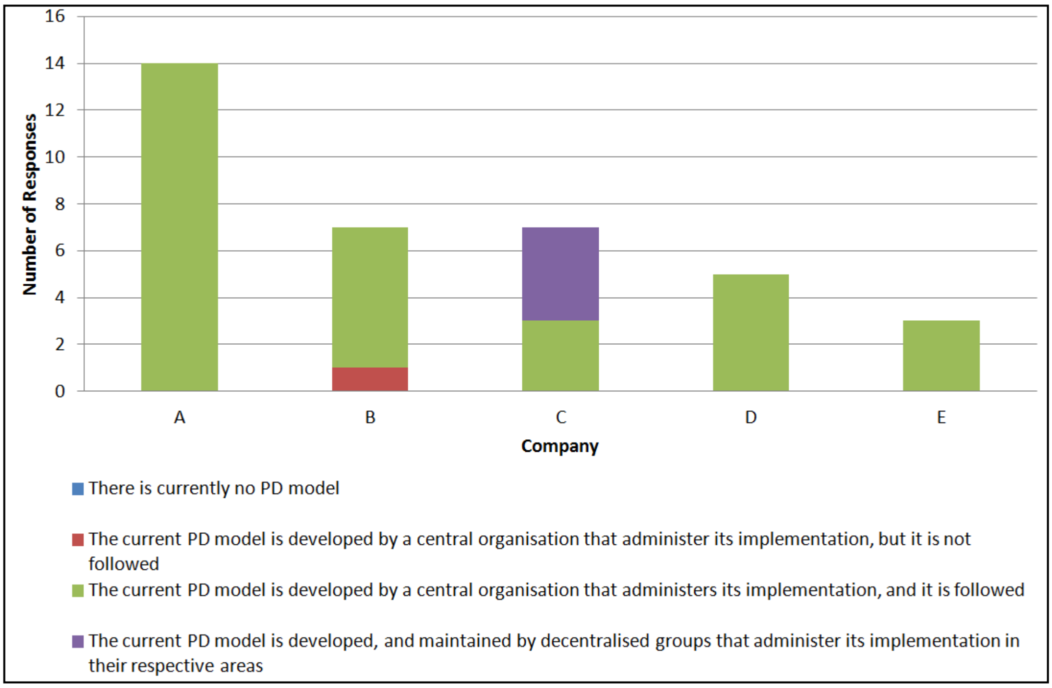

Figure 4.1 Question 1.1a: Do you have a formal product development (PD) model?

Despite the development of PD models, the actual guidance that they provide to PD teams is questionable. According to Figure 4.2, almost all respondents from four out of the five companies consider their model to be somewhat effective in guiding PD operations.

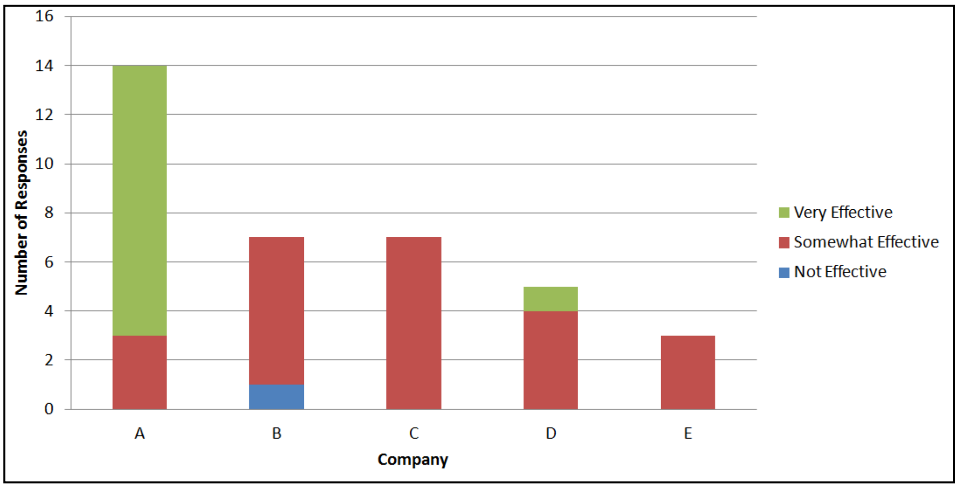

Figure 4.2 - Question 1.1b: Is your PD Model effective in guiding PD operations?

Engineers and managers have varying degrees of flexibility with regards to how they perform their responsibilities. Figure 4.3 shows that most of the respondents are permitted to manage the order of tasks for which they are responsible, while some are empowered with a greater level of flexibility.

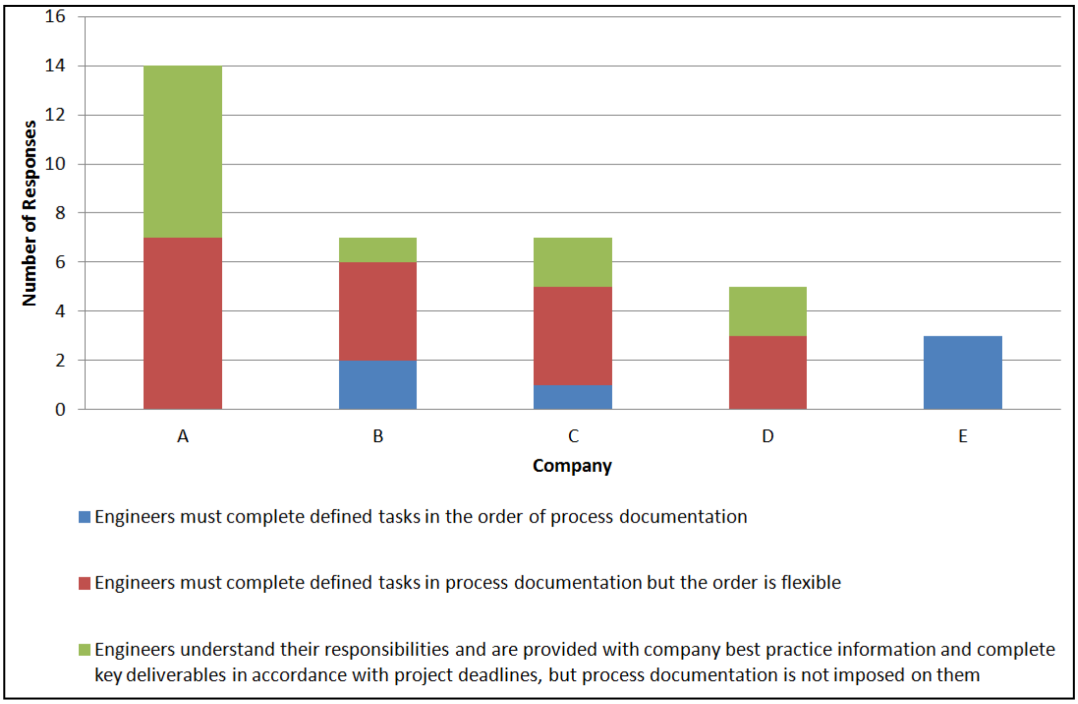

Figure 4.3 – Question 1.2: Do you have flexibility in how you do your job?

The ‘Chief Engineer’ title has a strong presence in industry, more often referring to a technical leader appointed after the concept stage. In most of the companies a non-technical project manager controls projects and is responsible for key decisions, as illustrated in Figure 4.4.

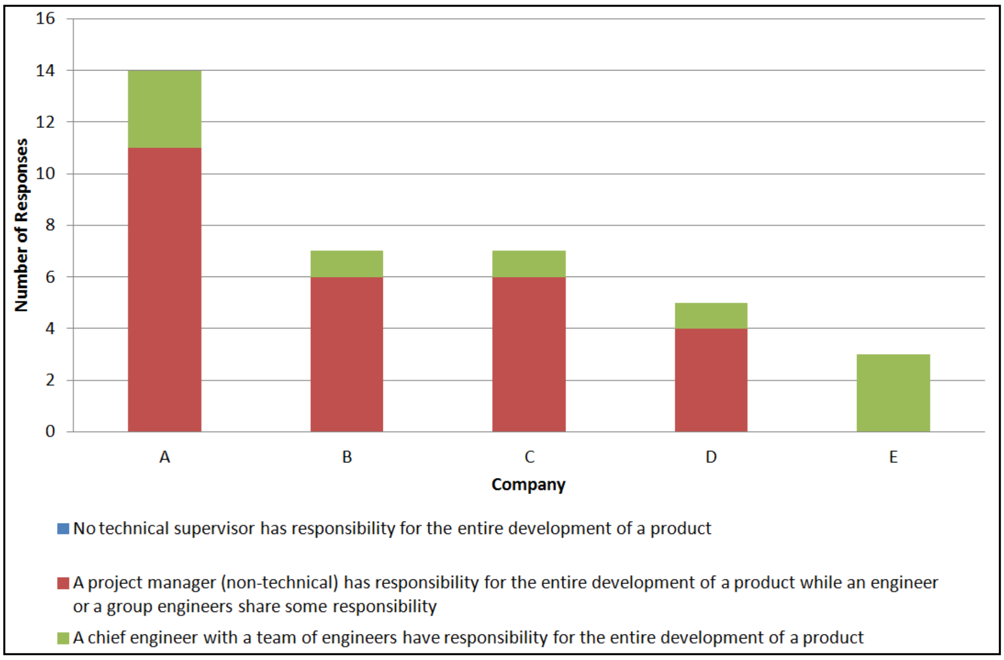

Figure 4.4 – Question 1.3a: Is there a technical leader who is responsible for the entire development of a product from concept to launch?

Different approaches to PD leadership are tainted with imperfection. According to the results provided in Figure 4.5, the majority of respondents considered their company’s approach to leadership somewhat effective; company C serving as a marginal exception.

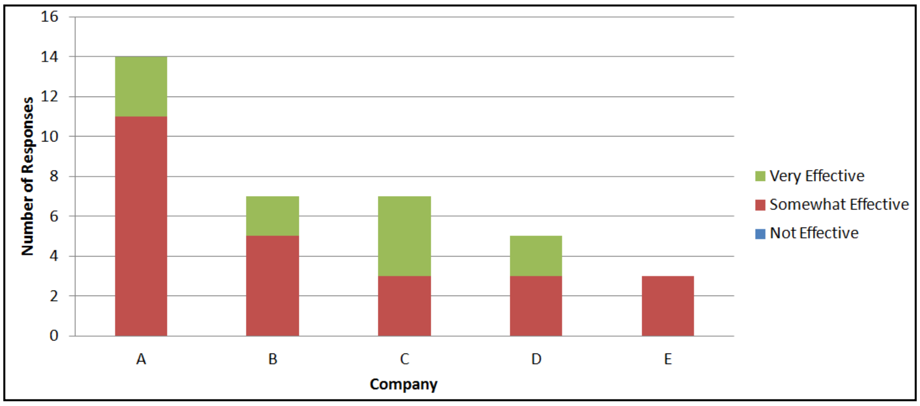

Figure 4.5 – Question 1.3b: How effective is your PD leadership?

The way that a product specification is stabilised varies across companies and is likely to be dependent on a number of factors. Figure 4.6 shows that a spectrum of approaches to specification exists.

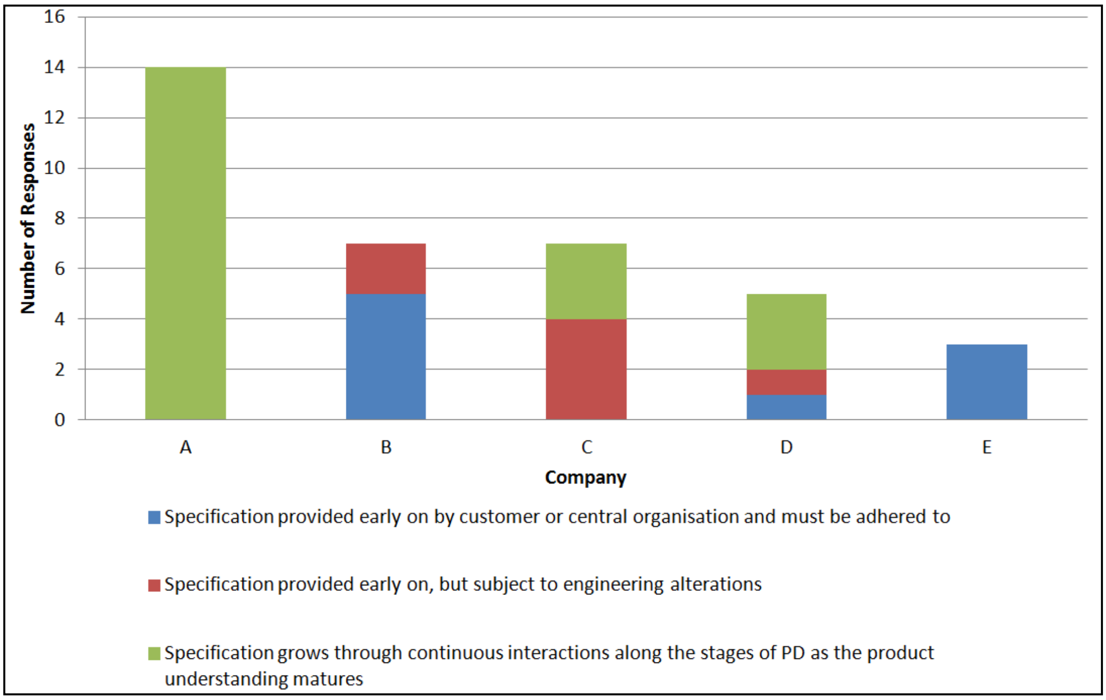

Figure 4.6 – Question 1.4: How is a product specification stabilised in your product development process?

None of the studied companies implement SBCE, as described in the literature. As indicated in Figure 4.7, companies may consider alternative design solutions, but only a single solution will be selected to be designed.

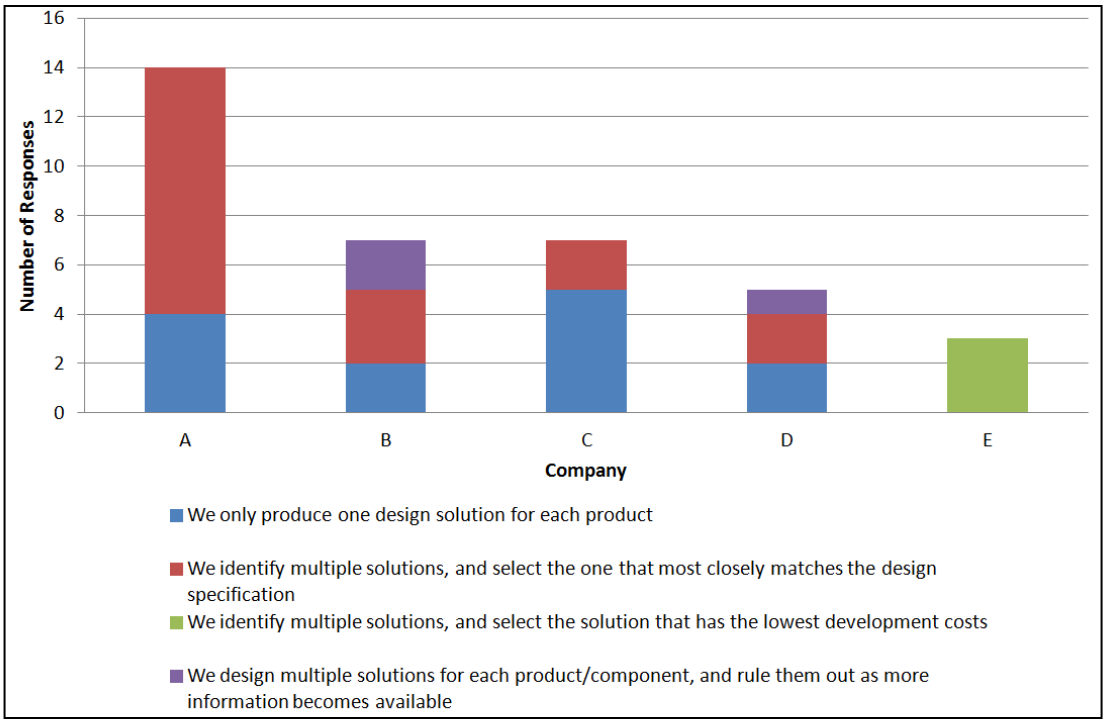

Figure 4.7 – Question 1.5: How do you select the design solution that will be developed?

Continuous improvement is something that companies strive for. Figure 4.8 provides evidence that formal mechanisms are in place at each of the companies to support the continuous improvement of PD. This includes regular organisational process reviews as well as formal mechanisms to incorporate improvement suggestions. Evidence that good ideas are regularly incorporated was only claimed by interviewees in one company that excelled in this area.

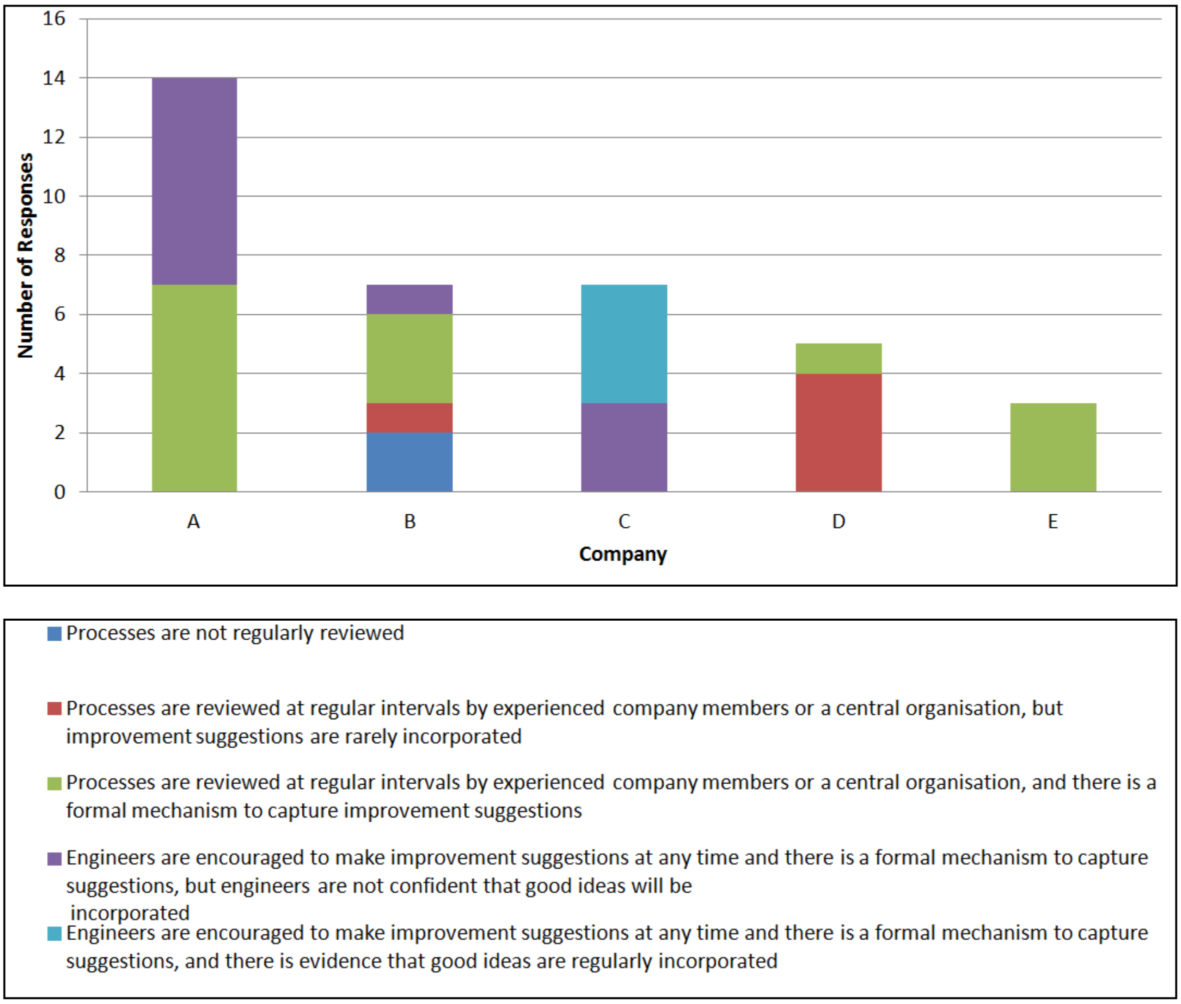

Figure 4.8 – Question 1.6: How are your current processes and work methods reviewed/improved?

Although in some cases manufacturing engineers are involved late in the design process, there is an increasing trend to involve them earlier. Figure 4.9 illustrates the spectrum of manufacturing involvement that interviewees have experienced at their companies.

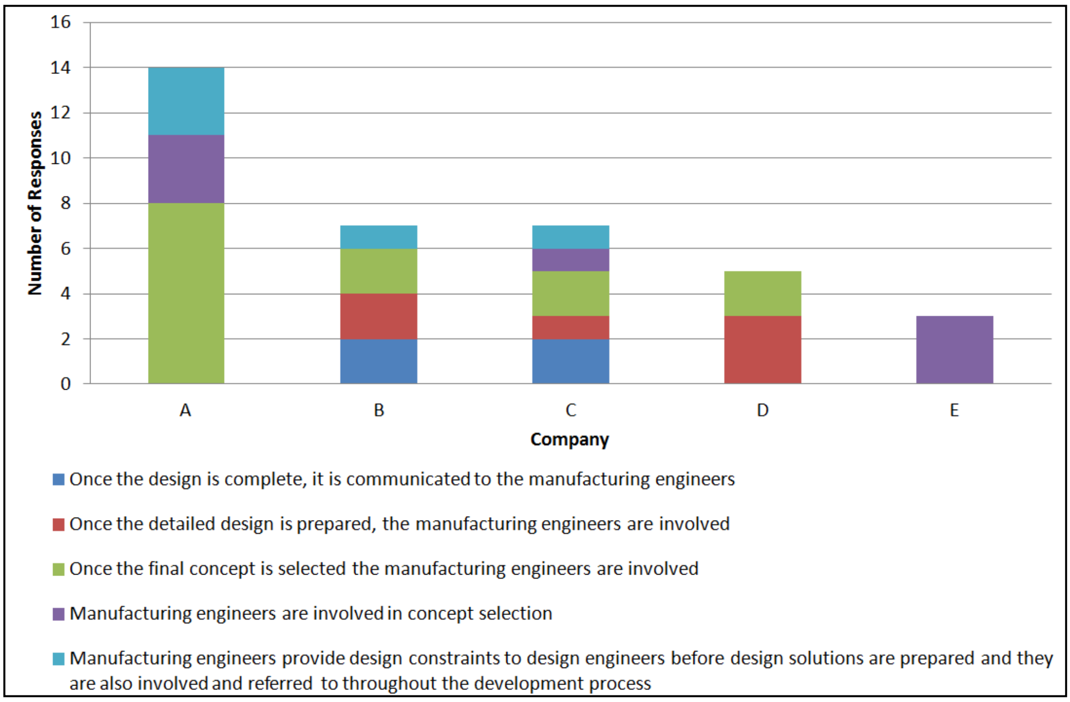

Figure 4.9 - Question 1.7: Do manufacturing (production) engineers play an active role in each stage of product development?

Engineering suppliers tend to provide single solutions, rather than multiple alternatives. It can be inferred based on Figure 4.10, that there is a trend to develop solutions with suppliers, and in some cases multiple alternatives.

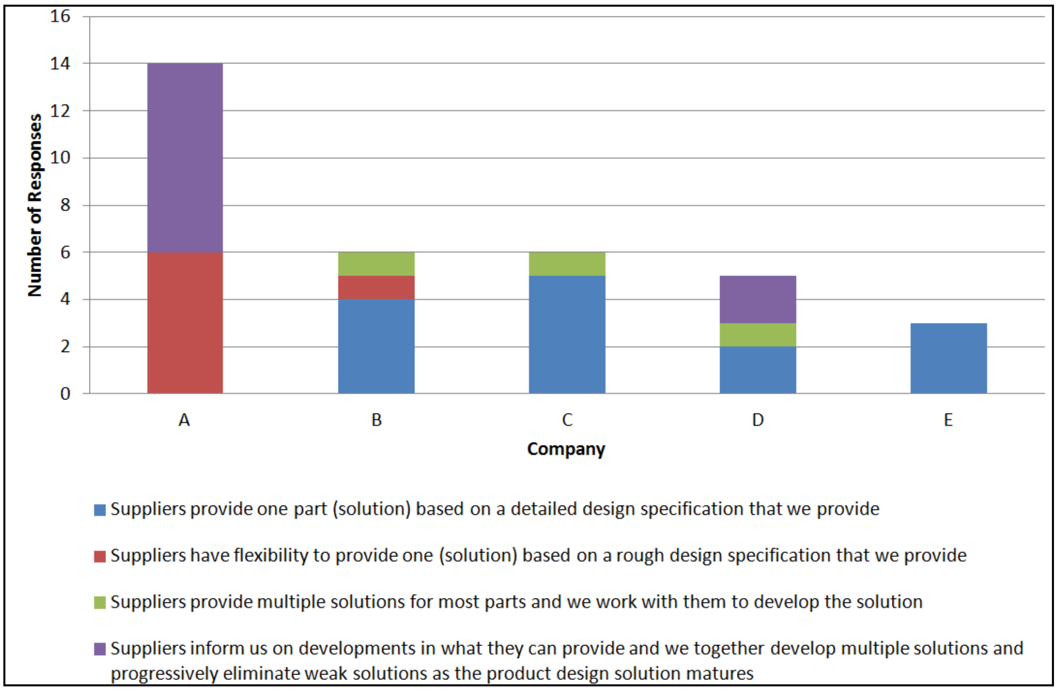

Figure 4.10 – Question 1.8: Do your suppliers provide you with multiple alternatives for a single part (component)?

Project initiation depends on whether a company is customer-driven (e.g. suppliers to an OEM) or market-driven (e.g. consumables). Figure 4.11 shows that most of the studied companies tend to respond to customer requests (and business opportunities), while one of the companies has a strategic and consistent drumbeat of development projects.

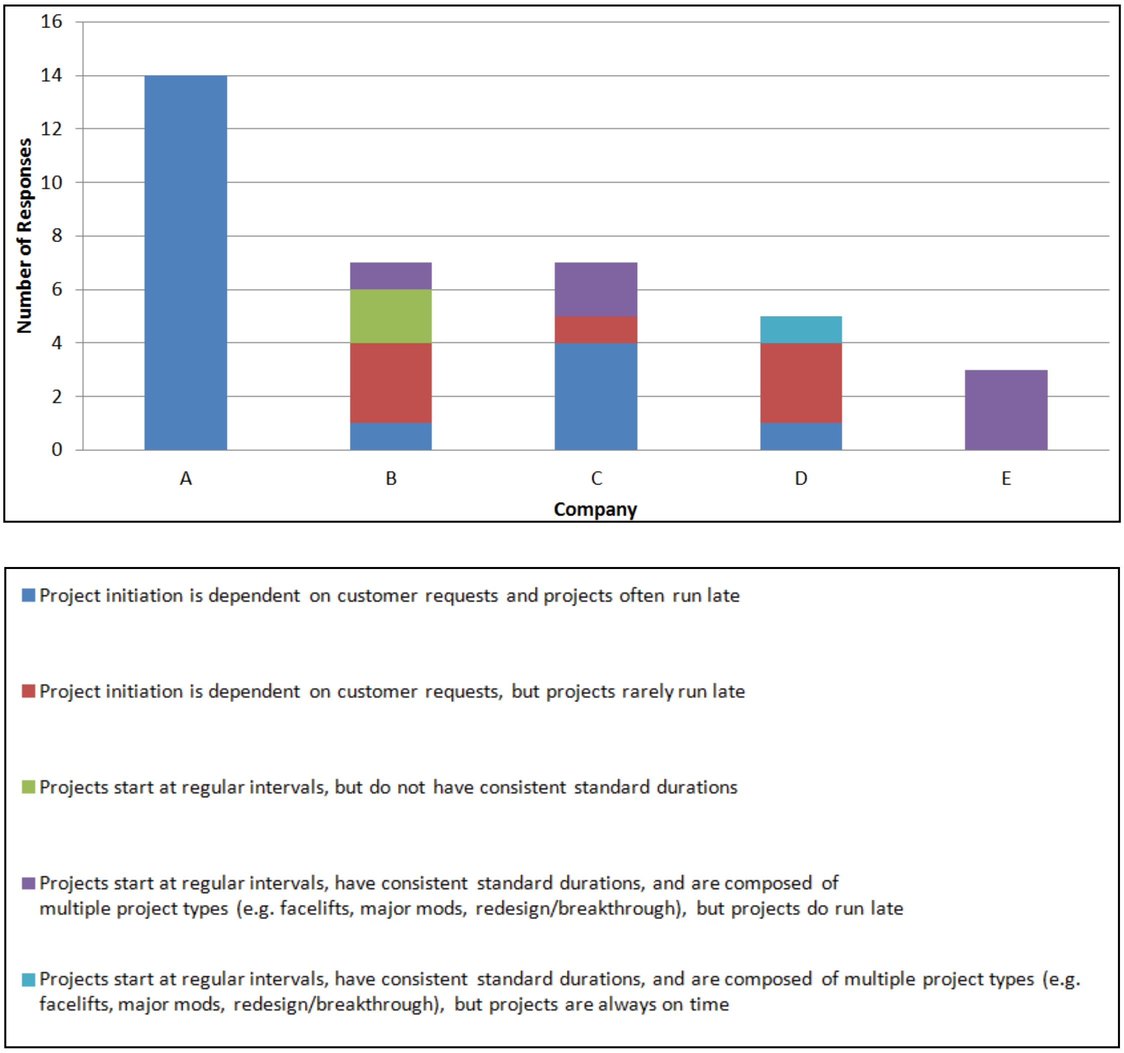

Figure 4.11 - Question 1.9: How are projects currently initiated, and does the product development process flow?

4.2.2 Product Development Challenges

This section presents the results regarding challenges faced at the five manufacturing companies studied. This section included open questions often with some options to allow cross-company analysis. It is important to note that this section was not repeated in every interview due to time constraints therefore the number of responses may vary.

A range of problems were identified in the PD models at each of the companies. Figure 4.12 highlights the presence of five proffered problems, which respondents associated with the PD models at their companies. All of these problems were recognised to be present in multiple companies.

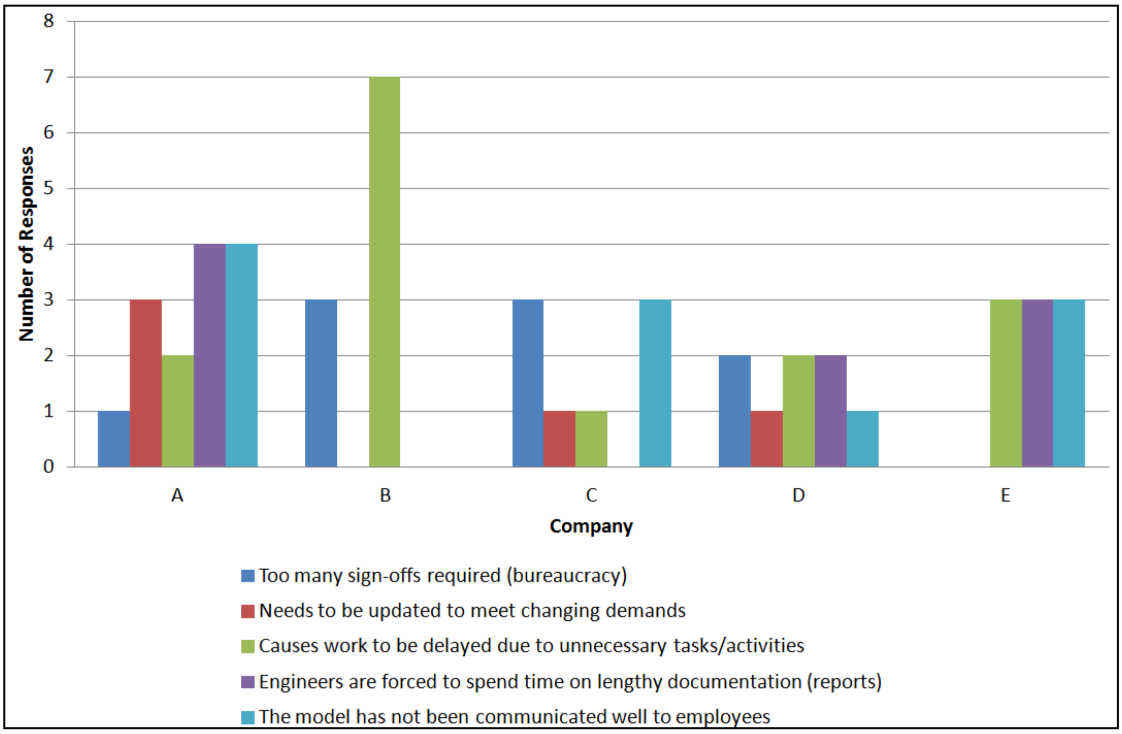

Figure 4.12 Question 5.1: What are the main problems with your product development model?

A variety of further problems were also expressed by respondents. Table 4.3 presents these problems, which are more often specific to the particular companies.

Table 4.3 Additional problems with company product development models

Company	Problems with the current PD model
A	There is a lot of rework in the process that is expensive
	Programme management is not effective (resourcing)
	We don't write enough reports
	Preliminary design could be a lot better
	Centralised groups need to support more and add work less
	Far too many overlapping processes/models
B	It needs to be completed
	Delayed activities put pressure on the final deadline
	Other departments need to be involved earlier in PD
	Engineers do not understand the PD model and process
	Current model does not accommodate for more innovation
C	The PD model is confusing
	Unclear roles and responsibilities
	No escalation if process is not followed
	Sometimes individuals are advised not to follow the process to meet deadlines
	Delivery pressures lead inevitably to process deviation
	Customers change requirements and there is no software change disciplines
	Groups working in chimneys
	Groups not knowing the causality of their own tasks (1 person depending on something from someone else)
	Late delivery of hardware
	Global organisation communication
D	Makes it difficult to meet new time-to-market reduction
	Model causes delays (does not deal with uncertainty effectively)
	Innovation and development are divided as part of the stage-gate model
	Over-the-wall communication
E	Process is dependent on other activities

Company	Problems with the current PD model
	Hidden waste in process

Challenges faced by engineering companies tend to be mutual. Figure 4.13 illustrates this commonality, in particular with regards to cost overruns and employees being overburdened by the quantity of work.

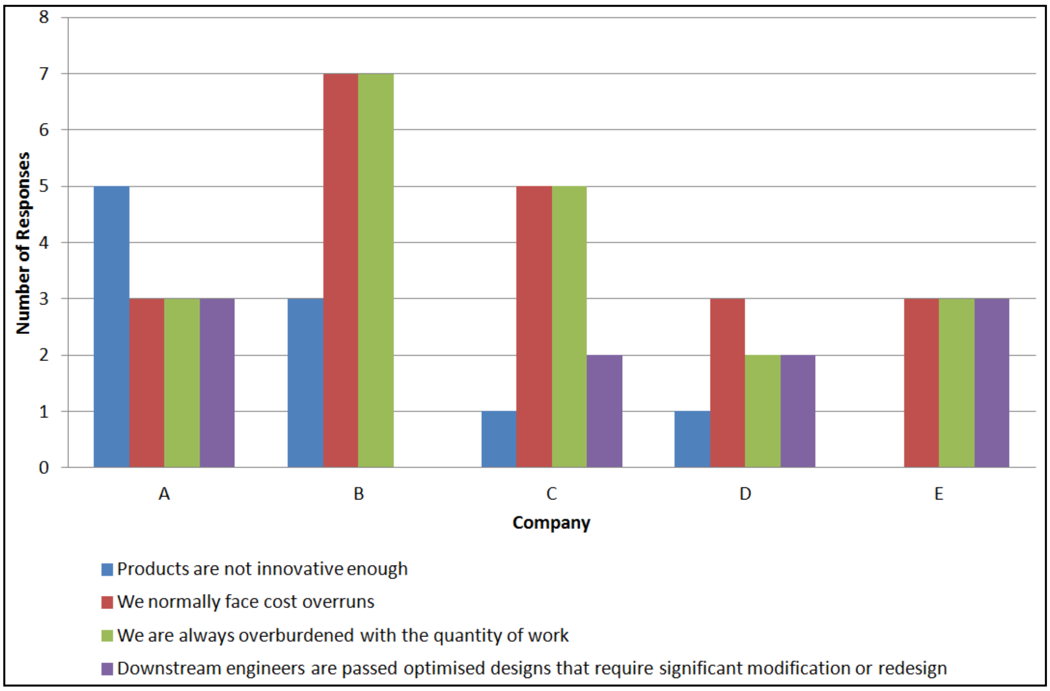

Figure 4.13 – Question 5.2: What are the main challenges faced in product development

A blend of supplementary challenges was expressed by interviewees. These challenges are presented in Table 4.4 which draws attention to some common themes including communication and rework.

Table 4.4 Additional challenges faced in product development

Company	Challenges faced in PD
A	Products hardly meet specification
	Concept phase lacks resources as they are tied in to rework, which is a recurring cycle
	Meeting market pressures by committing more technology with less cost
	Integrating functions in a single plan that suits everyone

Company	Challenges faced in PD
	Attacking unit cost
	Programme time scales are not synchronous with OEM programmes
B	Innovation vs. cost
	Competitors are more experienced
	Innovation for the growing international market
	Designing for multiple customers
	Communicating the process to everyone
	Meeting weight and cost targets
	Machining and final assembly are not considered in design
	Communication culture is poor, especially between departments
	Fire fighting: the focus is on 'day-work' rather than learning and innovation
C	Platforms (integration) team receive optimised designs that require significant modification/ rework
	Design starts without requirements
	Emails are time-consuming
	Very hard to establish requirements and document interrelations
	Ambiguous requirements
	Time frame
	Shifting requirements
	Being reliant on internal personnel to do tasks that influence your own function
	Unclear requirements
	Advanced technology/PD
	Quantity of work
D	Design doesn’t meet specification
	Lack of openness between departments
	Lack of flexibility in constraints
	Communication
	Time pressure - not capable of delivering fully validated products

Company	Challenges faced in PD
E	System complexity and the impact of design changes Too much information and too many computer systems

Capturing knowledge is viewed as a time-consuming activity in most of the companies, and designers subsequently find it difficult to extract knowledge from previous projects. As indicated in Figure 4.14, each of the proffered problems was recognised to be present in multiple companies.

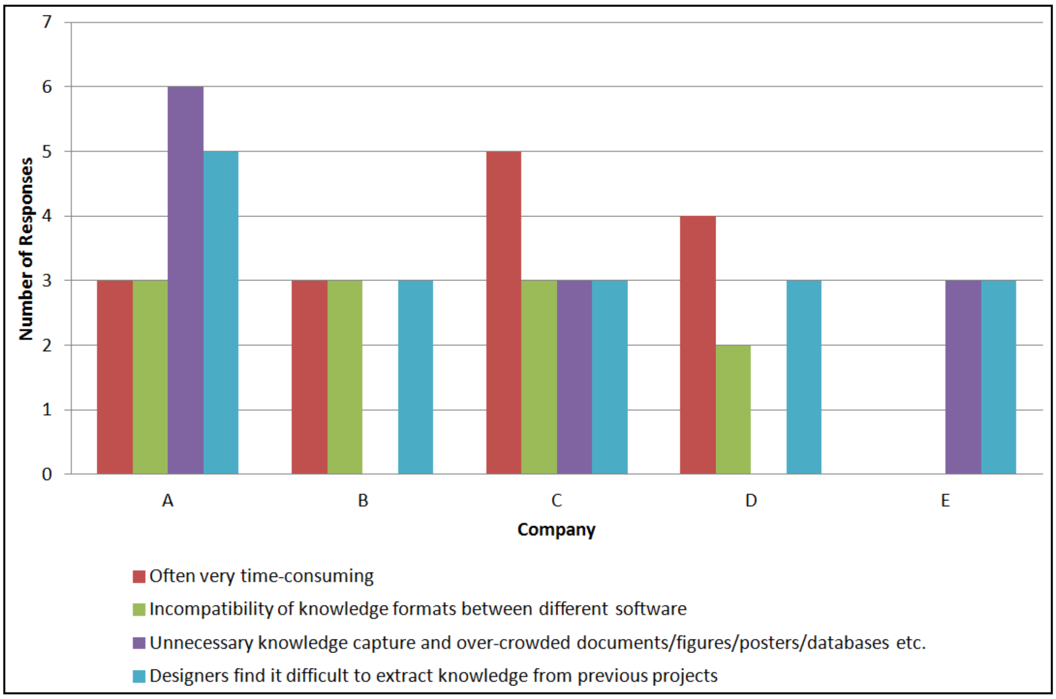

Figure 4.14 – Question 5.3: What are the main challenges faced in capturing and representing knowledge

Other challenges that were expressed by interviewees are presented in Table 4.5. Common subjects that are visible include locating knowledge and knowledge obsolescence.

Table 4.5 Additional challenges faced in capturing and representing knowledge

Company	Challenges faced in capturing and representing knowledge
A	Old CAD files often cannot be read due to technology obsolescence It can be very difficult to find knowledge

B	Lessons learnt are captured but not used effectively for new projects
C	Capturing tacit knowledge Design starts before knowledge capture Lack of bookshelf designs Filenames and numbering systems are not common/standardised Mechanical drawings and referenced specifications are often inconsistent (book-shelving would be good) Knowledge is lost Cost data is not easily accessed by everyone Inadequate filtering of knowledge Not capturing knowledge properly
D	CAD files are not easy to find and retrieve No standard template for knowledge capture Capturing tacit knowledge Lessons learnt are captured but not used effectively for new projects
E	Difficult to get the right information in the right place at the right time

4.3 Discussion of Results

The findings provided in this section have been established by performing a qualitative analysis of data gathered at the five studied engineering companies. Both the results and findings from this study were compiled in a report. This report was sent via email to representatives from each of the companies for review, in order to ensure triangulation of results. This process helped to identify shortcomings and refine the overall findings.

4.3.1 Product Development Models and the Implementation of Lean Product Development Enablers

Formal PD models have been developed by all of the companies involved in this study, in one case over 20 years ago. The primary benefit that respondents suggested company models provide is an overview of PD stages and quality gates/milestones. Respondents in all of the companies identified limitations in their PD models, in particular the lack of guidance that they provide for PD projects. Some departments within two of the companies have developed and currently administer local models to support project teams and guide them through the PD process. One of the companies had previously developed and mandated detailed guides for their PD models amounting to several hundreds of pages; however this approach was discontinued due to various issues including ownership, control, and adherence, amongst others. Problems with PD models that were found to be most widely held by interviewees were that they often cause important project work to be delayed due to unnecessary tasks or activities and they are not communicated well to employees. Communication of the PD model was not highlighted as a problem in Company B, however a number of interviewees were just about aware that a PD model existed at this company. Managers and engineers alike asserted that projects are often different therefore a single inflexible model should not be imposed on all projects as it would inevitably become a liability. Some interviewees mentioned that non-conformance to processes was common. All of the companies had made efforts to incorporate flexibility into their PD models. This leads to the first key finding: PD models should be enabling, simple, flexible, and not coercive.

The flexibility given to designers, engineers, and also managers is encouraging. A general satisfaction was conveyed by employees regarding the level of flexibility that they had and that engineers in their company were afforded. In most of the companies employees were empowered to control the order of activities under their jurisdiction, while respondents in four of the companies felt there was a healthy degree of methodological flexibility as well. A degree of process rigidity in one company was communicated by way of results; similar sentiment was found in other companies as well. It was felt that the level of individual responsibility and employee empowerment was linked with company culture.

Sobek et al. (1998) suggested that USA companies were moving towards a heavyweight project-management structure, and results from this study indicate the same trend in Europe. One company formally implements a chief engineer system, wherein a technical leader is personally involved in market research and is technically responsible for a product from concept to launch. However, as in the other companies, a non-technical project manager is always managing the project. Another company has trialled this approach informally and witnessed substantial results. Other companies do employ technical leaders but they tend to be appointed after the concept stage or there are multiple leaders that lead different stages of PD. Despite the title 'chief engineer' or its equivalent being used at all of the companies, their approaches are all different and none are equivalent to the purist description of the chief engineer system employed at Toyota (Ward, 2007). Each of the approaches has its merits and demerits, yet it is unclear which approach is supreme. Most of the respondents considered their company's approach to leadership as somewhat effective.

Through the study of the five companies, it has been concluded that none of the companies applies SBCE as described at Toyota (Sobek et al., 1999). This finding is converse to what was concluded by Baines et al. (2007) about the presence of SBCE in the automotive and aerospace industries. Evidence was found for the consideration of multiple alternatives at each of the companies; however one solution is quickly selected based on subjective analysis. What is more is that the consideration of alternatives often takes place informally and is only reported for some specific analysis such as cost. One company has however, formally implemented a pseudo-set-based approach in the concepts stage of their PD, considering and evaluating multiple alternatives based on a given customer-focused criteria. However, simulation and prototyping was found to take place after conceptual decisions were made and the design concept was finalised. Physical prototyping is seen as costly and substitutable with computer models and simulation software, however the production of full-scale prototypes remains vital in every project for each of the companies. Two companies have tested a set-based approach informally, where multiple alternatives were taken forward and simultaneously designed, but did not progress alternatives sufficiently to allow convergence upon optimum design solutions. None of the companies intentionally delay their specification of products and they tend to work in a constrained design space that limits their innovation. The culture to specify and select design solutions as early as possible prevents the consideration of more of the design space. This lack of exploration is a manifestation of the project-focused attitude in PD, which is somewhat contrary to the learning-centric or KB environment employed at Toyota.

Despite the efforts made by companies to improve, it could not be concluded that a culture to continuously improve was present at all of the companies. All of the companies have formal mechanisms to capture improvement suggestions, yet interviewees in most companies were not encouraged by the level of incorporation of ideas. One of the companies did excel in this area and employees seemed more optimistic, and consider contribution of improvement suggestions to be worthwhile. Lessons learnt are captured by all of the companies, but are not used effectively. However one company has a formal lessons learnt strategy which captures lessons from each project. Employees are encouraged to make suggestions which are fed back into the processes.

All of the companies employ a systems engineering approach in conjunction with a combination of specification and requirements documents. Cross-functional module development teams are only employed in one of the companies, however they are formed late in the design process. Manufacturing engineers tend to be involved in the design of products and their level of involvement increases as the project develops, however only three of the companies involve them in the concept stage albeit minimally. There is nonetheless a trend to increase manufacturing involvement in concept development.

Three of the companies employ a supplier strategy in which some suppliers are interlocked with the company, while others are given less flexibility to design components (Figure 4.10). Suppliers to these companies do not employ SBCE, but they do sometimes offer alternative solutions based on a rough specification. This finding is similar to the study by Liker et al. (1996) which found that a set-based approach was not prevalent amongst USA suppliers.

It was found that at the systems level, project initiation may follow a drumbeat due to standard launch windows in certain product markets. However, all of the companies are responsive to customer requests, some in competition with other suppliers. Projects tend to run late in all of the companies, and activities are often sacrificed in order to meet launch dates. One of the key reasons for the lack of punctuality is the unplanned design changes and pervasive rework in engineering projects. This subject was discussed at length with interviewees and the two main causes that were highlighted were changes to customer requirements and poor decisions during the under-resourced concept phase of PD.

Knowledge tends not to be pulled; rather it is pushed onto engineers, however almost all interviewees suggested that most design problems would be solved if the correct knowledge was in the right place at the right time. It was also found that most of the interviewees spend 80% of their time on routine tasks, with the exception of one company that puts special emphasis on innovation. However, none of the companies focus primarily on learning and increasing enterprise knowledge. Evidence for the use of trade-off curves was found in one company; however checklists were employed in all companies with varied usage and effectiveness.

Only one of the companies has a separate research department dedicated to R&D, which offers mature technology to new products. Other companies have R&D departments that push their technology onto new products.

A3 group problem solving is employed by two of the companies during design, both of which follow a plan-do-check-act learning cycle. One of these companies find it difficult to follow as the problem solving meetings are generally virtual and a single-sheet representation is not always used, while the other company finds that different departments vary in their methodologies.

Mistake proofing is considered where possible in all of the companies, but there is no evidence that it is formally considered as part of their PD processes. Design for six sigma is used sometimes by three of the companies to 'design in' quality. Robust design and Taguchi methods are also used in two of the companies.

The results from the field study show that a number of lean PD principles and practices are indeed present in industry. This is the second key research finding from this study. As indicated in Table 4.6, each company formally implements an assortment of the lean PD enablers, however, evidence was not found for the formal implementation of many of the enablers in industry.

Table 4.6 Formal implementation of lean PD enablers by companies A to E[13]

Lean Product Development Enablers	A	B	C	D	E
Set-based concurrent engineering					
Multiple alternatives (designed)					x
Delaying specification					
Minimal constraint				x	
Extensive simulation/prototyping (including full-scale models)					x
Convergence on optimum solution					
Integration/target events					
Chief engineer technical leadership (one leader throughout a project)					x
Design concept document					
Cross-functional module development teams & manufacturing involvement during the concept phase of PD	x		x		x
Knowledge-based environment (learning focus)					
Rapid learning/comprehension					
Knowledge/information pull (in right place at right time)					
Trade-off curves	x				
Check sheets/lists	x	x	x	x	x
Technical design standards and rules	x	x	x	x	x
A3 single-sheet knowledge representations			x		x

[13] This table is based on the framework for lean PD enablers presented in Table 5.1; table rows that have been coloured grey indicate the enablers that were not enquired about as part of the interview process.

Lean Product Development Enablers	A	B	C	D	E
Digital engineering (CAD/CAM/CAE/Simulation etc.)	x	x	x	x	x
Mentoring by senior employees (Genchi Gunbutsu)					
Learning cycles (PDCA/LAMDA)			x		x
Expert workforce development					
Employee empowerment/individual responsibility	x	x	x		
Value-focus (planning and development)					
Customer-focus (customer needs/wants)					
Value-stream mapping					
Supplier strategy (supplier types and interlocking)	x		x		x
Supplier Set-Based Concurrent Engineering					
Standardisation of processes, skills, and design methods	x	x	x	x	x
A3 group problem solving (Nemawashi and Obeya)			x		x
Root-cause analysis and 5 whys			x	x	x
KB engineering system (know-how database)					
Knowledge reuse	x	x	x	x	x
Lessons learnt reflection process (Hansei)			x		
Test-to-failure (Ijiwara)					
Limit curves					
Test-then-design					x
Design concepts matrix	x	x	x		x
Quality matrix (QFD)	x		x		
Early problem solving					
Mistake proofing (Poke Yoke)					
Robust design (Taguchi) methods					
Design in quality	x	x	x		
Design structures functional plan (K4)					
Multi-project plan and strategy				x	x
Separating research from development			x	x	x
Continuous improvement (Kaizen) culture			x		
Standard architectures (and modularity)	x	x			x
Number of lean PD enablers formally implemented by Co.	13	9	18	9	19

4.3.2 Challenges in Product Development

The challenges that have been identified may be organised around 12 over-arching categories. These categorised were formulated by the author by identifying major themes. The categories were refined via an iterative process through which feedback from researchers and practitioners was incorporated.

Quotes from the interviews have been included here (as stated) in support of the proposed challenge categories. The 12 categories are:

1. *Design changes – detrimental to schedule, cost, workload etc.*
    a. "There is a lot of rework in the process that is expensive and time consuming"
    b. "Customers change requirements and there is no software change disciplines"
    c. "Platforms (integration) team receive optimised designs that require significant modification/ rework"
    d. "System complexity and the impact of design changes"
2. *Customer value – misunderstood, poorly represented, and often not achieved*
    a. "Design starts without requirements"
    b. "Very hard to establish requirements and document interrelations"
    c. "Ambiguous/unclear requirements"
3. *Design specification – documentation not customer-focused, causes* delays, and often not met
    a. "Products hardly meet specification"
    b. "Design doesn't meet specification"
4. *Knowledge – decisions made without knowledge, resistance to knowledge capture, lack of knowledge reuse, and loss of technical expertise*
    a. "It can be very difficult to find knowledge"
    b. "Old CAD files often cannot be read due to technology obsolescence"
    c. "Inadequate filtering of knowledge"

   d. “No standard template for knowledge capture”
   e. “Lessons learnt are captured but not used effectively for new projects”
   f. “Difficult to get the right info in the right place at the right time”
   g. “Too much information and too many computer systems”
   h. “(Difficulty in) capturing tacit knowledge”
5. *Process flow – often disjointed, phase-gate system doesn’t facilitate flow, and causes work to be pushed onto employees rather than pulled*
   a. “Far too many overlapping processes/models”
   b. “Model causes delays (does not deal with uncertainty effectively)”
   c. “Innovation and development are divided as part of the stage-gate model”
   d. “There is hidden waste in the process”
6. *Communication – process not communicated well, lack of collaboration between departments, lengthy reports not effective*
   a. “PD model is confusing”
   b. “Global organisation communication (difficult)”
   c. “Over-the-wall communication”
   d. “Other departments need to be involved earlier in PD”
   e. “Engineers do not understand the PD model and process”
   f. “Lack of openness between departments”
7. *Leadership – ineffective, lack of coordination, ambiguous responsibilities, and lack of process ownership*
   a. “No escalation if process is not followed”
   b. “Unclear roles and responsibilities”
8. *Management – excessive bureaucracy, ineffective reward system, destructive pressure, and reducing profit margins*
   a. “Makes it difficult to meet new time-to-market reduction”
   b. “(Excessive) quantity of work”
9. *Innovation – engineers distracted from innovation, inhibiting design standards, lack of exploration etc.*
   a. “Preliminary design could be a lot better”

   b. “Current model does not accommodate for more innovation”
   c. “Concept phase lacks resources as they are tied in to rework, which is a recurring cycle”
   d. “Lack of flexibility in constraints”
   e. “Fire fighting - the focus is on 'day-work' rather than learning and innovation”
10. *Planning – ineffective planning and use of resources, false promises, and inefficient document release process*
   a. “Sometimes individuals are advised not to follow the process to meet deadlines”
   b. “Delivery pressures lead inevitably to process deviation”
   c. “Delayed activities put pressure on the final deadline”
   d. “Process is dependent on other activities”
11. *Time management – ineffective scheduling, not enough time to test, and design changes affect schedule*
   a. “Programme management is not effective (resourcing)”
   b. “Late delivery of hardware”
   c. “Programme time scales are not synchronous with OEM programmes”
   d. *“Time pressure - not capable of delivering fully validated products”*
12. *Process improvement obstacles – meetings not favoured, VSM received with negativity, and preconceived ideas inhibit improvements*
   a. “Centralised groups need to support more and add work less”

Although the 12 categories are general and apply to the product lifecycle, the challenges appear to be skewed towards the early phase of PD. The root-causes of the various challenges may be numerous, however one common element that is intertwined with many of the challenges is the perpetual ‘rework cycle’ that was discussed by interviewees at all of the companies that were studied (see Figure 4.15). One of the causes of what is referred to as the rework cycle is the under-resourced concept development phase, which was found to be filled with ambiguity, or is as many authors described it ‘fuzzy’ (Koen et al., 2001).

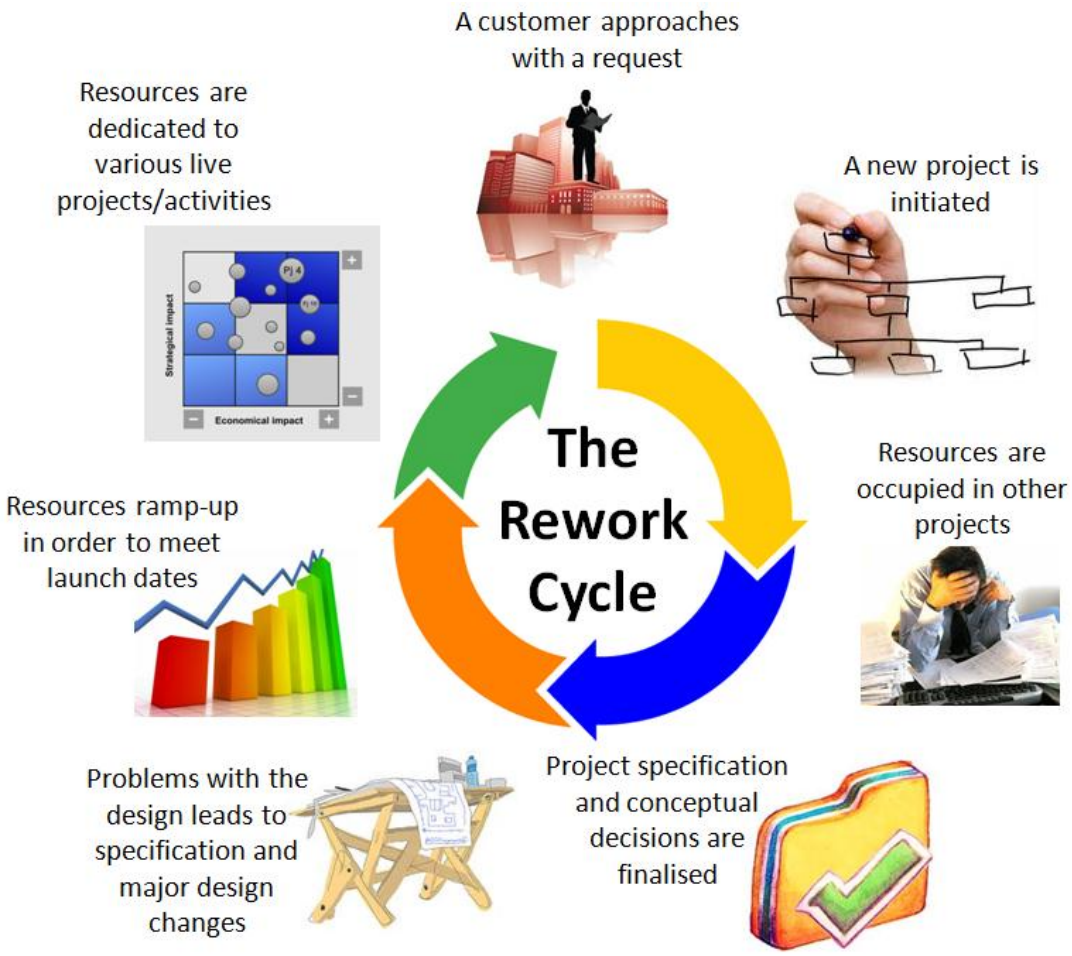

Figure 4.15 The rework cycle

This leads to the third key finding from this study: rework is a common PD challenge faced by industry which may be addressed by improving the concept development phase.

4.4 Summary

In this chapter an industrial field study carried out to better understand the industrial context for this research is presented.

The research presented in this chapter helped to develop a general understanding of the research context. Nuances in language, culture and behaviours at the different companies were noted and industrial interests were delineated. Particular interest in SBCE was aired throughout the study.

The results presented indicate clearly that lean PD principles and practices have a presence in industry. Some of these have been formally implemented in all of the companies that were studied, many of which are not unique elements of lean PD. Other lean PD enablers, such as SBCE were not found to be present in industry as described in the literature. These gaps warrant industrial applications and case based research.

A plethora of challenges are being faced by PD teams and departments in industry, many of which stem from the concept development phase. One of the most prominent challenges is the prevention of design rework which often results from poor conceptual decisions.

Although the construction of an all-encompassing lean PD model was initially envisaged, the literature review conducted and industrial field study have steered the research to focus on conceptual design. Previous research in this area has highlighted that conceptual design is where Toyota is most distinctive through their implementation of SBCE (Sobek et al., 1999). Liker and Morgan (2011) also recommended research in this area. Furthermore, the research findings underline the industrial warrant and justification for more focused research in conceptual design.

The implications for the lean PD model are the following: (1) the scope of the model will be constrained to implementing lean PD principles and practices in conceptual design, (2) the research will focus on enhancing key conceptual decisions in order to prevent rework, and (3) research will be centred around SBCE for which no methodology has been found in the literature and none of the companies were found to be implementing.

The next chapter describes the development phase of this research, and effectively the construction of the lean PD model.

5 MODEL CONSTRUCTION

This chapter presents the construction of the lean PD model. The research presented in this chapter addresses the third and fourth research objectives: extract lean PD principles and enablers from literature and define a framework that combines them; and develop a process model through which lean thinking can be implemented in PD.

The chapter is divided into 6 sections:

In section 5.1 the development of a framework for lean PD enablers is presented. As chapter 3 provided a literature review for lean PD in general, a summative literature review of SBCE is provided in section 5.2. SBCE is effectively the process through which lean thinking can be applied in conceptual design. In section 0 the construction of the lean PD model for conceptual design is described. The lean PD model is composed of activities which are each described alongside their respective methodology in section 5.4. Recommended tools to support the implementation of the lean PD model are presented in section 5.5, including tools that were developed specifically to support the model. The implementation process is outlined in section 5.6. A summary of the chapter is provided in section 5.7.

5.1 A Framework for Lean Product Development Enablers

In order to construct a lean PD model, lean PD itself requires some further definition. The approach adopted was to first formulate a list of lean PD enablers presented in Table 3.2. Principles, methods, tools, and techniques that have been described by the researchers and practitioners who base their work on TPDS were analysed. Enablers that were mentioned in multiple publications were prioritised, while those mentioned unilaterally were scrutinised further and included on a case by case basis. Enablers that appeared to be overlapping were merged, while others that combined multiple practices were divided. Some of the enablers were merely included in descriptions of TPDS, while others were advocated as integral elements. The differences between descriptions of TPDS could be due to the research manuscript being incomplete such as in the case of Ward (2007), restricted to part of the puzzle (Ward et al., 1995; Sobek et al., 1999), or constrained to a particular example (Kennedy, 2006; Kennedy et al., 2008). Forty seven enablers were identified as integral elements of TPDS. These enablers were classified into three categories: (1) core enablers; (2) techniques; and (3) tools. The core enablers are those that have received the most attention in the literature and appear to be the most distinctive elements. The core enablers for lean PD are depicted in Figure 5.1.

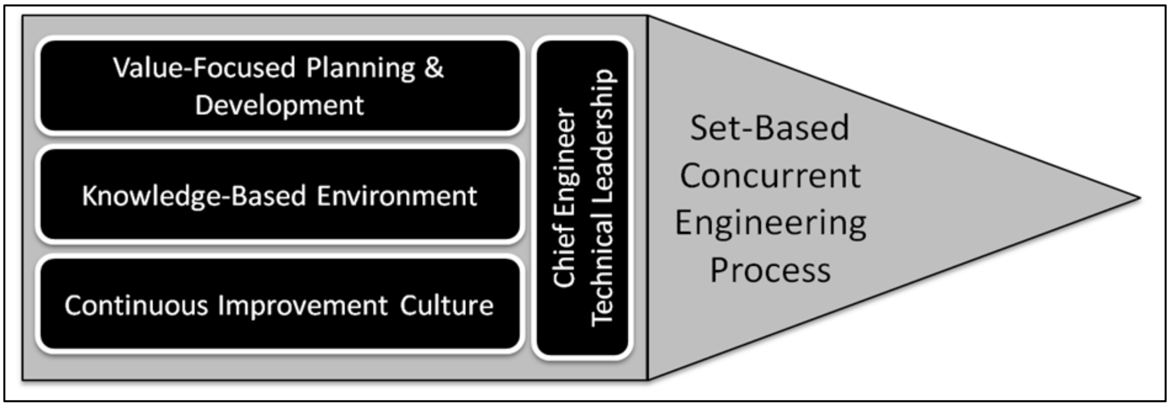

Figure 5.1 The core enablers for lean product development

The core enablers represent the crux of lean PD and in the author's humble opinion characterises a complete PD system. The constituents being the following: (1) a development process: set-based concurrent engineering; (2) vision, strategy and planning: value-focused planning and development; (3) a leadership system: chief engineer technical project leadership; (4) people, infrastructure, and other capabilities: knowledge-based environment; and (5) the organisational culture: continuous improvement. The five core enablers are supported by various techniques (methods or sub-enablers) and tools (hardware, software, and documents). With this in mind the lean PD enablers have been structured into a framework, presented in Table 5.1.

Table 5.1 Framework for lean product development enablers (Khan et al., 2011)

Core Enablers	Techniques	Tools
Set-Based Concurrent Engineering	Multiple alternatives (designed)	Design concepts matrix
	Delaying specification	Design structures functional plan

Core Enablers	Techniques	Tools
	Minimal constraint	Design concept document
	Extensive simulation/prototyping (possibly including full-scale models)	Digital engineering (CAD/CAM/ CAE/Simulation etc.)
	Early problem solving	
	Test-then-design	
	Convergence on optimum solution	
	Supplier strategy (supplier types and interlocking)	
	Supplier Set-Based Concurrent Engineering	
	Mistake proofing	
	Design in quality	
	Robust design methods	
	Integration/target events	
Value-focus (planning and development)	Value-stream mapping	Quality matrix (QFD)
	Customer-focus (customer needs/wants)	
	Multi-project plan and strategy	
Chief engineer technical leadership	Cross-functional module development teams & manufacturing involvement	
Knowledge-focus (knowledge-based environment)	Knowledge/information flow/cadence/pull (in right place at right time)	Trade-off curves Check sheets/lists
	Knowledge reuse	KB engineering system (know-how database)
	Expert workforce development	
	Mentoring by senior employees	
	Test-to-failure	Limit curves
	Rapid learning/comprehension	A3 single-sheet knowledge representations (including problem reports)
	A3 group problem solving	
	Learning cycles (PDCA/LAMDA)	
	Root-cause analysis and 5 whys	
Continuous improvement (Kaizen) culture	Employee empowerment/individual responsibility	Technical design standards and rules
	Lessons learnt reflection process	Standard architectures (and modularity)
	Standardisation of processes, skills, and design methods	
	Separating research from development	

The framework for lean PD enablers provides a succinct reference for lean PD. This framework was instrumental in developing the research further. Although this contribution brings together the research presented in the literature, additional research was required in order to develop a testable process. Furthermore, it was necessary to focus on developing a model based on SBCE due to the research findings from the literature review and industrial field study.

5.2 Previous Research on Set-Based Concurrent Engineering: Theory and Applications

The research presented in chapter 3 addressed lean PD in general, however, with the focus on SBCE, an overview of research in this area is also required. Despite the distinctiveness of SBCE, it is firmly based on many generic engineering principles, and the associated literature is vast. This section is therefore not intended as an extensive review of the subject, but does provide a summary of research in this area.

5.2.1 The Theoretical Foundation for Set-Based Concurrent Engineering

The theoretical underpinning for SBCE is likely to be the natural progression of product design and development, although it has also been attributed to Japanese manufacturers (Ward et al., 1995). The notion to explore a set of alternative solutions before taking them through a structured evaluation process is common in engineering textbooks (Buhl, 1960; Ulrich and Eppinger, 2000, Buede, 2009). The systematic process of divergence and convergence is however a formidable engineering challenge (Clark and Fujimoto, 1991), and design teams that are under pressure to meet pre-specified time and cost targets are all too likely to make rushed selections (Tebay et al., 1984). When exploring alternative solutions a firm should consider modelling and prototyping solutions in parallel to allow objective analysis and comparison (Dahan and Mendelson, 1998). Thomke (1998) suggests that the optimal prototyping and testing strategy should balance the cost of prototyping and the cost of redesign. The early specification of design concepts is another common problem as it results in expensive design changes and other consequences later in the design process. Bacon et al. (1994) found from their studies of high technology industries that an unchanging product specification in a dynamic environment is, at best, an elusive goal. Delaying commitment was eloquently promoted by Thimbleby (1988), who found that it often leads to new insights. He attributed delaying commitment to experts, and suggested that amateurs try to get things completely right the first time and often fail because they try to solve too many problems at once. Thimbleby also identified two problems when searching for a design solution: (1) the search may not be conducted effectively; and (2) a good idea or design may not be recognised or conversely a bad one may be mistakenly assumed to be good. Both of these problems are more likely to occur when designers are under excessive pressure, which results in a tendency to prefer early specification and reasonable decisions so that concrete problems can be concentrated on rather than abstract problems. By delaying commitment to the specification and design of a particular module, other modules are not as sensitive to any necessary design changes (Thimbleby, 1988). All of the ideas summarised above are likely to have been formulated without input from case studies of Japanese companies.

Ward et al. (1995) were the first to coin the term SBCE and advocated that it is potentially an underlying cause for Toyota's various successes. They looked for evidence of a set-based PD approach in the automotive industries of Japanese and the USA, and found it being practised at the Toyota Motor Co. This work provided a case study of Toyota PD, but does not present a detailed process or methodology for SBCE. Sobek et al. (1999) built on this case study and developed the SBCE idea further. The authors describe SBCE through an organised group of principles and a number of supporting mechanisms. The authors described the process as follows:

“Design participants practise SBCE by reasoning, developing, and communicating about sets of solutions in parallel. As the design progresses, they gradually narrow their respective sets of solutions based on the knowledge gained. As they narrow, they commit to staying within the sets so that others can rely on their communication.”

Ward also compiled a textbook that described SBCE supported by trade-off curves as the key elements of lean PD. In this approach the team breaks the system down into subsystems and sub-subsystems, identifies broad targets at each level, and creates multiple concepts for each component and whole system. They then filter concepts by 'aggressive' evaluation, while capturing information in the form of trade-off curves, and finally filter and converge based on the knowledge acquired (Ward, 2007).

5.2.2 Concurrent Engineering and Set-Based Design

Concurrent engineering is considered by many to be a breakthrough in the response to contemporary engineering challenges, and more and more companies continue to adopt this methodology even after 20 years since its inception. In concurrent engineering PD activities that previously took place sequentially, should be parallelised so that design, manufacturing, and other functions are better integrated. The primary objectives are essentially to reduce the elapsed time required to bring a new product to the market, and to facilitate the consideration of many aspects of a product's lifecycle early in the design process. Although the objectives of concurrent engineering are logical, there is no single approach to achieve them. Concurrent engineering research has focused on supporting socio-organisational mechanisms with special emphasis on communication. It may be argued that typical concurrent engineering does not sufficiently address the logical and scientific nature by which product design problems need to be solved. This realisation led some researchers to divide product design into two groups: point-based design (PBD), and set-based design (SBD) (Ward et al., 1995). Point-based design starts by defining the problem typically through a specification document or functional requirements. A number of possible system solutions are generated, and after preliminary analysis the most promising or lowest-risk solution is selected. This is followed by an unconstrained number of iterations wherein parts of the solution (subsystems) are designed and modified by the functional groups involved until the system design is sufficiently close to the product definition. This is not always the case in first and second tier suppliers who may often only consider a single solution. If the selection in both cases is deemed infeasible by any functional group at any time during PD, either the product definition has to be amended or the design process must effectively go back to the start but this time with increased time pressure. This ‘design optimisation’ approach involves repeated modifications, which can invalidate preceding design work and decisions, requiring activities to be repeated. This is quite simply in opposition to the lead time reduction sought by the parallelisation of activities. Typical concurrent engineering adds multiple actors and social structures to this simplistic model. Some companies have invested great effort to arrive at a PD process in which the sequence of activities and decisions minimises the number of design changes. However, this places more stress on the decisions, and leads to prolonged meetings and lengthy review processes which again increase lead time or cause PD tasks to be disregarded.

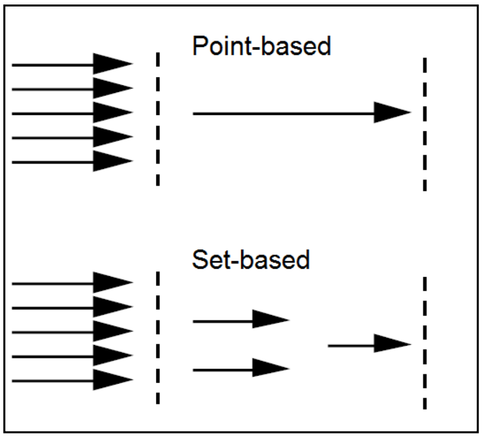

Figure 5.2 Comparing point-based and set-based approaches (adapted from Sobek et al., 1996)

Set-based design on the other hand, also begins by defining the problem and idea generation, but there is no selection of a system design solution. Set-based design differs by each functional group broadly considering sets of possible subsystem solutions, and gradually narrowing their respective set while communicating with each other to converge on a final integrated system solution (Figure 5.2). The set of possibilities might include numerous discrete designs or a range of parameter values, and sets from previous projects can lead to a focused search and rapid convergence in subsequent projects. Set-based design offers a pertinent solution to the organisational challenge of differentiating functional groups and integrating project teams (Figure 5.3).

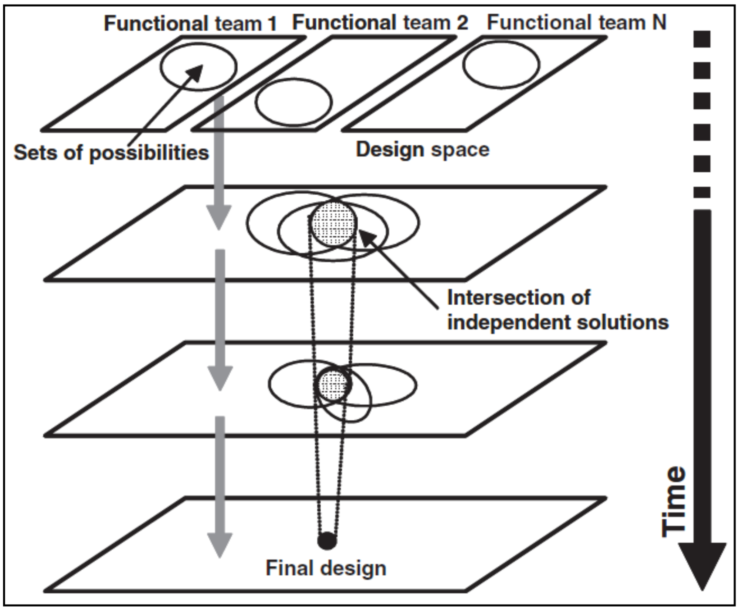

Figure 5.3 Functional interaction in set-based concurrent engineering (Nahm and Ishikawa, 2005)

The set-based design approach, when combined with concurrent engineering forms SBCE although the terms set-based design and SBCE have been used interchangeably (Liker et al., 1996). SBCE forces three important cultures: exploration of the design space, communication between interdependent groups without which no system can be formulated, and delayed commitment, which can only be achieved when feasibility is established. Table 5.2 provides a literature-based comparison between point-based design and set-based design.

Table 5.2 Comparing point-based and set-based design (Sobek et al., 1999; Ballard, 2000; Ward, 2007)

Point-based design (PBD)	Set-based design (SBD)
Costly design iteration feedback loops due to late design changes require lengthy meetings and invalidate previous decisions	Decisions are delayed, while multiple prototypes are pursued, preventing late changes being required
Detailed early design specifications & standards prescribe single solutions	Loose ‘constrain where necessary’ specification developed late to allow a range of acceptable alternatives and a

Point-based design (PBD)	Set-based design (SBD)
	creative design environment
Regular communication with suppliers about design (joint design)	Strong relationships and loose specification allows suppliers to provide solution sets without the need to check up on them
Collocated dedicated design teams force communication (can lead to loss of expertise)	Corporate communication culture does not require collocated teams
Designers spend a large percentage of time in meetings	Designers spend the majority of their time creating and analysing
Design teams focus on working together to arrive at an 'agreed' single solution	Design teams focus on learning more about the alternatives
Creativity is inhibited by the need for agreement	Allows for creative 'radical' improvements to be pursued with a fair degree of safety

5.2.3 Contemporary Research on Set-Based Concurrent Engineering

SBCE has attracted a fair amount of attention in recent years. Ballard (2000) hypothesised that the application of SBCE in combination with a number of additional lean PD enablers would reduce negative iteration in design. He suggested a number of strategies for reducing negative iteration in design listed in Table 5.3.

Table 5.3 Strategies for reducing negative iteration (Ballard, 2000)

Restructure the design process • use value-stream mapping (VSM) to re-sequence • use pull scheduling to reduce batch sizes and achieve greater concurrency
Reorganise the design process • make cross-functional teams the organisational unit • use team problem solving (call a meeting) • share ranges of acceptable solutions
Change how the design process is managed • pursue a least commitment strategy • defer this decision (defer commitment) • practise set-based design • use the Last Planner system of production control
Overdesign (design redundancy) when all else fails

Ford and Sobek (2003) developed a system dynamics model to simulate a PD process in which four alternative automobile systems (e.g. cooling) are simultaneously designed. The authors associate the simultaneous development through the early stages of PD with 'real options theory'. The central premise of real options theory is that, if future conditions are uncertain and changing the strategy later incurs substantial costs, then having flexible strategies and delaying decisions can increase project value when compared to making all key strategic decisions early in the project (Ford and Sobek 2003). The authors conclude that delaying managerial decisions can add value by keeping alternatives alive, and that purposeful and structured management of flexibility can potentially increase new PD project value significantly.

Recently the focus of research has been specifically on concept selection. This includes the incorporation of fuzzy set theory/logic and the automated analysis of design parameters by means of mathematical algorithms (Nahm and Ishikawa, 2005; Telerman et al., 2006; Avigad and Moshaiov, 2010; Moreno-Grandas et al., 2010; and Qureshi et al., 2011). These studies are also concerned with decisions under uncertainty, design optimisation and incorporating designer preferences. Nahm and Ishikawa (2006) extended their previous work by incorporating designer preferences for alternative solutions with 3D CAD. Further to this research a design support system has been produced that generates a ranged set of design solutions that satisfy performance requirements (Inoue et al., 2010). After the functional parameters are input into the system, 3D CAD models are automatically amended due to a series of analyses and a recommended model is provided.

Augustine et al. (2010) contribute a framework through which the best traits from an initial set of designs are combined to create a new set of hybrid concepts (Figure 5.4). This framework is an outstanding offering to the research field.

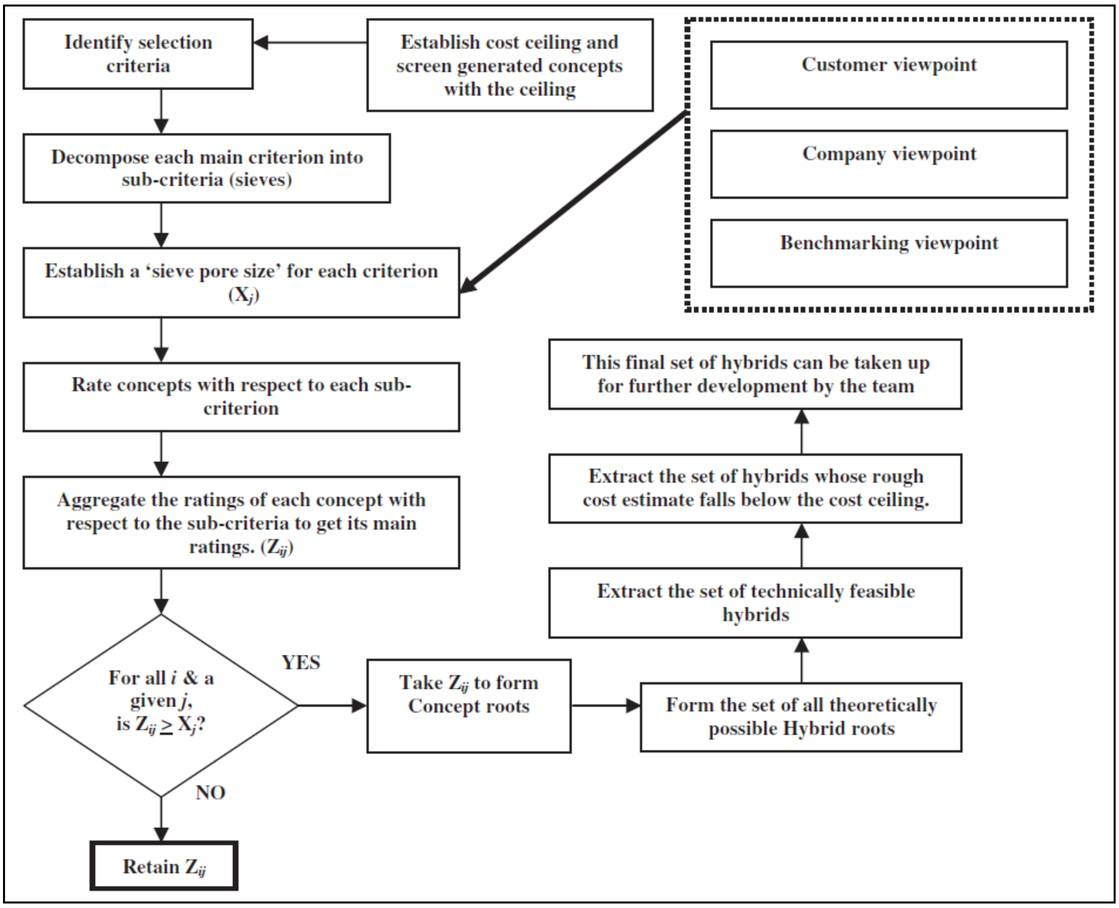

Figure 5.4 Framework for concept convergence process (Augustine et al., 2010)

5.2.4 Set-Based Concurrent Engineering Case Studies

Two case studies were identified in which set-based design approaches were implemented. Madhaven et al. (2008) developed what they refer to as a set-based approach to multi-scale design illustrated in Figure 5.5.

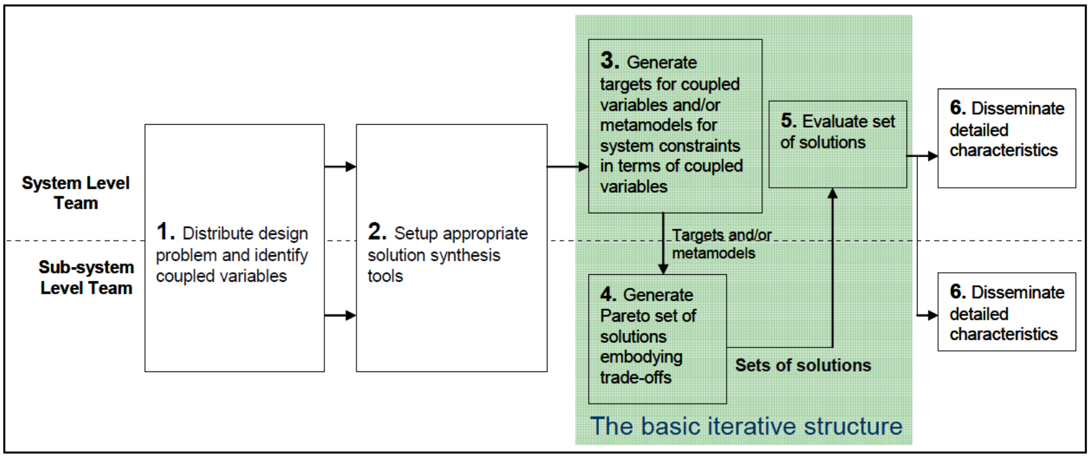

Figure 5.5 Schematic representation of a set-based approach to multi-scale design (Madhaven et al. 2008)

The authors tested the approach initially by means of modelling and simulation tools and were encouraged by the results (Carlos et al., 2006). Two key benefits were identified: (1) creating a greater variety of solutions improves the chance of finding a good solution and possibly even faster; and (2) there is a lower risk of not finding any feasible solution and having to go through expensive iterations. Madhaven et al. (2008) explain how an intern converted the previous/current design process at Schlumberger, a developer of oil tools and services, to incorporate the developed approach. An industrial trial of the approach was conducted to test if the benefits obtained in the laboratory would be obtained in an industrial setting. The researchers found that the set-based method (SBM) resulted in a reduced number of costly iterations, and a better exploration of the design space which may have led to better quality and innovation.

Raudberget (2010) conducted a number of case studies to test principles of SBCE, based on the work of Sobek et al. (1999). Participating design teams were encouraged and optimistic after initial applications. The researchers did not produce a generic SBCE process, but rather they altered current processes to test the framework of principles proposed by Sobek et al. (1999). Case studies were conducted on mechanical engineering products or subsystems from three automotive companies and one company from the paper industry. Case study participants noted improvements in product cost and performance, level of innovation, project risk, and a reduction in engineering changes. These were suggested to have been achieved at the expense of increased lead times in three out of five case studies, and development costs in two. One possible reason for this is that the research focused on the set-based method and not enough attention was placed on the concurrency of activities. The researchers provide some recommendations for the introduction of SBCE in pilot projects (Table 5.4), but provide little information regarding the methodological changes that were actually performed.

Table 5.4 Recommendations for the introduction of set-based concurrent engineering in pilot projects (Raudberget, 2010)

Recommendation	Description
Sidestep current development practices	Allow teams to bypass the standard development processes when appropriate Avoid freezing concepts or product structures at early stages of development
Train engineers and managers	Create a broad acceptance for the methodology by training a core team of managers and engineers Only select individuals that are willing to participate
Adapt and use the three principles	Match the intentions of the principles to the tasks at hand, without taking any shortcuts
Allow flexibility in specifications	Set broad targets initially for the most important specifications and leave the rest unconstrained Use the loosest possible constraints to create flexibility
Narrow sets stepwise	Gradually reduce the size of the sets as soon as information is available
Decisions by elimination	Reject solutions (based) on tangible reasons only Base decisions on results of tests, simulations, technical data, trade-off curves or other knowledge
Include a low risk member in each set	Use back-up solutions for (the pursuit of) innovative or low-cost members of a set
Avoid process design	Postpone the formulation of a new development process until the experiences of SBCE are clarified

Recommendations and other lessons from the case studies presented in this section were carefully considered prior to implementation of the lean PD model.

5.2.5 Set-Based Concurrent Engineering Principles

Perhaps the most detailed publication about SBCE was produced by Sobek et al. (1999). The SBCE framework that is presented provides a combination of principles that characterise a SBCE process. The structured set of principles is based on a detailed case study of the TPDS, and is provided below:

1. Map the design space
    a. Define feasible regions
    b. Explore trade-offs by designing multiple alternatives
    c. Communicate sets of possibilities
2. Integrate by intersection
    a. Look for intersections of feasible sets
    b. Impose minimum constraint
    c. Seek conceptual robustness
3. Establish feasibility before commitment
    a. Narrow sets gradually while increasing detail
    b. Stay within sets once committed
    c. Control by managing uncertainty at process gates

Morgan and Liker (2006) briefly describe the SBCE process and provide examples of how Toyota implements it. They also describe some additional characteristics that are not mentioned in other works.

Ward (2007) describes how SBCE works in a logical order which is useful in structuring a SBCE process. The following six steps are proposed:

1. The team breaks the system down into subsystems and sub-subsystems, into the smallest pieces feasible
2. They identify broad targets for the system and each subsystem

3. They create multiple concepts for the system and each subsystem, including both product and manufacturing systems
4. They filter these concepts by aggressive evaluation, identifying failure modes and finding failure points for each. They also filter by integration, eliminating concepts that don’t fit with each other, the customer’s needs (preferably as expressed after seeing what is possible), the competitive situation etc.
5. Failure information goes into a trade-off knowledge base that guides the design. Trade-off curves describe the limits of performance that are possible with a given design approach
6. As they filter, they increase the accuracy, detail, and cost of the concept models and tests. They tune the rate of convergence, the rate of detailing, and the level of innovation so that the last concept standing is well proven and optimised

Principles of SBCE have therefore been identified in several literature sources. These principles have been classified into five categories (Table 4) as an extension of the initial set of principles proposed by Sobek et al. (1999). There are two additional categories: strategic value research and alignment, and create and explore multiple concepts in parallel; all of the categories have been supplemented by constructive additions from other researchers. The principles have also been supported by expert opinion from representatives of the five industrial collaborator companies.

Table 5.5 Categorisation of set-based concurrent engineering principles

Category	Identified principles
Strategic value research and alignment	• Classify projects into a project portfolio (Morgan and Liker, 2006; Ward, 2007) • Explore and establish customer value for projects (Morgan and Liker, 2006) • Align each project with the company value strategy (Ward, 2007) • Translate customer value to designers (via concept paper) (Sobek et al., 1999; Morgan and Liker, 2006)

Category	Identified principles
Map the design Space	• Break the system down into subsystems and sub-subsystems (Ward, 2007) • Identify targets/essential characteristics for the system (Ward, 2007) • Decide on what subsystems/components improvements should be made and to what level (selective innovation) (Ward, 2007) • Define feasible regions based on knowledge, past experience and the chief engineer/technical leader, and consider different perspectives/functional groups (Sobek et al., 1999)
Create and explore multiple concepts in parallel	• Pull innovative concepts from R&D departments (Ward, 2007) • Explore trade-offs by designing multiple alternatives for subsystems/components (Sobek et al., 1999) • Schedule time for innovation and problem solving while the set of alternatives is broad (Morgan and Liker, 2006; Ward, 2007) • Ensure many possible subsystem combinations to reduce the risk of failure (Ward, 2007) • Perform extensive prototyping (physical/parametrical) of alternatives to test for cost, quality, and performance (Ward et al., 1995; Sobek et al., 1999; Morgan and Liker, 2006; Ward, 2007) • Perform aggressive evaluation of design alternatives to increase knowledge and rule out weak alternatives (Sobek et al., 1999; Ward, 2007) • Transfer information into a trade-off knowledge base that can be used to guide the design (Ward, 2007) • Communicate sets of possibilities (Ward et al., 1995; Sobek et al., 1999; Morgan and Liker, 2006)
Integrate by intersection	• Look for intersections of feasible sets, including compatibility and interdependencies between components (Sobek, 1999; Morgan and Liker, 2006; Ward, 2007) • Impose minimum constraints: deliberate use of ranges in specification and initial dimensions should be nominal without tolerances unless necessary (Sobek, 1999) • Seek conceptual robustness against physical, market, and design variations (Sobek, 1999; Ward, 2007) • Consider lean product design and lean manufacturing concurrently (Sobek et al., 1999)

Category	Identified principles
Establish feasibility before commitment	• Narrow sets gradually while increasing detail: functions narrow their respective sets in parallel, based on knowledge gained from analysis (Ward, 2007) • Delay decisions so that they are not made too early or with insufficient knowledge (Sobek et al., 1999; Ward, 2007) • Design decisions should be valid for the different sets and should not be effected by other subsystems (Sobek et al., 1999) • Stay within sets once committed and avoid changes that expand the set (Sobek et al., 1999) • Control by managing uncertainty at process gates (Sobek et al., 1999) • Ensure manufacturing evaluates the final sets and dictates part tolerances (Sobek et al., 1999) • Ensure manufacturing begins process planning before a final system concept has been concluded (Sobek et al., 1999) • Delay releasing the final hard specification to major suppliers until late in the design process (Ward, 2007)

This categorisation is a significant contribution for a number of reasons. Firstly, it combines lean PD principles for focusing on value with the initial principles of SBCE described by Sobek et al. (1999) which depend heavily on the chief engineer concept for the link with customer value. The previous work did not consider strategic advantages that can be taken from projects. Secondly, the most critical area of the SBCE process is the creation and exploration of solution sets, which Sobek et al. (1999) spread across their framework with little methodological guidance. In this categorisation the creation and exploration of solution sets has been highlighted as a category in its own right and important additions have been incorporated. The third contribution is the link with lean manufacturing which was not emphasised in previous research.

5.3 The Construction of the Lean Product Development Model

Based on the research presented thus far (including the literature review, industrial field study, and investigation of SBCE), a process model for applying lean thinking to conceptual design has been developed. This is referred to throughout this thesis as the lean PD model. The model which has been developed is illustrated in Figure 5.7. The lean PD model combines Toyota PD principles and practices with industry requirements, recommendations and contextualisation. The process model was developed as an embodiment of the framework of lean PD enablers (section 5.1, Figure 5.1), and thus combines SBCE, a focus on value, a knowledge based environment, chief engineer leadership, and continuous improvement. The lean PD model also draws on other lean PD enablers outlined in section 5.1. The lean PD model provides a workable flow of activities for a PD project that is principle-based and can also be supported by company practices. The model may also be customised for each company in which it is implemented.

A number of phases were first defined in order to represent the top-level process. Although the phases may appear similar to some traditional PD models, the activities within them are unique which is why typical phase names have not been used. This is important because typical phase and activity names will be understood based on prior perceptions, which may be better avoided. Phases were determined based on key conceptual decisions that must be made during PD. These decisions were based on the Osborne-Parnes ‘creative problem solving’ process (Figure 5.6) and a review of PD decisions by Krishnan and Ulrich (2001).

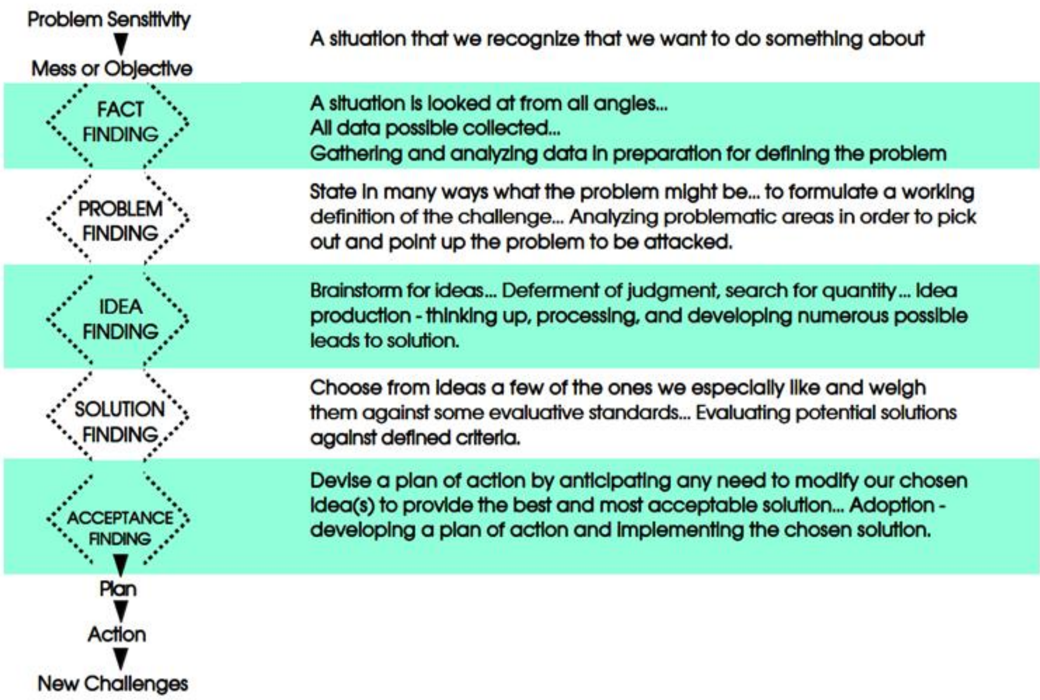

Figure 5.6 Creative problem solving model V2.3 (Isaksen and Treffinger 1985)

The following five questions were developed to represent the key decisions that have to be made during the conceptual phase of PD.

1. What is the design challenge? (This includes fact finding, problem statement, specification, aim, objectives etc.)
2. Which sub-system design options can be considered? (This includes generating options/ideas)
3. Which sub-system design options will be considered for system integration? (This includes evaluating ideas based on knowledge gained through design activities against criteria)
4. What is the optimum system solution identified? (This includes evaluating product system concepts)
5. How can the system solution be optimised for acceptance? (This includes the detailed design, optimisation and qualification of products)

These key decisions were then extrapolated to five phases of conceptual design. The five phases represent a bottom-up process for SBCE.

The five phases of the lean PD model are:

1. **Define value:** the initial product concept definition is developed based on strategic goals, customer requirements, and any other factors that need to be considered
2. **Map design space:** design participants or subsystem teams define the scope of the design work required as well as feasible design options/regions
3. **Develop concept sets:** each participant or subsystem team develops and tests a set of possible conceptual subsystem design solutions; based on the knowledge produced in this phase some weak alternatives will be eliminated
4. **Converge on system:** subsystem intersections are explored and integrated systems are tested; based on the knowledge produced in this phase the weaker system alternatives will be purged allowing a final optimum product design solution to progress into phase 5
5. **Detailed design:** the final specification is released, manufacturing engineers provide tolerances and the process continues with detailed design activities

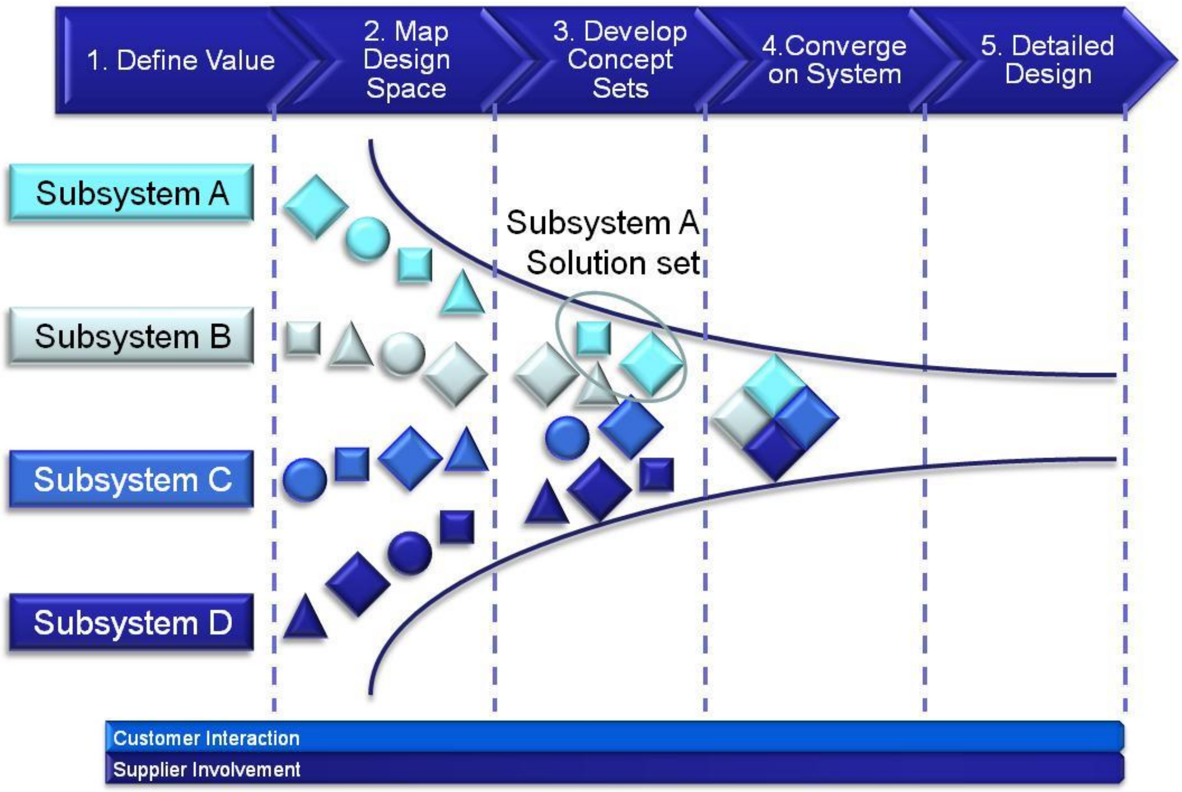

Figure 5.7: The Lean PD model for conceptual design

5.4 Lean Product Development Model Activities

The lean PD model is broken down further into activities as depicted in Figure 5.8. Activities were initially defined by embodying lean PD principles and practices (based on Table 5.1 and Table 5.5) into steps in the process. A series of review meetings were held with representatives from industrial partner companies in order to refine the process[14]. In this section the activities will be described and step-by-step methodologies will be provided. The methodologies were developed to serve as recommendations; however the matter of importance is the presence and correct implementation of the activities in the PD process.

1. Define Value	2. Map Design Space	3. Develop Concept Set	4. Converge on System	5. Detailed Design
1.1 Classify projects	2.1 Identify sub-system targets	3.1 Extract (pull) design concepts	4.1 Determine intersections of sets	5.1 Release final specification
1.2 Explore customer value	2.2 Decide on level of innovation to sub-systems	3.2 Create sets for sub-systems	4.2 Explore possible product system designs	5.2 Manufacturing provides tolerances
1.3 Align project with company strategy	2.3 Define feasible regions of design space	3.3 Explore sub-system sets: simulate, prototype & test	4.3 Seek conceptual robustness	5.3 Full system definition
1.4 Translate value to designers (via product definition)		3.4 Capture knowledge and evaluate	4.4 Evaluate possible systems for lean production	
		3.5 Communicate sets to others	4.5 Begin process planning for manufacturing	
			4.6 Converge on final system	

Figure 5.8: The Lean PD model: activities view

Although a sequential approach has been communicated, the chronological position of some activities within the model may be interchangeable. It is intended that the model would serve as a guide for a project team to organise

[14] A number of researchers from the LeanPPD project consortium supported the development of methodological recommendations for activities in the lean PD model

and guide their PD efforts. Due to the breadth of activities within the lean PD model, the activities have not been defined to every minute detail. Moreover, it was assumed that a high-level of granularity would reinforce the flexibility of the lean PD model. The activities within each phase are described as follows[15]:

Phase 1. Define Value:

1.1 Classify project: Each project should be classified in order to forecast the time and cost commitment. The expected level of innovation at both the system and subsystem level should be clarified in addition to other relevant parameters. The intended market should also be clarified in the case that it impacts subsequent engineering activities.

Methodology for activity 1.1:

1. Create project classification matrix (refer to section 5.5.2.1) using a table or spreadsheet
2. Create project name and schedule
3. Determine customer/intended market
4. Classify the level of innovation by colour-labelling the system design architecture and identify level of innovation required in each subsystem/module (refer to section 5.5.2.2)
5. Estimate project costs e.g. man-month effort, cost investments, ROI, etc.
6. Input additional parameter information

1.2 Explore customer value: Customer needs and desires should be thoroughly understood in order to determine system targets (e.g. reduce weight by x%) and ensure the necessary provision of customer value; The extent of this activity will depend on the level of innovation; design criteria will be determined based on customer value amongst other factors, to support the evaluation of alternatives product designs

[15] A number of supporting tools are mentioned throughout the activity methodologies, these tools are elaborated upon in the subsequent section

Methodology for activity 1.2:

1. Customer value (needs and desires) should be internalised by technical project representatives using customer request documentation, requirements, market research methods, and meetings with customer representatives
2. Customer value should be decomposed into attributes and structured/represented by creating a product value model (see section 5.5.2.3)
3. System targets (requirements) should be defined in order to clarify how the value attributes will be achieved; Special emphasis may be directed towards how the product will be a unique offering in contrast with competitive products

1.3 Align with company strategy: Each project should be aligned with the company PD strategy, in order to take strategic advantages from projects. This will prevent value (benefits) gained through projects from being wasted and ensure the enhancement of the PD process

Methodology for activity 1.3:

1. Identify strategic PD goals from company documentation (company strategy, engineering strategy, and R&D strategy documents)
2. Create a matrix through which strategic goals may be structured and the impact of current projects may be analysed: goals vs. projects (refer to section 5.5.2.4)
3. Analyse current projects against strategic PD goals to determine the strategic impact of each project on PD and populate this data via the matrix created
4. Evaluate each future project against strategic PD goals using the same matrix and determine new goals where appropriate

1.4 Translate value to designers: The information developed in this phase should be compiled in a document referred to as the product concept definition: both the strategic objectives and the understanding of customer value will be translated to the designers that are involved in the project via this document

Methodology for activity 1.4

1. A product concept definition template can be used by internal technical personnel to translate customer value to engineers; customer value may be represented visually using videos, photographs, sketches, diagrams etc. in addition to the necessary requirements, text and maths - this can be achieved using additional web-based techniques if necessary; the template should cater for different departments/functional groups as they will develop their subsystems/work based primarily on this document
2. The product concept definition template combines the knowledge created in phase 1 in a single document; it may be that multiple versions are created for different audiences (e.g. senior managers) from the same information

Phase 2. Map Design Space:

2.1 Each subsystem team should decide based on the product concept definition which sub-subsystems/components to improve and to what level of innovation; this will help to prevent over-engineering while encouraging the necessary innovation and enhancements

Methodology for activity 2.1

1. The product concept definition should be used by subsystem participants/teams to understand the strategic objectives, system targets, and the level of innovation required for their particular subsystem
2. Based on the product concept definition subsystem participants/teams can further classify the level of innovation required for each component or sub-subsystem; using a subsystem architecture template that depicts the modular breakdown of the subsystem architecture the level of innovation for the different product components or sub-subsystem may be labelled (refer to Figure 5.11)

2.2 Identify subsystem targets: Each subsystem or component participant/team will analyse their architecture and identify their own lower-level targets (lower level requirements) based on the product concept definition

Methodology for activity 2.2

1. System targets will be analysed in order to determine modifications to components or sub-subsystems that could help to achieve them
2. Based on the product concept definition and innovation classification diagrams, lower-level targets (requirements) will be identified for sub-subsystems and components (e.g. reduce component weight by x%)
3. Subsystem targets will be reviewed by the technical leader at the system level in order to ensure the correct flow down of system targets
4. A subsystem concept definition template can be used to capture and communicate subsystem targets in addition to the innovation classification

2.3 Define feasible regions of design space: Appropriate design possibilities should be defined based on knowledge and past experience, while considering the views/constraints of different functional groups

Methodology for activity 2.3:

1. Each subsystem participant or team should identify and document design constraints on their subsystem: what can/cannot/should not be done. This information can be extracted from lessons learnt logs, design standards, best practize guides and checklists
2. Each subsystem participant or team should identify ("map-out") possible options for their subsystems, sub-subsystems and components. Feasible regions may include different fundamental concepts, components, arrangements, properties or geometry; R&D departments should be engaged in order to understand state-of-the-art technologies
3. Representatives for the other subsystems may be referred to at this stage to develop a pre-emptive understanding of interdependencies
4. Manufacturing engineers should be consulted to understand their current/future production capabilities and constraints before developing any of the potential options. Manufacturing engineers can be requested to provide the relevant information in a simple visual format to aid the designers (checklists, diagrams etc.)
5. Subsystem design constraints, manufacturing constraints and capabilities, interdependencies with other subsystems, possible options and related information should all be documented in the subsystem concept definition template which is used as the basis for the development of subsystem concept sets

Phase 3. Concept Set Development:

3.1 Extract design concepts: Concepts should be drawn from previous projects, R&D departments, and competitor products (benchmarking)

Methodology for activity 3.1:

1. Subsystem criteria should be defined based on value attributes, system targets, constraints etc.
2. Alternative subsystem and component design documentation/files should be extracted from previous projects, R&D departments, and competitor products based on the subsystem concept definition
3. Knowledge-based engineering system (or product data/lifecycle management software) can be used as a central database from which information concerning previous projects and competitor products is captured and reviewed
4. Alternative options may be mapped against subsystem criteria using matrices in order to filter some of the alternatives

3.2 Create sets for subsystems: This time is scheduled specifically for design teams to brainstorm and innovate so that a set of possible design solutions is proposed; The set for a particular subsystem may be only 2 options, while a subsystem or component that is not being changed would not require a set; Alternatives within a set may comprise of differences in fundamental concepts, components, arrangements, properties or geometry

Methodology for activity 3.2:

1. Based on the subsystem concept definitions, design teams can compose initial sets of design solutions for each of the subsystems which will include the extracted design concepts from activity 3.1
2. Idea generation techniques (e.g. brainstorming) and innovation frameworks (e.g. TRIZ) can be used in order to provoke creativity and facilitate innovation
3. Conceptual solutions can initially be sketched with minimum constraints: the deliberate use of ranges in specification, and initial dimensions should be nominal without tolerances unless necessary
4. Where feasible, CAD software may be used to represent the conceptual ideas

3.3 Explore subsystem sets: alternative solutions shall be simulated, prototyped, and tested for lifecycle cost, quality, and performance

Methodology for activity 3.3:

1. A plan should be produced for testing each sub-system/component alternative in order to ensure that the knowledge created through testing enables weak solutions to be exposed and increases confidence in the design; the plan can focus on rapid and low-cost techniques if necessary (refer to section 5.5.2.5)
2. The plan referred to here as 'subsystem knowledge creation plan' should be translated into a document template which defines the test outputs and representations that would support the comparison of sets and other decision making
3. The different options should be explored and analysed through simulation, rapid-prototyping, mathematical modelling etc. to determine their feasibility, benefits, and potential costs and the results should be incorporated in the same template

3.4 Knowledge capture and evaluation: Knowledge that has been created will be captured (quantitative and qualitative) in order to evaluate the sets

Methodology for activity 3.4

1. The knowledge created through testing should be represented in the relevant graphical formats: limit curves for representing breaking points (and safe zones) for a single design option, and trade-off curves to compare the set of alternative subsystems/components against subsystem design criteria(e.g. cost and expected performance)
2. A SWOT analysis may also be conducted for the evaluation of options

3.5 Communicate sets to others: Each subsystem or component team will present their set to the other teams at an event (meeting) in order to get feedback and understand constraints

Methodology for activity 3.5

1. Conceptual solutions may be represented using an A3 template or MS PowerPoint presentation. The presentation should include the background, current condition, proposal, sketch/CAD drawing, and SWOT analysis
2. A ‘design set (integration) event' can be used as a milestone, where design teams come together to present their sets to each other
3. The set will also be presented using comparative tools such as trade-off curves, and function means analysis
4. Design teams will evaluate sets based on their constraints and will provide recommendations to each other; ideally, any subsystem design decision after this point should neither affect other subsystems nor be affected by other subsystems
5. Based on the evaluation, some of the alternative options may be discarded from the sets

Phase 4. Concept Convergence:

4.1 Determine set intersections: Subsystems that progress into phase 4 can be considered for system integration. The intersection of feasible sets will be reviewed, considering compatibility and interdependencies between subsystems and components

Methodology for activity 4.1:

1. Populate a design concepts matrix with subsystem/component sets in order to illustrate the possibilities for intersection/integration of the various sets into systems
2. Identify any dependencies
3. Determine which system combinations are possible and/or feasible using the concept intersection matrix (refer to section 5.5.2.6)
4. Analyse the effect of subsystem or component selection on the system targets
5. Discount system combinations that are infeasible based on knowledge from previous projects, dependencies, and potential/expected conflicts

4.2 Explore system sets: Potential systems can be simulated/prototyped (parametric and physical), and tested for cost, quality, and performance

Methodology for activity 4.2:

1. A plan should be produced to test system combinations in order to ensure that the knowledge created enables weak system alternatives to be exposed and increases confidence in the design; The plan can focus on rapid and low-cost techniques, and check sheets can be used to track the tests (refer to section 5.5.2.5)
2. The plan referred to here as the ‘system knowledge creation plan’ should be translated into a document template which includes recommended representations for test results that would support the comparison of sets and other decision making
3. The different options should be explored and analysed through simulation, rapid-prototyping, mathematical modelling etc. to determine their feasibility, benefits, and potential costs and the results should be incorporated in the same template
4. The knowledge created should be represented in the relevant graphical formats: limit curves for representing breaking points (and safe zones) for a single design option, and trade-off curves to compare the set of alternative subsystems/components against design criteria (e.g. cost and expected performance)

4.3 Seek conceptual robustness: Conceptual robustness will be sought against physical, market, and design variation in order to reduce risk and improve quality

Methodology for activity 4.3:

1. Identify adverse impacts that may arise from physical variation and noise factors such as manufacturing tolerances, aging, usage patterns, environmental conditions, etc.
2. Brainstorm potential market influences and customer requirements/specification changes which may impact the final design solution
3. Consider the effects of potential market influences and customer requirements/specification changes to the final design solution
4. Brainstorm potential effects that may result from any unexpected changes
5. Analyse the effect of the potential changes to the final design solution using a matrix
6. Analyse the system combinations and rank each solution based on the analysis

4.4 Evaluate sets for lean production: Once the potential systems have been explored, they will be evaluated for lean production to assess the costs, efficiency, problems etc.

Methodology for activity 4.4:

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

4.5 Begin process planning for manufacturing: Once the potential systems have been evaluated, manufacturing and assembly chains will be considered. The effects on cost, time, quality, efficiency, potential problems etc. will also be considered.

Methodology for activity 4.5:

1. Identify design criteria which are related to the manufacturing and assembly process (including criteria from design for manufacturability (DFM) and design for assembly (DFA))
2. Develop manufacturing process webs (refer to section 5.5.2.7)
3. Develop assembly process webs (refer to section 5.5.2.7)
4. Filter process alternatives based on design criteria, filtered design alternatives, etc.
5. Identify knowledge required to evaluate manufacturing and assembly process chains
6. Explore and evaluate candidate manufacturing process chains against cost, time and quality parameters
7. Explore and evaluate candidate assembly process chains against cost, time and quality parameters
8. Use a decision matrix to rank/compare alternative manufacturing and assembly process chains

4.6 Converge on the final set of subsystem concepts: Based on the evaluations and knowledge captured, sub-optimal system designs will be eliminated and the proven optimal design from the system alternatives will be finalised

Methodology for activity 4.6:

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

The lean PD model provides a process for conceptual design up until design freeze and the initiation of detailed design. There are some activities that have however been included as recommendations for detailed design that will be described briefly here.

Phase 5. Detailed Design:

5.1 Release final specification: The final specifications will be released once the final system concept is concluded; this is important because by communicating that the specification will be released after all of the activities in phases 1 to 4, it will be more likely that the specification and commitment will be delayed

5.2 Define manufacturing tolerances: Manufacturing will negotiate part tolerances with design teams; this is another aspect of delaying commitment in design

5.3 Full system definition: Further detailed design work will follow; it is assumed that companies may continue with their detailed design processes for assurance and qualification of design solutions which is normally industry and product-specific

5.5 Supporting Tools

5.5.1 Tools Recommended to Support the Lean Product Development Model

A list of recommended tools was developed for the lean PD model activities (Table 5.6). These tools were amalgamated from three sources: (1) identified lean PD enablers (Table 5.1); (2) practice at industrial collaborator companies; and (3) new tools developed to support the lean PD model (see section 5.5.2). Representatives from industrial partner companies asserted their preference for tools that their employees were already familiar with. Many of the tools from the lean PD enablers are standard engineering tools and are commonplace in industry. Representatives from industrial partner companies were however receptive to new tools that would provide significant benefit. New tools that have been developed to support the lean PD model will be summarised in the subsequent section.

Table 5.6 Recommended tools for the lean product development model activities

	Recommended tools for the lean product development model activities	Lean product development model activities																	
		1.1 Classify project type	1.2 Explore customer value	1.3 Align with company strategy	1.4 Translate value to designers	2.1 Decide on level of innovation to subsystems	2.2 Identify subsystem targets	2.3 Define feasible regions of design space	3.1 Extract (pull) design concepts	3.2 Create sets for sub-systems	3.3 Explore subsystem sets	3.4 Capture knowledge and evaluate	3.5 Communicate sets to others	4.1 Determine intersections of sets	4.2 Explore possible product system designs	4.3 Seek conceptual robustness	4.4 Evaluate possible systems for lean production	4.5 Begin process planning for manufacturing	4.6 Converge on final system
Identified lean PD enablers	Design concepts matrix								■			■	■			■	■	■	■
	Design concept document (product definition)				■														
	Digital engineering (CAD/CAM/CAE etc.)									■	■				■				■
	Quality matrix (QFD)		■		■		■												
	Trade-off curves											■	■		■				■
	Check sheets/lists							■							■				
	Know-how database (KBE system/PDM/PLM)								■					■					
	Limit curves											■			■				
	A3 single-sheet reports												■						■
	Technical design standards and rules							■							■				
	Standard architectures (modular diagrams)	■				■													
Additional tools included from industry	Market research tools		■																
	Stakeholder analysis			■															
	Requirements management software		■		■		■												
	Requirements documents		■		■														
	Lessons learnt logs							■											
	Best practice guides							■						■					
	Manufacturing process diagrams							■									■	■	
	Function means analysis								■				■		■				■
	Functional flow diagram				■														
	Parts tree								■						■				
	Idea generation techniques (e.g. Brainstorming)									■									
	Innovation frameworks (e.g. TRIZ)									■									
	Rapid prototyping										■				■				
	Modelling and simulation software										■				■			■	
	SWOT analysis												■		■				
	DFMEA/FMEA															■			
	Risk analysis															■			
	Analytical hierarchy process (AHP)																		■
	Design for manufacture & assembly (DFM/DFA)																	■	
Additional tools developed for the lean PD model	Project classification matrix	■																	
	Customer value model		■																
	PD strategy matrix			■															
	Innovation classification diagrams	■				■													
	Knowledge creation plan										■				■				
	Concept intersection matrix													■	■				
	Manufacturing and assembly process webs																	■	

Although the recommended tools are important, it is the activities themselves that are essential for the lean PD model to be implemented. There is a vast array of tools that have been developed for design and engineering purposes, many of which may be substituted with those that have been recommended here. Moreover, the recommended tools for a particular activity may overlap with one another, and a tool may also be used for multiple activities.

5.5.2 Tools Developed to Support the Lean Product Development Model

Whilst defining the lean PD model activities, a number of gaps were identified where the development of bespoke tools was warranted. In some cases a substitutable tool was found, however a simpler tool could be easily developed for the same purpose. In this section the developed tools will be presented[16]. A summary of the background for each of the developed tools is also provided.

5.5.2.1 Project Classification Matrix

A tool was required to classify the level of innovation of company/department projects, and also present project parameters to support the shift towards a better multi-project plan and strategy. A number of project management and technology assessment tools were reviewed, but none of these provided the simple and flexible functionality that was sought.

A matrix was developed to fill this gap which maps projects against a number of project parameters. A fictional motorcycle company has been used as an example in Figure 5.9.

Project Name	Start Date	Duration (months)	Estimated End Date	Level of Innovation	Intended Market	Man-Month Estimate	Cost Investment	Estimated ROI	Risk
Yamoha SR500 LI4	01/01/2011	12	31/12/2011	2	Gents 25-40 years	300	£500,000	£3M	
Yamoha SR300 MI2	01/07/2011	18	31/12/2012	3	Ladies 25-40 years	500	£750,000	£2.5M	

Figure 5.9 Project classification matrix example

[16] A number of researchers from the LeanPPD project consortium supported the development of the tools described in this section and their efforts must be acknowledged

The matrix includes the project name which ideally follows a standard format, scheduling information, the level of innovation, intended market, resource and cost data, and any other critical information deemed necessary. Risk has been included in the last column of the matrix as an example. The level of innovation has been numbered according to a scale developed to combine advantages from other classifications including technology readiness levels (TRLs), novelty, technological uncertainty, complexity and pace (NTCP), and approaches put forward by Ward (2007) and Oosterwal (2010). The numbered levels are as follows:

1. No change
2. Low innovation derivative
   - Change of geometry
   - Change of arrangement
   - Feature level changes
3. Medium innovation derivative
   - Change product architecture
   - Change subsystems or components
4. High innovation
   - Introduce new technology
   - New fundamental design concept
5. Research and development
   - Strategic breakthrough

This classification is not only relevant when classifying and planning future projects, but also when considering the level of innovation to be incorporated in systems, subsystems, and components.

5.5.2.2 Innovation Classification Diagrams

A tool was required to communicate the level of innovation required to different subsystems and components during a project. This tool would support the focus on value that was sought, preventing both over-engineering and under-engineering[17].

The approach that was developed adopts the ‘level of innovation’ numbering scheme employed in the project classification matrix (see section 5.5.2.1). The levels are colour-coded, and subsystems and components may subsequently

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[17] This may be the result of designers being unclear about where to innovate or development projects being under-resourced

be labelled to visually communicate the planned focus for innovation efforts in a particular project (Figure 5.10 and Figure 5.11).

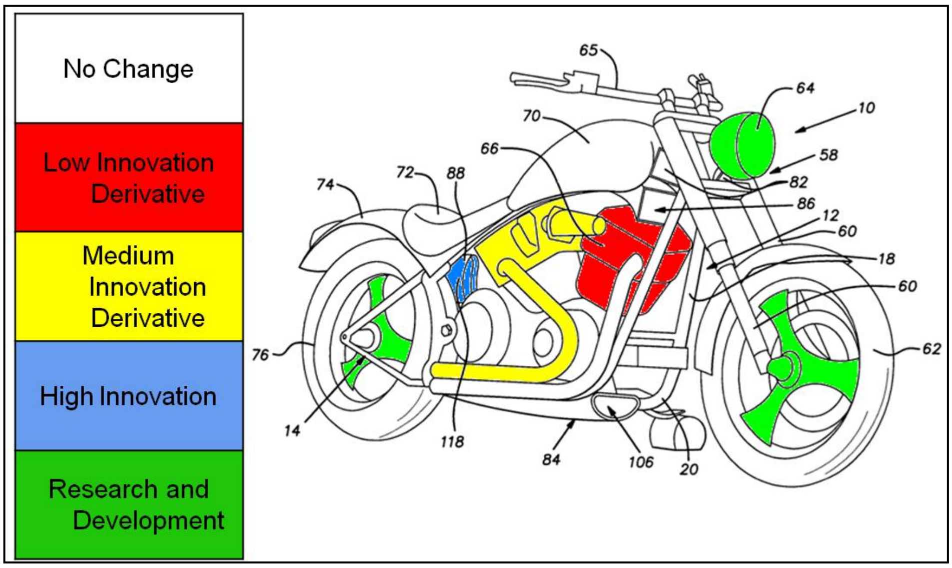

Figure 5.10 Innovation classification diagram system-level motorcycle example

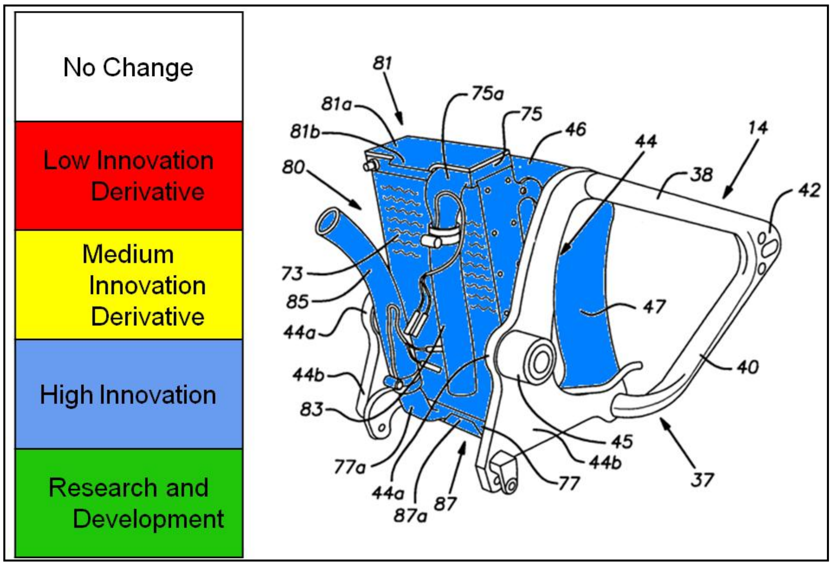

Figure 5.11 Innovation classification diagram subsystem-level motorcycle exhaust example

5.5.2.3 Product Value Model

Capturing and translating customer needs and desires is of paramount importance in PD. Designers and engineers must understand these needs and desires (referred to as customer value), and design and develop products accordingly. A simple representation was developed to bring together customer (or product) value attributes (Figure 5.12). The product value model structures customer/product value attributes for a particular project into five categories: (1) general functional, (2) product/sector-specific, (3) service and support, (4) psychological/sensory, and (5) other necessary attributes. The attributes may also be divided into primary and secondary goals. The central purpose of the product is also made clear.

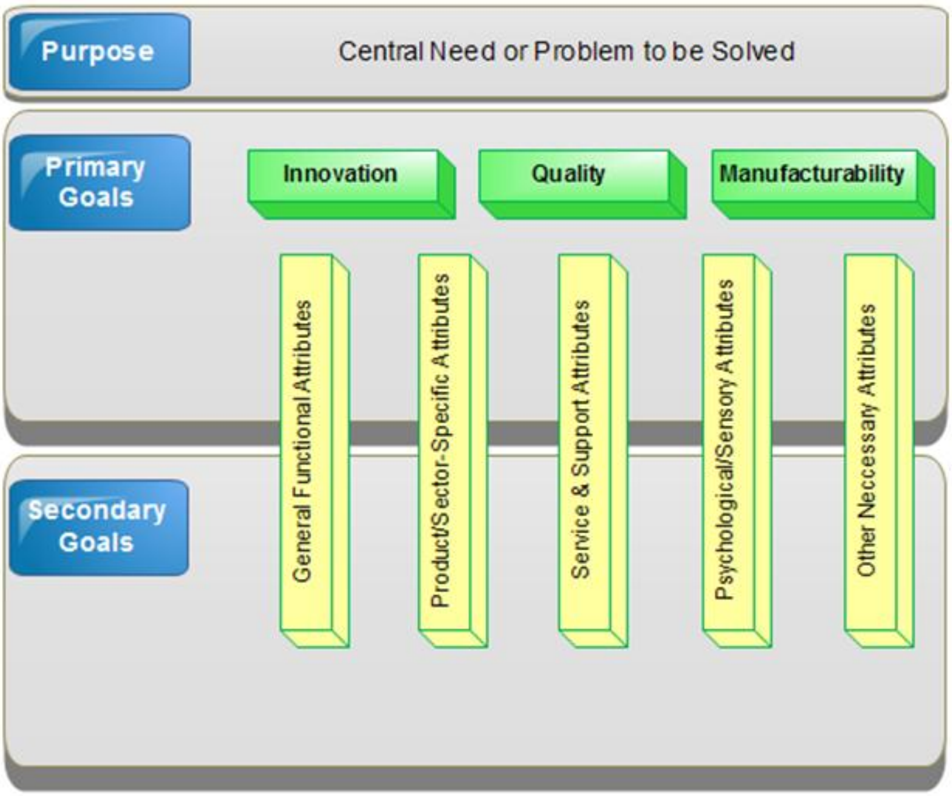

Figure 5.12 Product value model

5.5.2.4 Product Development Strategy Matrix

A tool was required to identify strategic benefits that can be sought from projects. This would enable a project team to focus not only on customer value, but also what is referred to as 'process value'. Process value is that which enhances the process of PD and the organisation's capability to develop products. The matrix that was produced structures strategic goals around four categories: (1) knowledge, (2) organisation, (3) capability, and (4) creativity (Figure 5.13).

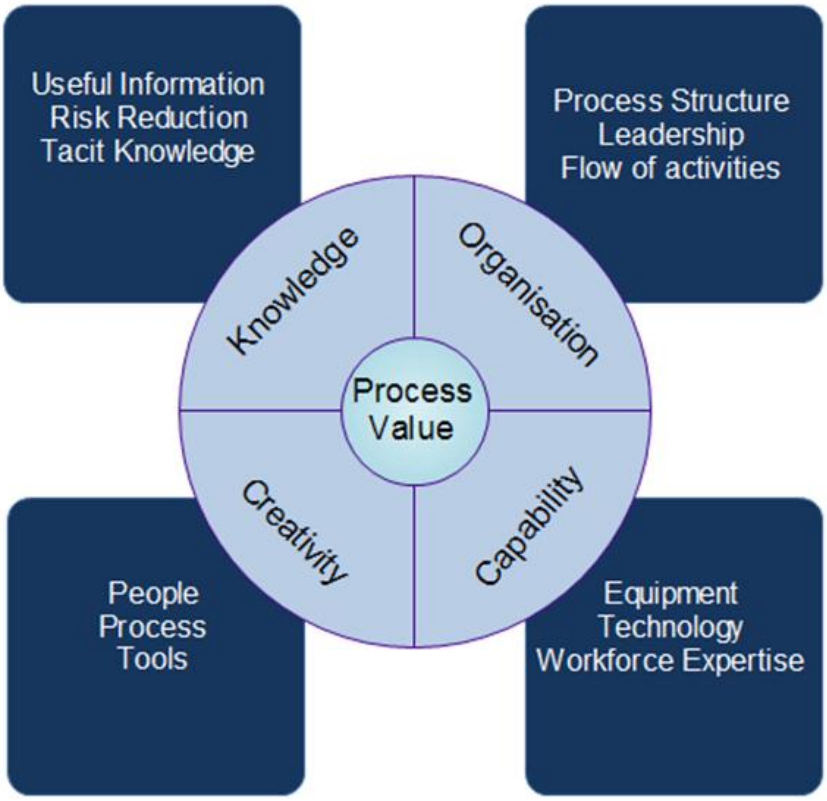

Figure 5.13 Process value model

A matrix was developed based on the process value model which aligns projects with process value attributes (Table 5.7).

Table 5.7 Product development strategy matrix

PD Process Value Category	PD Process Value Attribute	Strategic Goal for PD	Strategic advantages of Project A	Strategic advantages of Project B
Creativity	People	Acquire skills	Skill x acquired	Skill x enhanced
	Process	Reduce process duration	Duration of b reduced to …	
	Tools	Acquire state of the art design software		
Knowledge	Useful information			
	Tacit knowledge			
	Risk reduction			

5.5.2.5 Knowledge Creation Plan

In order to focus concept testing activities on creating representations of knowledge that would support decision making, a document template was proposed. A knowledge creation plan could be produced for each system, subsystem, or component in order to ensure that the knowledge created enables weak solutions to be exposed, and increase confidence in the prominent design solutions. The document was envisaged to serve both as a prescriptive test plan, as well as a live test and evaluation report in which results and outcomes can be populated (Figure 5.14).

Contents:

1. Aim & objectives:
2. Alternative design solutions (set)
3. Knowledge creation activities
    a. Modelling
    b. Simulation
    c. Prototypes
4. Knowledge representations
    a. Pugh matrices
    b. Function means analysis
    c. Trade-off curves
    d. Limit curves
    e. A3 reports
    f. FMEA
    g. Cost analysis graphs
    h. SWOT analysis
    i. Concept evaluation matrix
5. Conclusions
    a. Findings
    b. Design solutions to be discarded (weak)
    c. Design solutions to be progressed

Figure 5.14 Knowledge creation plan contents example

5.5.2.6 Concept Intersection Matrix

A matrix was required to evaluate integration between sets of subsystem or component alternatives. The concept intersection matrix that was developed makes use of a traffic light colour coding approach in which green indicates that two components or subsystems are easy to integrate, amber (or orange) indicates that there is likely to be some conflict, and red indicates that the two do not integrate (Figure 5.15). The selection of colours is based on knowledge from previous projects and actually analysing or testing combinations. The results from this activity help to filter the sets of solutions in order to formulate system combinations. An excel-based tool was developed to extend this matrix so that further analysis could be done to filter alternatives. This tool automates some analysis of system combinations and will be presented in chapter 6.

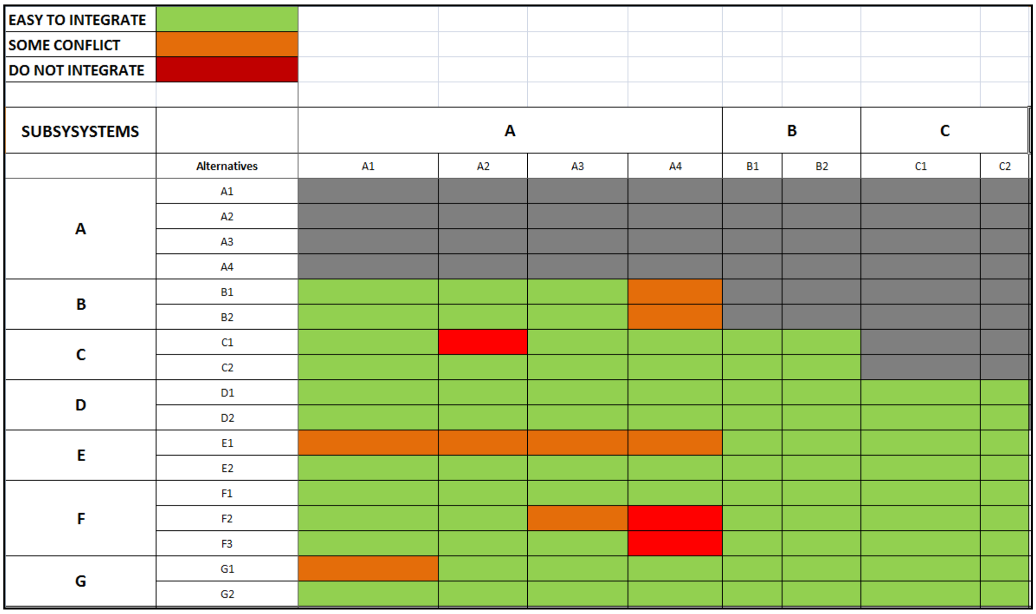

Figure 5.15 Concept intersection matrix

5.5.2.7 Manufacturing and Assembly Process Webs

A simple visual representation was needed to understand the available manufacturing and assembly process options for a number of system combinations. This task is rather unique because in point-based engineering manufacturing and assembly are only considered for a single design. Process options are categorised according the manufacturing or assembly activities (Figure 5.16). Arrows are used to denote the possible process sequences.

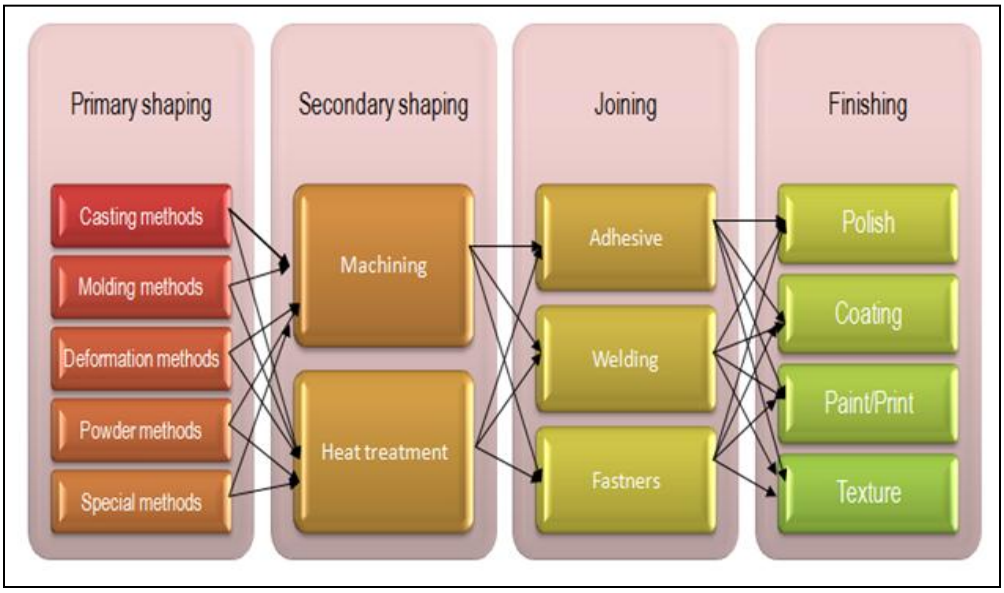

Figure 5.16 Manufacturing and assembly process web example (Kerga et al., 2012)

5.6 Implementation Process

In order to successfully implement the lean PD model in a company, the implementation process requires careful consideration. The recommended process is illustrated in Figure 5.17. The process summarises and represents the steps taken in this research, which were arrived at through interaction with researchers and practitioners.

Figure 5.17 Lean PD model implementation process

The first step towards implementation of the lean PD model is to understand the requirements. This may be achieved by conducting a number of activities, including:

- Hold preliminary meetings to present the lean PD model, outline potential advantages, and gain buy-in from top management and other stakeholders
- Identify and select a suitable case study for implementation
- Perform internal benchmarking and gap analysis in order to evaluate the concept development process of a historic case

The second step is to design the new approach to be implemented on the selected case study. This may be achieved through the following activities:

- Develop a recommendation for the implementation of lean PD model activities, based on the requirements
- Hold workshops to refine the bespoke lean PD model approach
- Develop an implementation plan for the case study

The third step is to implement the new approach on the selected case study. The following activities are suggested:

- Form a core design team to implement the lean PD model
- Train the core team for the implementation of the lean PD model activities and supporting tools
- Implement the model on the case study project

5.7 Summary

In this chapter the construction of the lean PD model was described.

Lean PD enablers extracted through the literature review were initially prioritised and structured into a framework. It was concluded that there are five core lean PD enablers: value-focused planning and development; the SBCE process; a knowledge-based environment; chief engineer technical project leadership; and a culture of continuous improvement. Due to the findings from the literature review and industrial field study, it was decided to focus on conceptual design, and a summative literature review was composed regarding SBCE. A model was developed for conceptual design based on the framework of lean PD enablers, and further principles of SBCE. This process model is referred to as the lean PD model. The lean PD model is divided into five stages which reflect five key decisions in PD. The phases are broken down into activities which embody the principles of lean PD and SBCE. A description and methodology for each activity is presented as well as a list of supporting tools. Some additional tools developed to support the lean PD model have also been presented and briefly described. The implementation process is also outlined in three steps: (1) understand requirements; (2) design the new approach; and (3) implement the new approach.

The next chapter describes two industrial case studies in which the constructed lean PD model has been applied. The chapter reports the implementation phase of this research.

6 INDUSTRIAL APPLICATIONS

Having constructed the lean PD model, the final objective was to test it in industry. In this chapter two case studies are presented in which the lean PD model was applied to live PD projects in industry.

The chapter is divided into 4 sections:

In section 6.1 a synopsis of the action research approach adopted during the case studies is described. The two conducted case studies involved the product architecture design for a car audio head unit, and the development of a helicopter engine. The results from the case studies are presented separately in sections 6.2 and 6.3. Case study descriptions are provided in addition to preparatory research conducted while developing the case studies. A summary of the chapter is provided in section 6.4.

6.1 Action Research Overview

The lean PD model provided a unique and coherent flow of activities which was based on both principles and contextual insight. Representatives of industrial collaborator companies showed conveyed both excitement as well as scepticism. This was important as the goal to apply the lean PD model on two live PD projects was idealistic and would require strong support from the companies involved. In selecting the case study companies practicality was also carefully considered. As per the action research approach adopted, the author would have to be involved in steering the case study projects which would require physical presence at company sites. The two companies that were selected were Visteon Engineering Services Ltd (VES) and Rolls-Royce Plc. (R-R)[18]. Both of these companies are UK-based and have design centres in the UK.

Preliminary meetings were held with project personnel at each of the companies to discuss the potential advantages of the lean PD model and to identify cases

[18] see section 1.4 for industrial collaborator descriptions

that were suitable for the study. The selection of cases was challenging due to a number of issues, including project timescales, the capacity of project personnel to support research, and case relevance. This process actually took several months at both of the companies. Once the case studies were selected, data was collected regarding a historic case by means of an open questionnaire. The questionnaire and results for the two historic cases are presented in Table 6.1 and Table 6.6. The purpose of this activity was to perform a gap analysis between the actual methodologies applied in projects with the methodologies proposed in the lean PD model.

The questionnaire that was developed for historical case analysis was intended to capture the actual PD process employed on a previous project. Questions were asked regarding different tasks in concept development and were structured according to the activities in the lean PD model. Results were confirmed by member checking in order to ensure triangulation. Based on the responses to questions, it became clear where the lean PD model would make the most impact. It was felt that in some areas the current PD processes were analogous to a particular lean PD activity, and thus no or little change was encouraged.

A bespoke lean PD approach was developed for each of the cases based on the gap analysis as well as subsequent meetings with company representatives. Once agreed these bespoke approaches were implemented with project personnel. Methodological recommendations provided in sections 5.4 and 5.5 were referred to, in order to implement the lean PD model activities. The aim of the case studies was to understand the response to the lean PD model by evaluating it in relevant contexts. Due to time limitations on the study, it was not possible for the lean PD model to be implemented in full. A metric-based evaluation was not intended as the focus was on understanding the response from industry.

In this chapter the two cases are presented separately. A description of each case study is provided, followed by information about the case study development, and finally the results. Some of the details regarding the cases have been omitted to ensure confidentiality.

6.2 Case Study 1: Product Architecture Design for a Car Audio Head Unit

6.2.1 Case Study Description

A number of proposals were put forward to test the lean PD model at VES (VES), including a motorcycle instrument cluster. However, as a first tier automotive supplier, customers often specify the design to an incredible level of detail. As SBCE is a key enabler of the lean PD model, a case with a fair amount of design flexibility was sought. The audio head-unit (AHU) of an in-car entertainment system was selected for the case study based on a series of meetings with engineers and managers at the company.

Products are currently divided by discipline at VES and are composed of the following: mechanical, electrical (hardware), software, and illumination. Company representatives directed the focus towards electrical hardware due to the potential to consider alternative design solutions. The electrical hardware for an AHU is referred to as the electronic main board, which has been depicted in Figure 6.1.

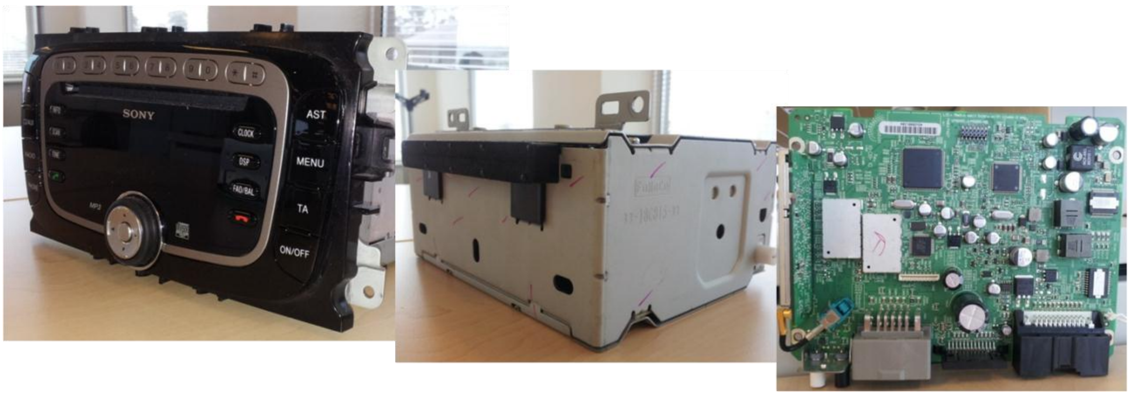

Figure 6.1 Audio head unit example: front view, rear view, and electronic main board (left to right)

The product architecture is the actual composition of electrical components, carefully arranged on the electronic main board. Alternative options are available for the components labelled on the AHU main board layout example in Figure 6.2.

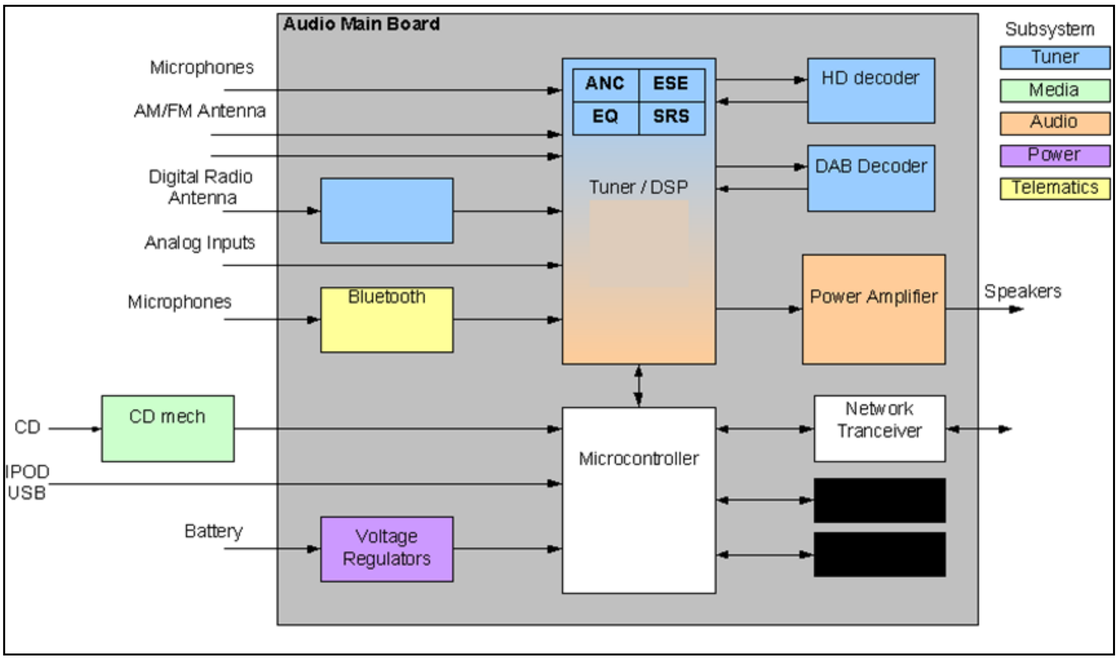

Figure 6.2 Audio head unit product architecture: main board components

6.2.2 Case Study Development

A project that had already passed through the concept development phase was analysed. This project was planned to deliver over four million products to a particular customer over the course of five years. This meant that a small reduction in cost would have considerable impact on profit margins. The project had 24 months from the onset until start of production to design the product; however the research involvement actually started 6 months after the project start date. Data regarding the methodology that was employed for concept development is presented as captured in Table 6.1.

The questionnaire was initially sent by email to a senior electrical engineer who worked on the project and later reviewed by means of a face-to-face follow-up. The respondent had 17 years of engineering experience, and his responses are included in the table verbatim.

Table 6.1 Historic case study 1 questionnaire results

Lean PD Activity	Questions	Answer/Description
1.1 Classify project type	How was the project classified and when did this classification take place?	No formal classification
1.2 Explore customer value	How was the voice of the customer represented to the design team? How do you ensure/measure that the design meets customer expectations?	Hardware/software requirements documents; (the) design team designs according to the specifications; once the designed part is available it is measured against requirements
1.3 Align with company strategy	How was the project aligned with the company strategy? Was the project used to improve PD?	Strategy alignment is assured by architecture group which defines the design architecture; (the) project is not used to improve PD
1.4 Translate customer value to engineers	How was the product/system concept communicated to designers?	By giving architectural representations of the system
2.1 Decide on level of innovation to subsystems	How did you control the amount of innovation that was designed into sub-assemblies/components?	Not controlled
2.2 Identify subsystem targets	Did subsystem participants identify lower-level system targets (e.g. reduce weight by x%)?	Since this is just a sub-system component in itself, we usually have overall target (e.g. cost) and this is difficult to sub-divide due to interaction and impact between components
2.3 Define feasible regions of design space	How did you ensure that designers/engineers designed within the constraints of manufacturing and other functions (without inhibiting innovation)?	We have design rules for all disciplines for manufacturing; we also keep manufacturing plant involved
3.1 Extract (pull) design concepts	Were previous projects, R&D projects, and competitor products considered? How did you ensure that designers considered a range of options?	Yes, both previous projects and competitor products considered; there is no process to ensure that designer considered range of options
3.2 Create sets for sub-systems	How were the initial sub-assembly design alternatives represented?	In the form of different block diagrams
3.3 Explore subsystem sets	What methods did you use to test subsystem/component design alternatives? Do you have a test strategy?	They are not tested until a decision is made for one solution then design and tests starts

Lean PD Activity	Questions	Answer/Description
3.4 Capture knowledge and evaluate	In order to compare alternative sub-assembly designs what are the most critical characteristics that should be analysed? What methods did you use to compare design alternatives?	Cost and performance; existing cost and performance information
3.5 Communicate sets to others	What information is required by different subsystem/functional teams in order to provide feedback and constraints regarding possible design alternatives?	Usually this is in component level (Integrated Circuit) and in the form of datasheets from suppliers
4.1 Determine set intersections	How can you determine whether or not components will intersect with each other and how difficult it will be?	No formal method, the architect knows about the functions and decides; the difficulty level is also hidden within the design process (i.e. there is no formal method of assigning difficulty levels)
4.2 Explore system sets	What methods do you use to test system design alternatives? Do you have a system test strategy? How did you evaluate the potential costs, quality, and performance of design concepts?	Alternatives are not tested until a decision for a single design solution is made; we have an engineering specification (document) which defines testing and limits in an excel chart
4.3 Seek conceptual robustness	How did you ensure that the design works, regardless of variations in usage, environment, or the manufacturing process? How do you ensure the system will not be affected by making changes?	Environmental tests; this is not part of the design requirement(s); (the) only issue can be component obsolescence but supply is assured by buyers
4.4 Evaluate sets for lean production	How did you analyse the effects of a design on its manufacturing process?	By liaising with manufacturing
4.5 Define advanced production process plans	How and when did you begin process planning for manufacturing?	Mechanical is at the very beginning; electrical is after architecture is fixed
4.6 Converge on final system	How did you decide/determine the final system design?	Based on the material and engineering cost and also agreement with the customer

Based on the answers provided, a number of gaps were identified; however there were suitable methodologies present for various activities as expected. These methodologies could simply be substituted into the process. Table 6.2 summarises the results for case study 1.

Table 6.2 Gap analysis results for case study 1

SBCE	1.1	1.2	1.3	1.4	2.1	2.2	2.3	3.1	3.2	3.3	3.4	3.5	4.1	4.2	4.3	4.4	4.5	4.6
VES	y	y	y	x	y		-	y	y				y	y	-	x	x	x

Key	
-	Expedient methodology already in place
x	Gap identified but not addressed
y	Gap identified and addressed
	Not considered for implementation

The case that was studied was a sub-assembly for which the components are “off-the-shelf” and therefore do not require individual analysis. This meant that some activities were not considered for implementation from the onset: lean PD model activities 2.2, and 3.3-3.5. As the project progressed a decision was made to select one system combination. Although this was not in line with the intended research, it was out of the researcher’s control. This meant that the final activities could not be completed (lean PD model activities 4.4-4.6).

6.2.3 Case Study Results

This section has been structured according to the lean PD model activities[19] and will describe the research undertakings.

Phase 1. Define value

1.1 Classify project type

There was no formal approach to project classification at the company, nor was there a common naming strategy. Although these are important issues, they cannot be addressed on a stand-alone project. A table was created to summarise project information and classify the level of innovation. As much of this information is confidential, a snapshot is provided in Table 6.3.

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19 Refer to section 5.4 for details of the lean PD model activities

Table 6.3 Case study 1 project classification information

Project Name	Start Date	Duration (months)	Estimated End Date	Level of Innovation
AHU	January 2011	24 months PD + 5 years production	2018	4

The project was a new product design and was expected to embody a high degree of innovation. It was expected that the project would include the introduction of new technology as well as a different overall product architecture. The level of innovation was proposed by a senior electrical engineer.

1.2 Explore customer value

As the product being developed will be eventually judged by end users, analysis of their desires and needs was advocated in this research. The OEM customer company provided 'statement of work' (SoW) and technical specification documents, as well as CAD diagrams (Figure 6.3), technical standards, and requirements for the project to deliver against.

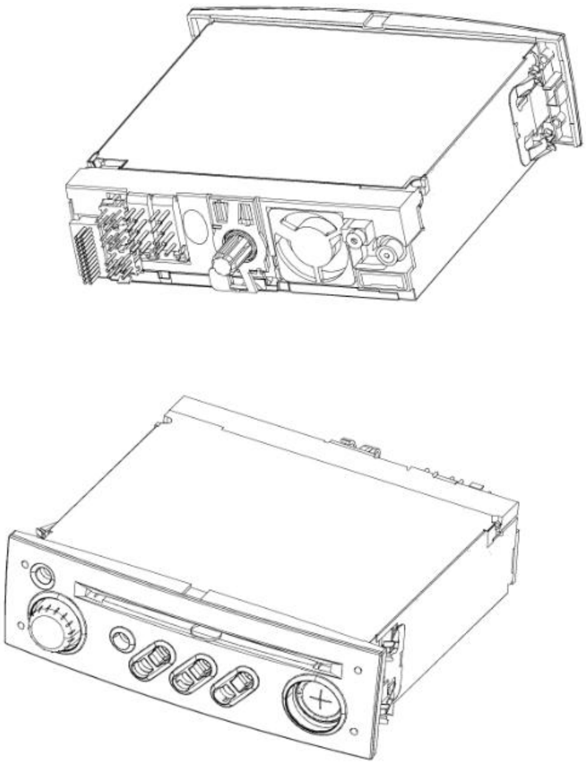

Figure 6.3 CAD representations of the AHU design overview

Ideally end users would be consulted to understand their desires and needs directly, however this was not possible. Despite this, the product value model was demonstrated. Based on information extracted from requirements and customer specification documents, 34 customer value attributes were identified. The attributes included safety, reliability, upgradeability, recycling operations, amongst others. Brainstorming sessions were held with a senior engineer[20] to identify un-elicited value attributes (Figure 6.4).

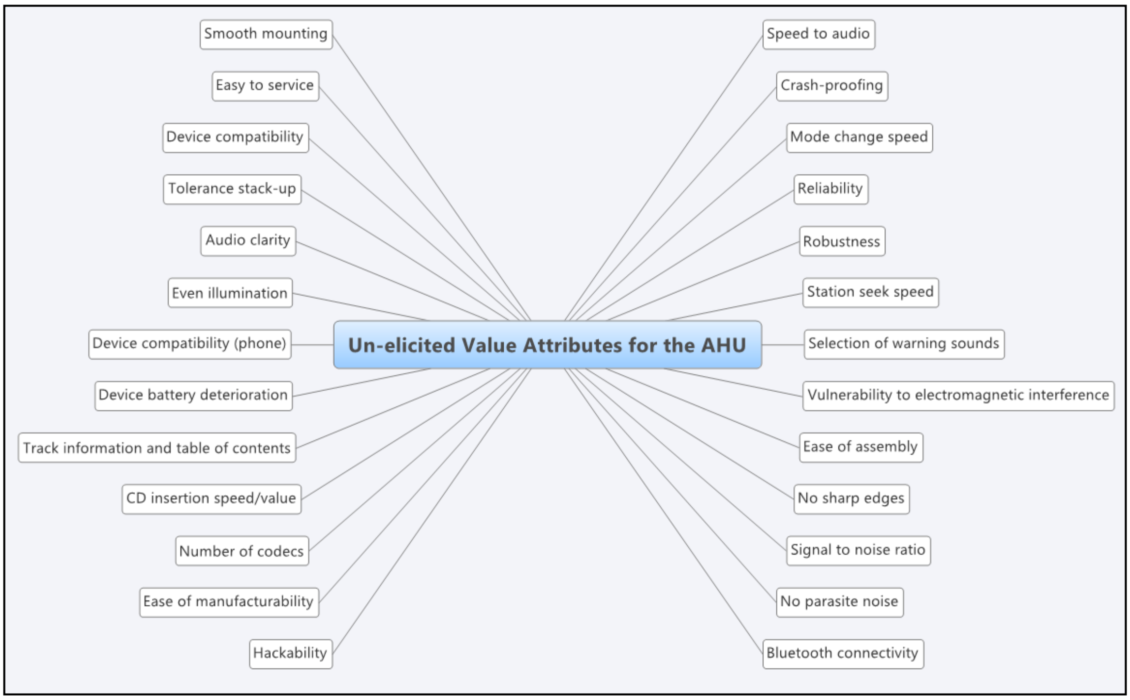

Figure 6.4 Mind map of un-elicited value attributes for case study 1

The value attributes were combined by the author to provide a visual representation of product value for the project (Figure 6.5). This representation was reviewed by 3 senior engineers from the company with 16, 17, and 20 years of industrial experience respectively.

[20] This is the same engineer mentioned earlier with 17 years of industrial experience

General/ Functional	Product/Sector Specific	Psychological/ Sensory	Service & Support	Other
Start-up Speed (to audio)	Device Safety and Compatibility	Low noise-floor (parasite noise)	Mounting & removal ease	Recyclability
Safety (power)	Smartphone cradle	Sound generation	Serviceability	
Crash-Proof	Smooth mounting	Welcome jingle	Firmware	
Speed (change mode/stn seek)	Steering wheel control (non-distraction)	Even illumination (hot-spots/leaks)		
Reliability	Hack-ability	Haptics		
EMC Vulnerability	BT Connectivity	Craftsmanship		
Mfg/Assembly ease?	Sound clarity and reception			
Hardware Upgradability	ToC and track info download speed			
	USB Charging			
	Noise filter (mic)			
	User interface			
	CD insertion			

Figure 6.5 Product value model for case study 1

Further analysis of the product value model was conducted with 3 engineers. The main purpose of the product was agreed to be to entertain the user, and therefore the most discomforting outcome for the user would be for the product to crash. Further to this realisation, components were analysed to determine whether an incorrect selection could result in a system crash. Using a QFD house of quality matrix, this analysis was mapped and metrics that could be used to compare components with regards to a potential crash were suggested.

1.3 Align project with company strategy

The project was aligned with the company strategy via a matrix that was developed in-house. This approach was not standard practice at the company; rather the matrix was developed for this project specifically. Furthermore, the matrix was actually used when evaluating product architecture options rather than the strategic alignment suggested at the start of the project. The matrix considered the alignment to PD strategy, future subsystem reuse, future business opportunities, and alignment to the overall corporate strategy.

1.4 Translate value to designers

The product concept was communicated to designers via requirements, specification and SoW documents. Although it was noted that this was not the ideal approach, the researcher had no control over this choice.

Phase 2. Map design space

2.1 Decide on level of innovation to subsystems

Based on the project information described in phase 1, an innovation classification diagram was produced (Figure 6.6). It became clear from this activity that the innovation and engineering effort should be focused on 3 main areas: (1) the tuner or digital signal processor (DSP); (2) the microcontroller; and (3) the main board layout.

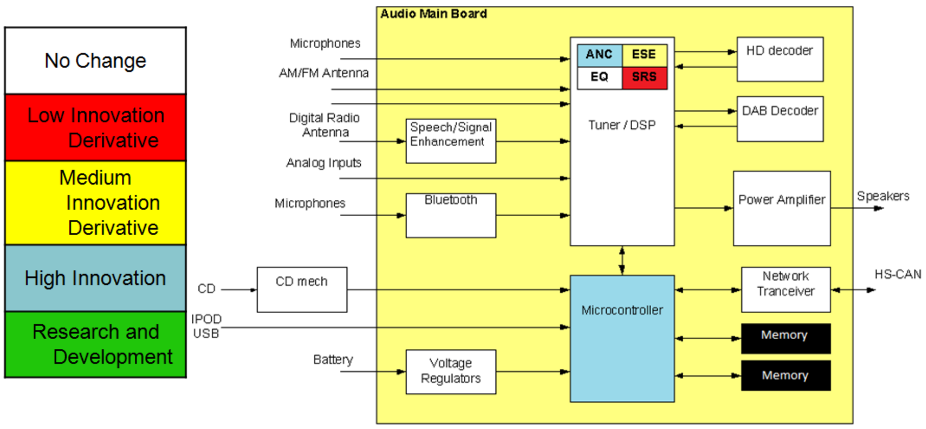

Figure 6.6 Innovation classification diagram for case study 1

2.2 Identify subsystem targets

As this case was a subsystem composed of ‘off the shelf’ components, there was no need to define lower level targets.

2.3 Define feasible regions of the design space

As the innovation in this project was restricted to specific components, this was not a lengthy activity. A variety of components were considered and reviewed by a number of parties involved from different international company locations. Constraints are considered via design rules and OEM customer standards. The research did not contribute to this activity.

Phase 3. Develop concept sets

3.1 Extract design concepts

A senior electrical engineer was responsible for identifying and analysing product architecture alternatives. However there were a number of parties involved from different international company locations, including the UK, USA and China. The design criteria for components were the requirements established from the technical specification. Components were only considered if they met functional requirements. Table 6.4 presents the extracted alternatives.

3.2 Create sets for subsystems

This activity was included to allow time for designers to ideate and think outside of the box. In this case the alternatives were selected based on requirements as explained and further innovation was not facilitated. Despite this a number of alternative components were examined. Table 6.4 presents the alternatives considered as well as descriptions regarding their sources. Component descriptions were provided by a senior electrical engineer working on the project.

Table 6.4 Alternative components considered for case study 1

Component	Alternatives	Description
Microcontroller	a1	Installed on previous design/s
	a2	Tested on a previous design
	a3	New ‘state of the art’
	a4	New ‘low risk’
Tuner	b1	Installed on previous design/s
	b2	New ‘state of the art’
Bluetooth	c1	Installed on previous design/s
	c2	Installed on previous design/s
Speech Processing	d1	Installed on previous design/s
	d2	Installed on previous design/s
DAB	e1	Installed on previous design/s
	e2	Installed on previous design/s
PSU	f1	Installed on previous design/s
	f2	Installed on previous design/s
	f3	New
CD	g1	Installed on previous design/s
	g2	New
Memory	h1	Installed on previous design/s
	h2	Installed on previous design/s
	h3	Installed on previous design/s
PCB	i1	Installed on previous design/s
	i2	Installed on previous design/s

Phase 4. Converge on system

4.1 Determine intersections of sets

Based on the alternative components considered in phase 3 there are 2,304 potential system combinations[21]. Many of these combinations are however not possible due to integration conflicts, amongst other factors. A concept intersection matrix was populated by a senior electrical engineer to highlight these integration conflicts (Figure 6.7). Once populated the matrix was reviewed in a meeting between the researcher and the same engineer.

[21] This number can be calculated by multiplying the number of alternatives for each component

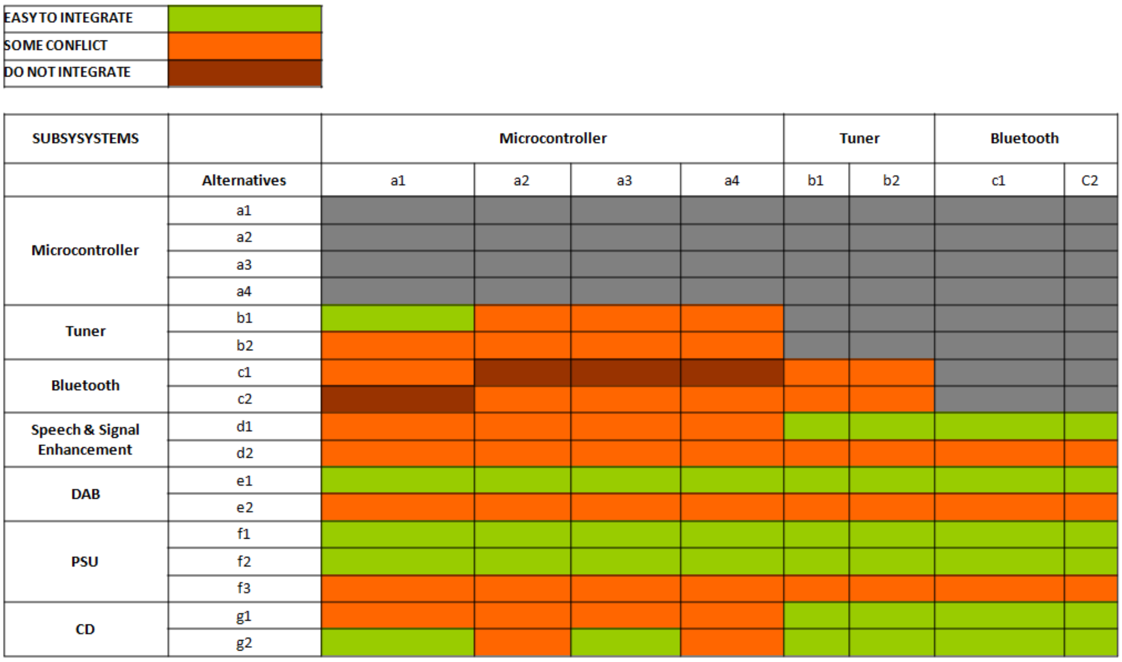

Figure 6.7 Snapshot of the concept intersection matrix for case study 1

This activity allowed combinations that were not actually possible to be eliminated. For example Figure 6.7 shows that microcontroller a1 does not integrate with bluetooth c2, while the other microcontrollers do not integrate with bluetooth c1. In this case the number of possible combinations was halved to yield 1152 possible combinations. No system combination was identified as easy to integrate, although upgrading a previous design solution was considered easier than replacing essential components with new components that had not been installed on previous projects.

One of the key design parameters in this project was cost. In order to understand the impact of selecting one of the possible system combinations, cost analysis was conducted. Possible system combinations were first computed using a spreadsheet in MS Excel as shown in Figure 6.8. Each system combination was allocated a system number.

System No.	Microcontroller	Tuner	Bluetooth	Speech Processing	DAB	PSU	CD	Memory	PCB
1	A1	B1	C1	D1	E1	F1	G1	H1	I1
2	A1	B1	C1	D1	E1	F1	G1	H1	I2
3	A1	B1	C1	D1	E1	F1	G1	H2	I1
4	A1	B1	C1	D1	E1	F1	G1	H2	I2
5	A1	B1	C1	D1	E1	F1	G1	H3	I1
6	A1	B1	C1	D1	E1	F1	G1	H3	I2
7	A1	B1	C1	D1	E1	F1	G2	H1	I1
8	A1	B1	C1	D1	E1	F1	G2	H1	I2
9	A1	B1	C1	D1	E1	F1	G2	H2	I1
10	A1	B1	C1	D1	E1	F1	G2	H2	I2
11	A1	B1	C1	D1	E1	F1	G2	H3	I1
12	A1	B1	C1	D1	E1	F1	G2	H3	I2
13	A1	B1	C1	D1	E1	F2	G1	H1	I1
14	A1	B1	C1	D1	E1	F2	G1	H1	I2

Figure 6.8 Snapshot of computed alternative system combinations

Costs associated with each of the components were associated with component codes (A1, A2, B2 etc.) captured in a table on a separate worksheet in MS Excel. The cost of each combination was determined by programming cells to look up the associated costs for each component and calculate their summation[22]. The resulting graph is presented in Figure 6.9.

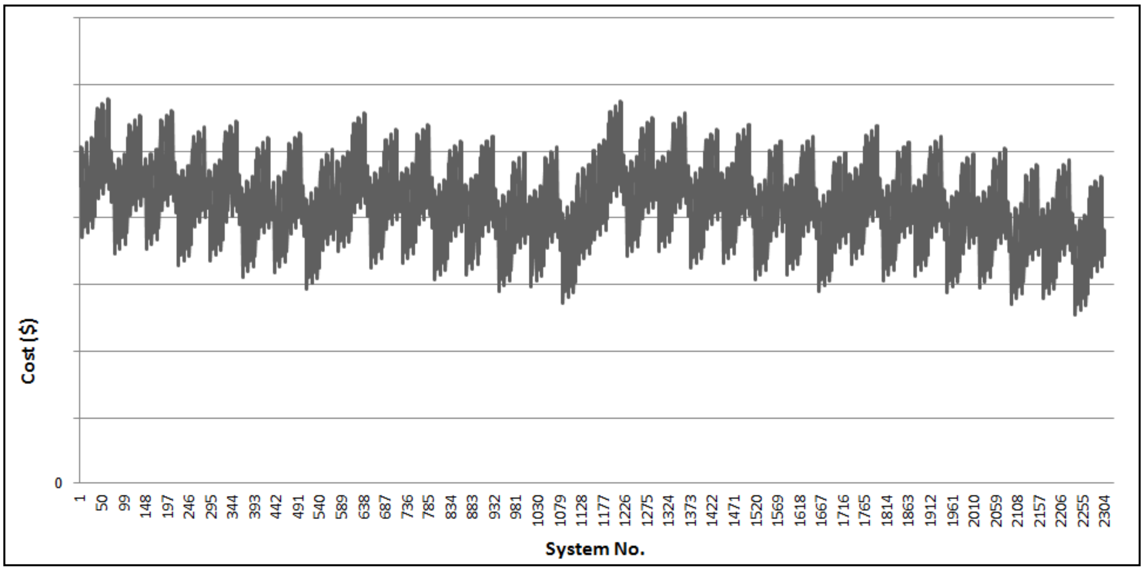

Figure 6.9 Variation in the cost of possible system combinationsfor case study 1

[22] This was achieved by using a complex combination of 'VLOOKUP' and 'SUM' functions

The standard deviation of system costs was calculated to be 3.06[23]. This finding highlighted the impact of the typical hasty selection of a system combination on the system cost. For the purpose of this study a cost threshold was set which was just below the medium cost of system combinations. This allowed 708 combinations to be filtered, yielding 444 combinations.

4.2 Explore system sets

Based on a subjective analysis of the alternative combinations one microcontroller, one PSU and one type of memory were filtered. This analysis primarily considered the alignment with design requirements. All of these components had been tested by the company and analysed in the past. This eliminated 272 options, leaving 172 combinations.

This number of combinations was still very high and therefore some further subjective decisions were required. A strategic analysis was conducted to evaluate system combinations. Factors that were considered in this analysis included: alignment with corporate and PD strategy, supplier reputation, and future business, amongst others. Based on this analysis a number of components were discarded. This resulted in the elimination of 1 tuner option, 1 speech recognition option, 1 DAB option, and 1 memory option. The remaining components are presented in Table 6.5.

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[23] For readers who are not au fait with statistical terms: the standard deviation shows the dispersion of system costs from the mean (or average) system cost

Table 6.5 Component sets recommended for further evaluation (case study 1)

Component	Alternative	
Microcontroller	A3	New ‘state of the art’
	A4	New ‘low risk’
Tuner	B2	New ‘state of the art’
Bluetooth	C2	Installed on previous design/s
Speech Processing	D2	Installed on previous design/s
DAB	E2	Installed on previous design/s
PSU	F1	Installed on previous design/s
	F2	Installed on previous design/s
CD	G2	Installed on previous design/s
Memory	H1	Installed on previous design/s
PCB	i1	Installed on previous design/s
	i2	Installed on previous design/s

Due to business pressures, the project was not able to accommodate the convergent approach recommended in the lean PD model. The project faced a milestone at which 4 out of 8 alternative system combinations were considered. Although the selection of the alternatives may be questioned, the fact that the project considered 4 alternative system combinations was remarkable.

The four combinations (or platforms) were reviewed against business and strategic objectives using a structured design criteria matrix. This allowed the team to quickly arrive at a final single system combination. This combination was among the combinations recommended for further evaluation. Despite thwarting the remaining activities of the lean PD model, the new approach that was adopted for this project was noteworthy.

6.3 Case Study 2: The Development of a Helicopter Engine

As the first case study was addressing component level design and the integration of a subsystem, it was important to test the lean PD model at the system level. However, the second case (with R-R) was addressing power systems and was likely to be for an aerospace application. This meant that there would be an extraordinary level of complexity (Figure 6.10) and potentially more resistance to application on a live project. Despite the complexity in power systems engineering, the researcher sought to apply the developed model at the engine level. This direction was supported by a senior expert at the company with 15 years of industrial experience.

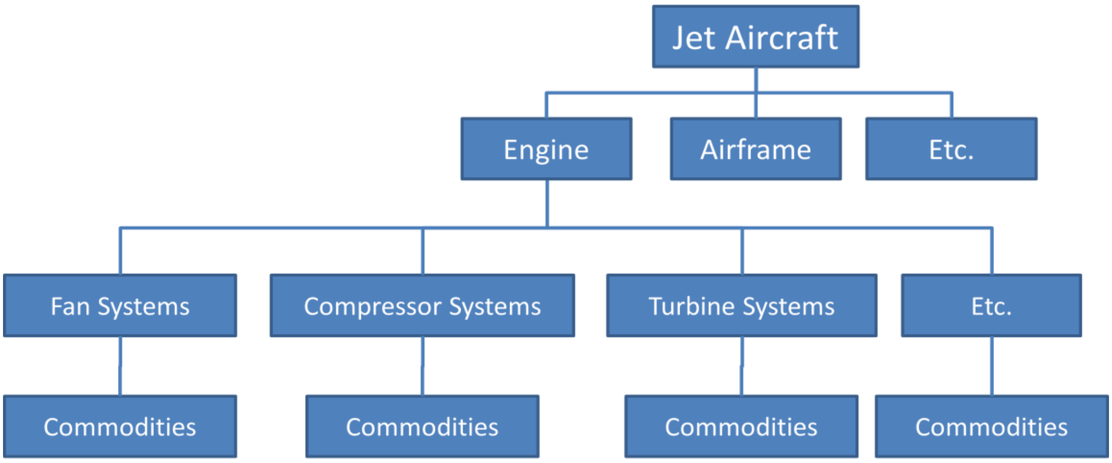

Figure 6.10 Aircraft topology

After numerous meetings in which the lean PD model was presented and discussed at one of the company sites, the research received considerable interest. A number of senior managers at the company were impressed with the lean PD model and were keen to see the process implemented on a real R-R project. One senior manager remarked that this approach could be the 'game-changer' that has been needed to address new projects where innovation and competitive advantage are discriminators. Various proposals were put forward to test the lean PD model at R-R, including a civil aircraft engine. However, it was not easy to find a project that was in its infancy where project leaders were willing to accommodate the research. After sustained efforts, a systems design leader at another company site was informed about the research and welcomed its implementation on a helicopter engine project. This was considered a breakthrough in the research, because not only was there an ideal system-level project but also someone willing to drive the case study forward within the company.

The lean PD model was employed on a turbo-shaft helicopter engine, which is perhaps the most common type of engine used on modern helicopters and is likely to be used on futures engines as well (Figure 6.11). The prevalence of the turbo-shaft engine for helicopter engines is due to its provision of large amounts of power and a low weight penalty.

Figure 6.11 Futuristic helicopter model image (Gizmag website)

The exhaust stream drives an additional (free) turbine which in turn drives a propeller or rotor system to generate thrust as illustrated in Figure 6.12.

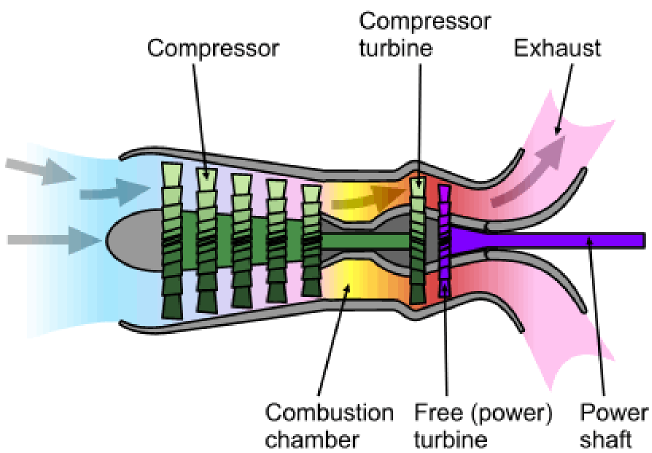

Figure 6.12 Turbo-shaft engine schematic (Wikipedia website)

6.3.1 Case Study Development

A recent project was selected for analysis in order to understand the PD process implemented for concept development on a real project. The goal of the project was to deliver an enhanced version of an engine to a particular customer, requiring a solution to some adverse environmental impacts experienced. The project had a relatively short duration from the onset until start of production to design the product. Data regarding the process that was employed for concept development is presented in Table 6.6. The questionnaire was initially sent by email to a senior engineer who worked on the project and was later reviewed by a follow-up interview. The respondent had 20 years of engineering experience and his responses are included here verbatim for the most part. Some answers have been amended for confidentiality purposes.

Table 6.6 Historic case study 2 questionnaire results

Lean PD Activity	Specific Questions	Answer/Description
1.1 Classify project type	How was the project classified and when did this classification take place?	Classified as a new engine/major redesign; it was classified after the problem was understood
1.2 Explore customer value	How was the voice of the customer represented to the design team? How do you ensure/measure that the design meets customer expectations?	Through meetings with the customer.
1.3 Align with company strategy	How was the project aligned with the company strategy? Was the project used to improve PD?	Aligned to company strategy of profit through sales (department) and maintaining customer satisfaction by responding to urgent requirements; the project raised the possibility of creating future business
1.4 Translate customer value to engineers	How was the product/system concept communicated to designers?	Requirements flow down and concept architectures modelling
2.1 Decide on level of innovation to subsystems	How did you control the amount of innovation that was designed into sub-assemblies/components?	The modelling activities identified those parts that should be changed, all others were kept as existing; the requirements documents and interfaces with exiting parts constrained the design
2.2 Identify subsystem targets	Did subsystem participants identify lower-level system targets (e.g. reduce weight by x%)?	Yes

Lean PD Activity	Specific Questions	Answer/Description
2.3 Define feasible regions of design space	How did you ensure that designers/engineers designed within the constraints of manufacturing and other functions (without inhibiting innovation)?	Using R-R standards and interface diagrams from existing design; mock-ups were used for the harnesses; collaboration with partner company/ies.
3.1 Extract (pull) design concepts	Were previous projects, R&D projects, and competitor products considered? How did you ensure that designers considered a range of options?	Based on previous designs; Advanced Projects (department) did a competitor technology comparison; (the) design process requires that alternatives are considered; e.g. different harness options considered
3.2 Create sets for sub-systems	How were the initial sub-assembly design alternatives represented?	(Not answered, however this was discussed with company representatives)
3.3 Explore subsystem sets	What methods did you use to test subsystem/component design alternatives? Do you have a test strategy?	Different harness options tested; rig testing (used to test alternatives); test plan (documents tests)
3.4 Capture knowledge and evaluate	In order to compare alternative sub-assembly designs what are the most critical characteristics that should be analysed? What methods did you use to compare design alternatives?	Visual comparison of the harnesses; analysis and comparison of test results
3.5 Communicate sets to others	What information is required by different subsystem/functional teams in order to provide feedback and constraints regarding possible design alternatives?	Physical geometry, aero and mechanical models
4.1 Determine set intersections	How can you determine whether or not components will intersect with each other and how difficult it will be?	Pre-determined split of models, trial Installations
4.2 Explore system sets	What methods do you use to test system design alternatives? Do you have a system test strategy? How did you evaluate the potential costs, quality, and performance of design concepts?	Performance models, whole engine models e.g. for blade off
4.3 Seek conceptual robustness	How did you ensure that the design works, regardless of variations in usage, environment, or the manufacturing process? How do you ensure the system will not be affected by market changes?	Product designed to meet (the) customer's operational envelope

Lean PD Activity	Specific Questions	Answer/Description
4.4 Evaluate sets for lean production	How did you analyse the effects of a design on its manufacturing process?	Harness considered for assembly
4.5 Define advanced production process plans	How and when did you begin process planning for manufacturing?	Planning for manufacture started in the concept stage
4.6 Converge on final system	How did you decide/determine the final system design?	Design and business reviews

Based on the answers provided, a number of gaps were identified; however there were appropriate methodologies present to support various activities as expected. Table 6.7 summarises the results for case study 2.

Table 6.7 Gap analysis results for case study 2

SBCE	1.1	1.2	1.3	1.4	2.1	2.2	2.3	3.1	3.2	3.3	3.4	3.5	4.1	4.2	4.3	4.4	4.5	4.6
R-R	y	y	y	y	y	-	y	y	y	y	y	y	y	y	x	x	x	x

Key	
-	Expedient methodology already in place
x	Gap identified but not addressed
y	Gap identified and addressed
	Not considered for implementation

The case that was studied was similar to the engine that was developed using the lean PD model. The analysis of the previous project helped to produce a realistic plan for the implementation of the lean PD model. The project followed the lean PD model, but also adhered to the review process defined by R-R quality procedures. Due to time restrictions the majority of phase 4 of the lean PD model was not applied. Similarly, activity 2.2 was not applied.

6.3.2 Case Study Results

This section has been structured according to the lean PD model activities and will describe the research undertakings for case study 2.

Phase 1. Define value

1.1 Classify project type

There was no formal approach to project classification at the company, nor was there a common naming approach. Although these are important issues, they cannot be addressed on a stand-alone project. A number of senior engineers did however, express their appreciation for the proposed approach for project classification. It was decided that the level of innovation would not be classified early on in this project. This was because one of the key outcomes was to determine how the system targets could be reached, and it was unknown at the time what level of innovation was required to achieve them. It was expected that the level of innovation would be between 3 and 5. A table was created to summarise project information and classify the level of innovation. As much of this information is confidential, a snapshot is provided in Table 6.8.

Table 6.8 Case study 1 project classification information

Project Name	Start Date	Duration (months)	Estimated End Date	Level of Innovation
Helicopter engine	August 2011	20 months PD (including full scale prototype and testing)	April 2013	3-5

It was initially expected that the project would include the introduction of new technology as well as the possible incorporation of new materials and manufacturing techniques. The level of innovation was proposed by project engineers.

1.2 Explore customer value

One of the aims of the project was to develop an engine to meet future customer requirements. A number of project leaders felt that the customers did not need to be consulted directly, however, there were some key personnel within the company who had expertise in this area due to both their role within the company and their past experience. Meetings were held with these experts in order to capture customer desires and needs. There was also an extensive amount of information available through company benchmarking reports and market studies which was taken into account.

A number of project brainstorming sessions were also held to identify value attributes. Through this extensive activity a product value model was produced, however the product value attributes were categorised according to the different stakeholders rather than the approach proposed (see Table 6.9). This was deemed appropriate because the product was not one that involves direct end user interaction.

Table 6.9 Approach used to initially structure value attributes

Stakeholders	Value attributes		
Rolls-Royce	Cost	Cost A	Cost 1
		Cost B	
	Compliance	Compliance A	
		Compliance B	
	Manufacturability		
End customer	Efficiency		
	Disruption		
	Serviceability		
Airframer	Weight		
	Mounting		
	Pay load		
World and environment	Emissions		
	Safety		
	Regulations		

The product value model included hundreds of attributes, which were later divided into primary and secondary attributes (Figure 6.13). Each attribute was coded in order for them to be referenced in future design work.

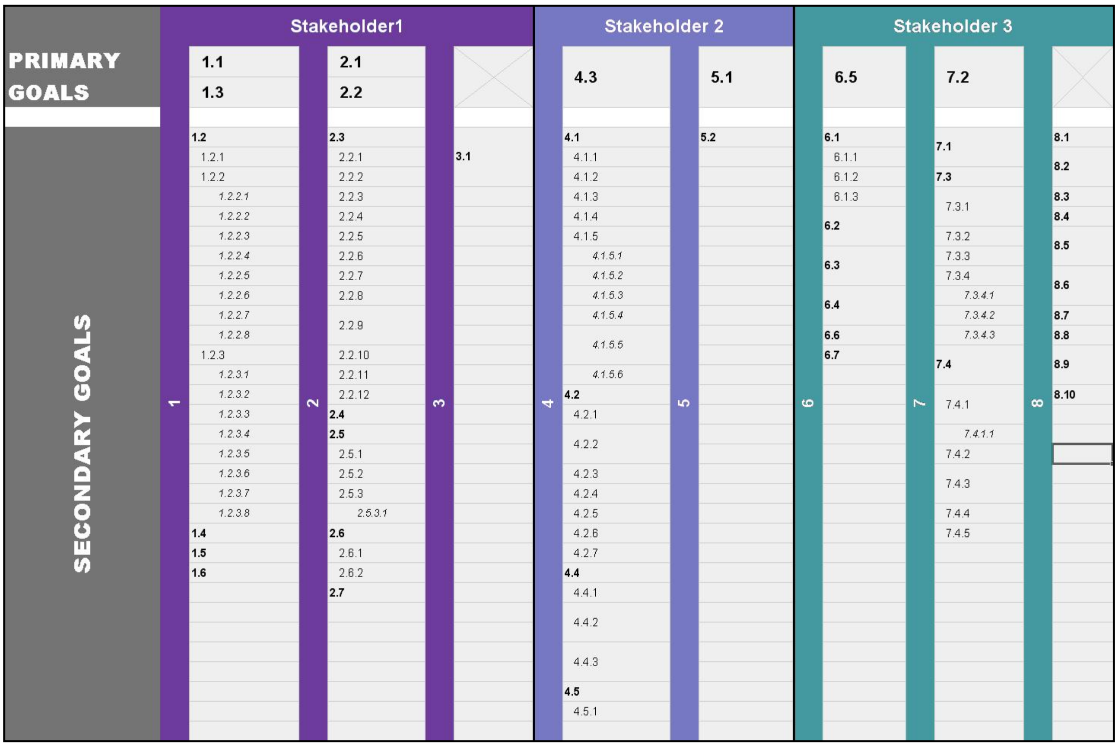

Figure 6.13 Product value model for case study 2

This yielded eight key product value attributes, which cannot be disclosed due to their confidential nature. The project team developed system targets for each of the eight key value attributes (Table 6.10); a fictitious list of key value attributes has been included.

Table 6.10 Approach used to identify system targets for case study 2

Key value attributes	System targets
Cost	Reduce cost by A%
	Reduce cost by B%
Compliance	Standard1
	Standard2
Manufacturability	Reduce complexity
Specific fuel consumption (SFC)	Reduce SFC by C%
Disruption	Reduce time between repairs
Serviceability	Reduce service time
Weight	Reduce weight by X%

Key value attributes	System targets
Mounting	Mounting time x hours
Pay load	Increase to x kg
Emissions	Reduce CO2 emissions
Safety	Comply with standards
Regulations	Comply with standards

It was difficult to weight system targets (and attributes) in order to understand the project priorities, as the weightings from different stakeholders were expected to be different. A survey was produced and circulated among company experts to gather expert weightings for the attributes. The results enabled the prioritisation of attributes based on the average response. The output of this process is presented in Figure 6.14 as percentages. Attributes with a higher percentage were considered to be of greater importance in this project.

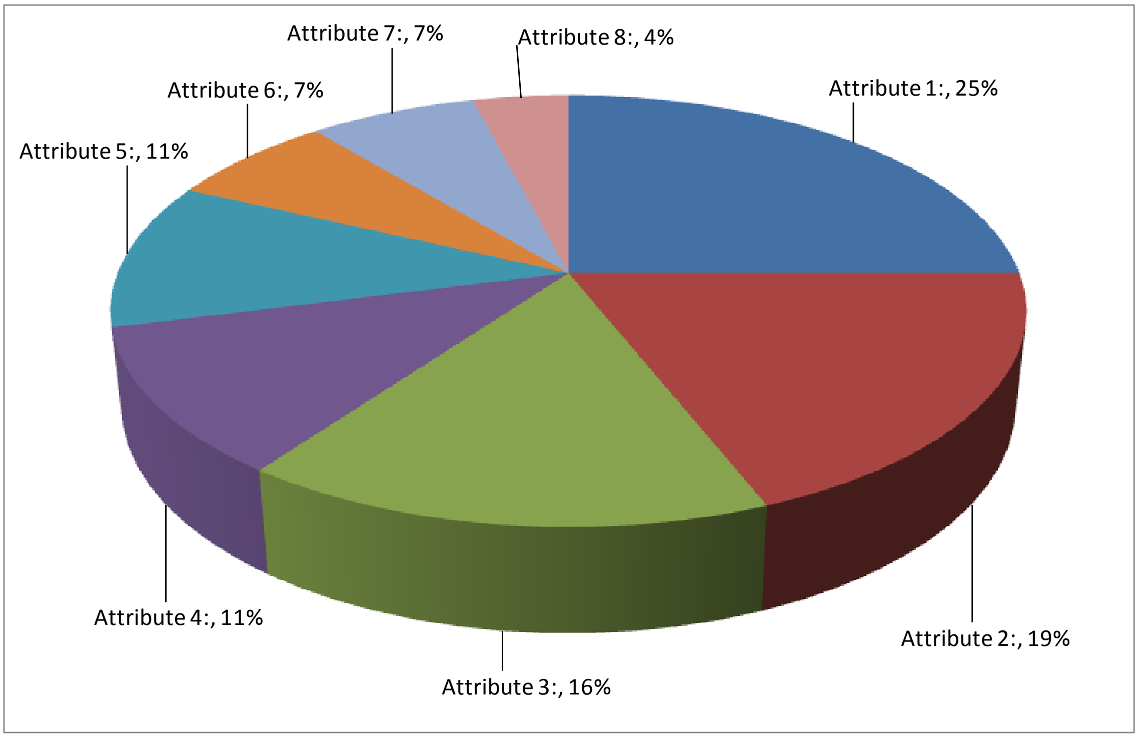

Figure 6.14 Prioritisation of product value attributes represented as percentages

Based on this analysis it was concluded that the four highest ranked value attributes should be focused on in this project. This resulted in four system targets which became the main drivers for the project.

1.3 Align project with company strategy

The project was aligned with the company strategy in a number of ways. First of all the 'chief project engineer'[24] was responsible for ensuring strategic alignment with business goals. Business strategy documents were reviewed in order to understand corporate strategies, while a number of meetings were held to understand product goals (for the specific engine) and goals for helicopters in general. No PD strategy was found to support the enhancement of the PD process. This provoked a meeting in which strategic PD goals were brainstormed.

A PD strategy matrix was produced to combine the strategic goals identified and analyse how well the project was aligned with them. The author did not have access to the matrix due to the confidential nature of the data, and thus it could not been presented here. This activity helped to direct the project towards specific strategic goals. Three of the strategic goals were: (1) boost innovation, (2) incorporate new skills, and (3) amalgamate customer value information. An assortment of corporate, product, and helicopter goals were also addressed.

1.4 Translate value to designers

One further activity that was proposed by the project leaders was to identify the system functions based on the key value attributes. Quality function deployment (QFD) was used to analyse the interaction between key value attributes and functions (Figure 6.15). This work was extended further to analyse competitor products and identify system target values for key value attributes (engineering metrics).

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[24] The 'chief project engineer' is different to the chief design engineer on the project who serves as the technical leader

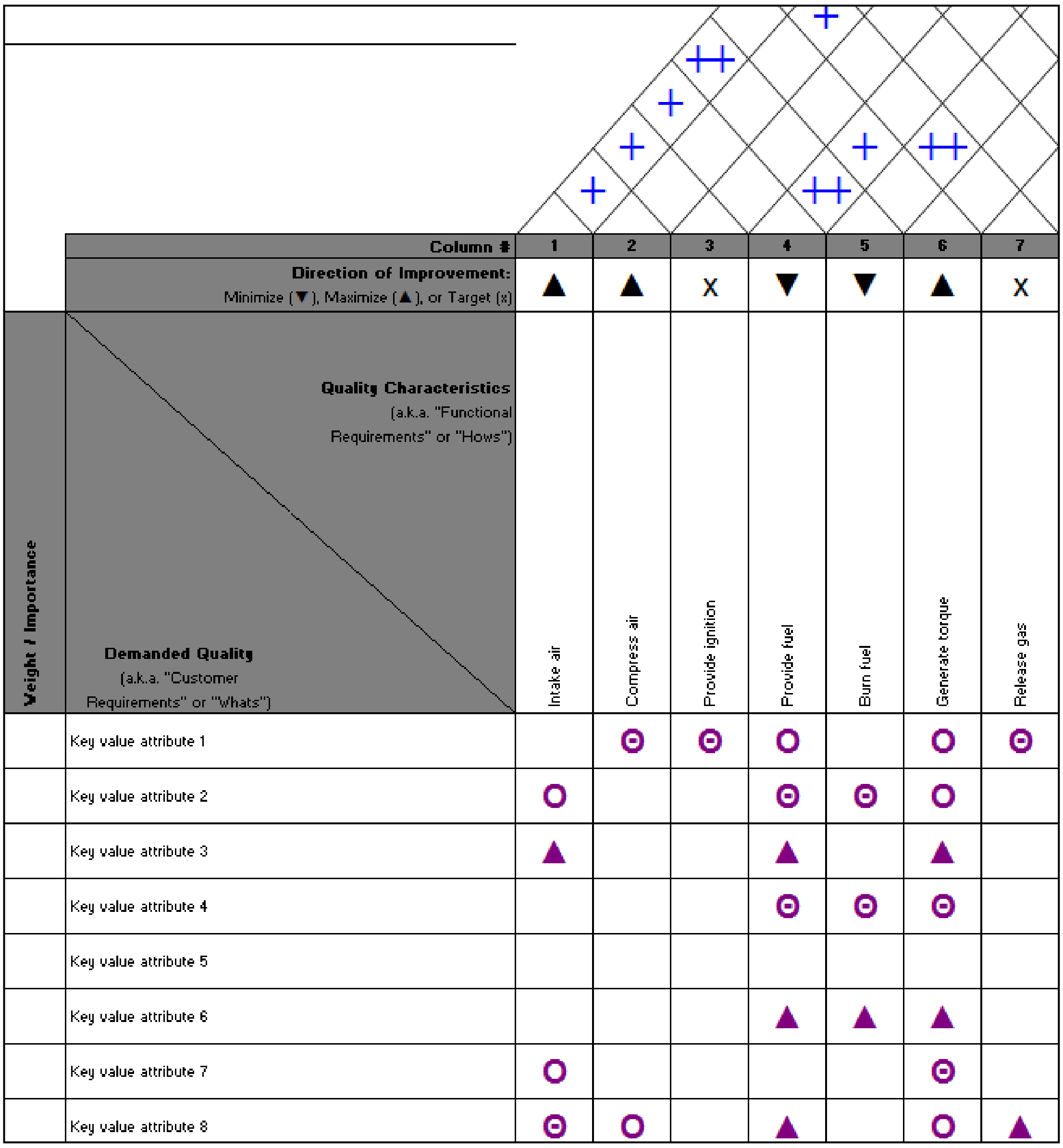

Figure 6.15 Quality function deployment: House of quality approach adopted for case study 2

In order to represent product functions, a functional flow diagram was developed. As the functions on this project were similar to that of a previous project, a functional flow diagram was adapted. Figure 6.16 illustrates the adopted approach.

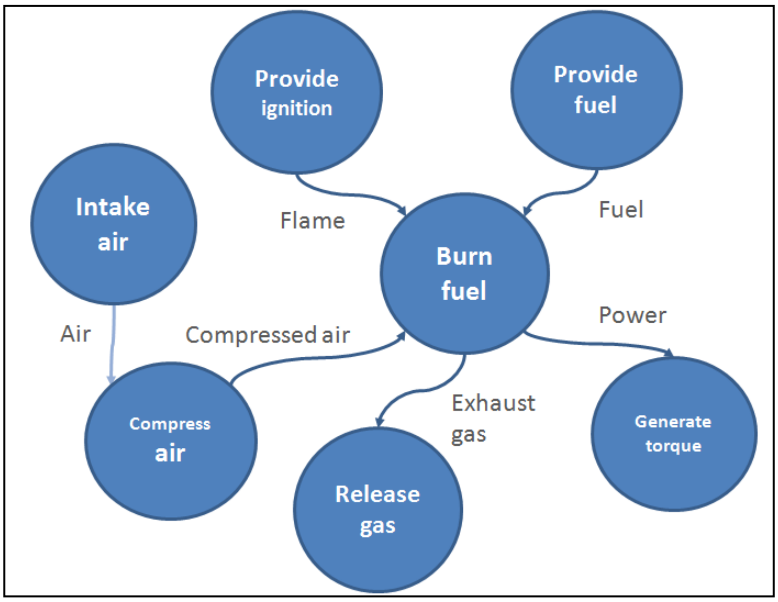

Figure 6.16 Functional flow diagram approach employed to represent product functions

The outputs of activities in phase 1 were compiled on a compact disc to communicate the product concept to designers. Initially a web-based approach was envisaged, however, due to time constraints on the project, interactive MS PowerPoint presentations were used with hyperlinks to access background information.

The culmination of phase one fell in line with the first project design review. The MS PowerPoint presentations were used by engineers working on the project to communicate the concept definition and a plan for future project activities. The review was chaired by the chief design engineer, while 8 additional senior engineers and company experts attended including the project manager, technical lead, and chief project engineer. A number of researchers also attended the review, including the author.

The chief design engineer on the project was happy for the project to progress to the next stage, despite the absence of structured (detailed) requirements as is typical at the first R-R project review. Senior engineers and project leaders felt that the project had challenged company practice and had made significant contributions, especially in the drive towards more innovation.

Phase 2. Map design space

2.1 Decide on level of innovation to subsystems

Based on the project information described in phase 1, an innovation classification diagram was produced (Figure 6.17). It became clear from this activity that the innovation and engineering effort should be focused on 3 main areas: (1) the intake, (2) the compressor, and (3) the turbine.

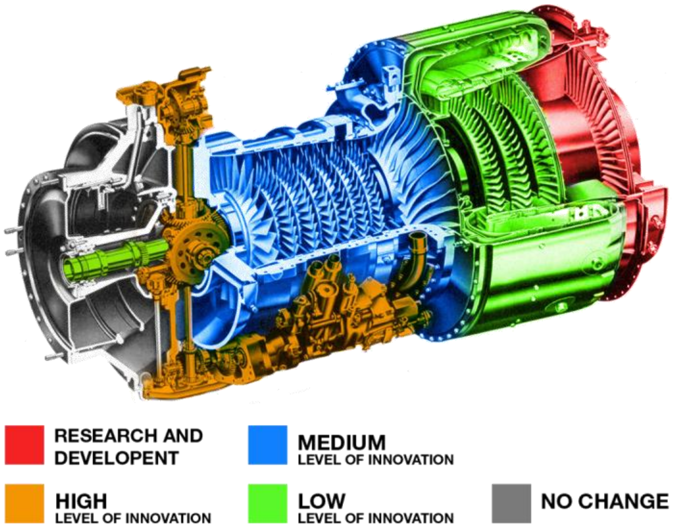

Figure 6.17 Innovation classification diagram exemplar for case study 2[25]

This method was received very well by personnel working on the project. The project manager actually suggested that this representation be used to project alternative system combinations and show the level of innovation within each alternative.

2.2 Identify subsystem targets

One of the main objectives of the project was to determine whether a number of challenging system targets could be achieved based on available technology. This was a formidable task within the project time scale. Subsystem targets were therefore not defined, although project personnel recognised this gap.

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[25] This is not the actual diagram produced for the R-R case study

2.3 Define feasible regions of the design space

A variety of opportunities for innovation were considered and reviewed by project personnel. Project personnel engaged with functional subsystem groups in order to understand design possibilities. Constraints are typically considered based on company design standards and interface diagrams and documents from existing designs. There were some special constraints in this project which required careful attention. Both constraints and feasible regions of the design space were discussed with functional experts. Feasible regions of the design space were not however, formally documented.

Phase 3. Develop concept sets

3.1 Extract design concepts

In order to ensure that a focused list of subsystem alternatives was developed, design criteria for subsystems were prepared with the support of a number of senior engineers. It was decided that technology maturity[26] would form the initial design criteria for subsystem alternatives. Many meetings were held between project personnel and functional subsystem groups to understand the available design concepts for subsystems. Design concepts were initially recorded as notebook entries. As most of the concepts were ‘known’ solutions, documentation regarding these concepts was collected.

3.2 Create sets for subsystems

This activity was included to allow time for designers to ideate and think outside of the box. Due to the time and resource restrictions on the project, idea generation was not given sufficient attention. A number of alternative subsystem modifications were however, considered for system integration. The application of phase 3 of the lean PD model focused on the intake subsystem. For the intake subsystem, a detailed study was conducted involving various

[26] R-R use the technology readiness level (TRL) approach to assess the maturity of evolving technologies

alternatives. Five alternative intake systems were considered[27], four power alternatives, and two alternatives for an additional capability. Table 6.11 presents the alternatives considered.

Table 6.11 Alternative components considered for the intake subsystem of case study 2

System	Power	Additional capability (Ac)
S1	P1	Ac1
S1	P1	Ac2
S1	P2	Ac1
S1	P2	Ac2
S1	P3	Ac1
S1	P3	Ac2
S1	P4	Ac1
S1	P4	Ac2
S2	P1	Ac1
S2	P1	Ac2
S2	P2	Ac1
S2	P2	Ac2
S2	P3	Ac1
S2	P3	Ac2
S2	P4	Ac1
S2	P4	Ac2
S3	P1	Ac1
S3	P1	Ac2
S3	P2	Ac1
S3	P2	Ac2
S3	P3	Ac1
S3	P3	Ac2
S3	P4	Ac1
S3	P4	Ac2
S4	P1	Ac1
S4	P1	Ac2
S4	P2	Ac1
S4	P2	Ac2
S4	P3	Ac1
S4	P3	Ac2
S4	P4	Ac1
S4	P4	Ac2
S5	P1	Ac1
S5	P1	Ac2
S5	P2	Ac1
S5	P2	Ac2
S5	P3	Ac1
S5	P3	Ac2
S5	P4	Ac1
S5	P4	Ac2

[27] The 'intake system' is a constituent of the intake subsystem

3.3 Explore subsystem sets

The knowledge creation plan was met with considerable support from project leaders and engineers. For the intake subsystem, a number of alternatives were considered and a knowledge creation plan was composed. The key representations sought through the intake knowledge creation plan were limit curves, trade-off curves, and a number of schematics. Each of the alternatives were modelled and tested by means of simulations, and in some cases physical tests.

3.4 Capture knowledge and evaluate

A limit curve was developed to characterise the impact of environmental conditions on the different intake system alternatives (Figure 6.18). System 1 and 4 provide the best efficiency results.

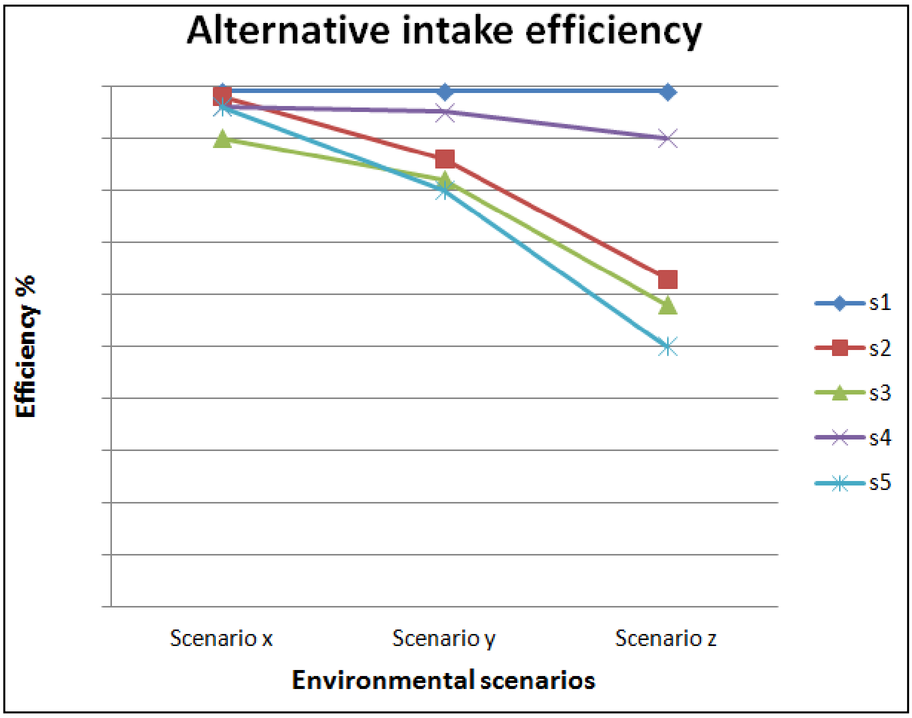

Figure 6.18 Efficiency of alternative intake systems: Limit curve for case study 2

A trade-off curve was composed to compare the five intake system alternatives against efficiency and pressure loss within the intake system (Figure 6.19). System 2 provides the best combination of efficiency and lowest pressure loss, with systems 5 and 3 also performing well.

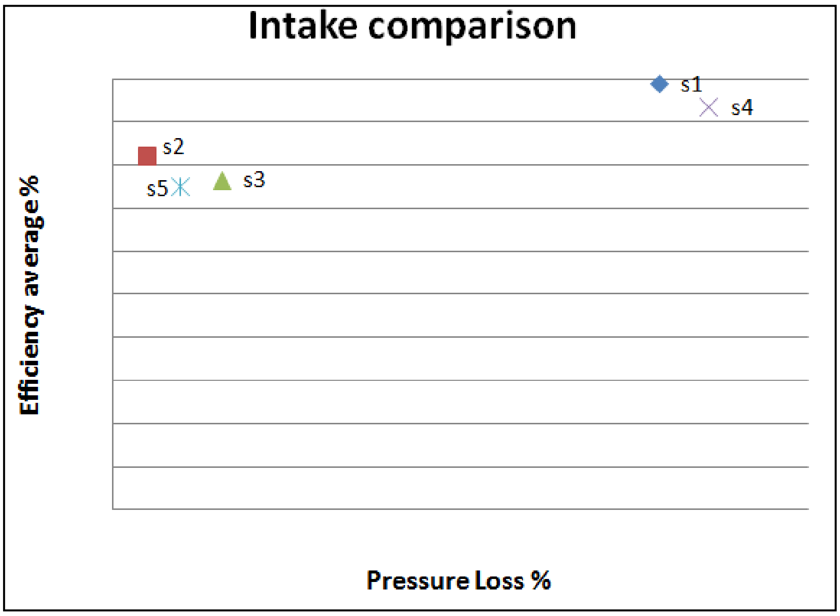

Figure 6.19 Efficiency (average) of intake system alternatives against pressure loss: trade-off curve for case study 2

Intake power alternatives were evaluated against a number of criteria including cost and power loss. A trade-off curve was developed to present the four alternatives against the parameters of cost and power loss (Figure 6.20). The graph shows that both cost and power loss is lowest for alternative p2, although p1 is marginally more costly.

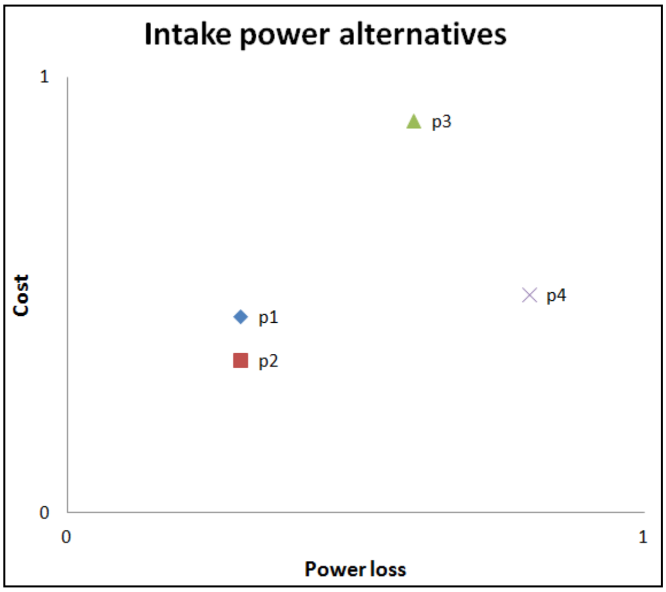

Figure 6.20 Cost of intake power alternatives against power loss: trade-off curve for case study 2

Based on the analysis conducted of intake system alternatives and the resulting knowledge representations produced, three intake options were proposed (Table 6.12). Additional capabilities were not tested.

Table 6.12 Intake alternatives proposed for system integration (case study 2)

Intake options	Intake system	Power	Additional capability
New 'state of the art' solution	s2	p2	Ac2
Intermediate solution	s2	p2	Ac1
Low cost solution	s5	p2	Ac1

3.5 Communicate sets to others

A second R-R design review was held after system combinations were analysed. The review will be discussed after presenting the results for lean PD activities 4.1 and 4.2.

Phase 4. Converge on system

4.1 Determine intersections of sets

Based on the alternative subsystems considered in phase 3 there are 1152 potential system combinations[28]. Table 6.13 presents the solution sets under consideration. All of these combinations were assumed to be possible; therefore integration was not considered to be an issue. The concept intersection matrix was therefore not used in this case.

[28] This number can be calculated by multiplying the number of alternatives for each subsystem

Table 6.13 Subsystem alternatives recommended for system integration (case study 2)

Subsystem	Alternatives	Description
Intake	a1	Installed on previous design/s
	a2	New
	a3	New 'state of the art'
Combustion chamber material	b1	Installed on previous design/s
	b2	New
	b3	New
Combustion chamber architecture	c1	Installed on previous design/s
	c2	New
Combustion chamber additional function 1	d1	No addition
	d2	New additional feature included
Combustion chamber additional function 2	e1	No addition
	e2	New additional feature included
Turbine material	f1	Used on previous design/s
	f2	New
Turbine architectural amendment 1	g1	No amendment
	g2	New amendment
Turbine architectural amendment 2	h1	No amendment
	h2	New amendment
Combustion chamber additional feature	i1	No addition
	i2	New additional feature included

4.2 Explore system sets

The subsystem alternatives were analysed against the key value attributes as well as other design criteria such as engineering costs and risks. Project leaders steered the design team to ensure system combinations were analysed in time for the second project design review. Function means analysis (FMA) was conducted to allow system combinations to be formulated. Six system combinations were put forward based on the FMA and analysed using a Pugh matrix. Four of the combinations were configured to focus on single system targets, and two were balanced systems which addressed all four system targets. The Pugh matrix was populated during a project meeting with senior project leaders. Based on this subjective analysis a single 'best rated' system combination was proposed for review. Figure 6.21 illustrates the results of the analysis performed for the best-rated system combination.

Scale	
Meets requirements	9
Some improvement	3
Minimum improvement	1
No change	0
Minimum negative change	-1
Some negative change	-3
Large negative change	-9

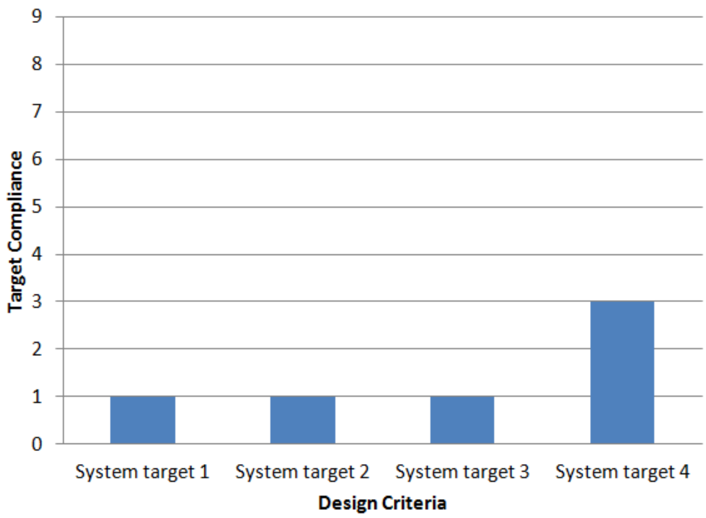

Figure 6.21 Target compliance of best rated system combination for case study 2

The second design review meeting was attended by 16 senior engineers and project leaders, 8 project engineers, and a number of researchers including the author. The review was chaired by the chief design engineer; the project manager, technical lead, and chief project engineer were also present.

Project engineers presented a summary of the project as well as the solution sets and best rated system combination. The main conclusion from the analysis was that the system targets could not be met using the available technology and under the current constraints. This meant that either more innovative solutions and design changes needed to be considered, or the system targets had to be reconsidered. There was a unanimous agreement that according to the criteria for a second R-R project design review, the project should be stopped as the system targets (or requirements) had not been achieved. However, as the process implemented was significantly different to typical R-R projects, it was agreed that the typical review criteria could not be used to judge the project. However, due to the momentum of the project and the impression created by the initiative, it was decided that more effort was required to develop superior concept sets. The group also agreed that more objective studies and analyses were required to understand alternative options better, and that the review should be repeated once further analysis had been performed. Further implementation of the lean PD model was decided to be continued in the future.

The lean PD model was credited with a number of substantial contributions to the project. Senior engineers highlighted the detailed analysis of customer value to be effective for understanding gaps in the market and future opportunities. The methodological consideration of alternatives was very helpful in enabling more innovation, and the process outputs provoked some fruitful discussions.

6.4 Summary

In this chapter two case studies are presented in which the lean PD model was applied to live PD projects in industry.

The two companies selected for case studies were Visteon Engineering Services Ltd (VES) and Rolls-Royce Plc. (R-R) The product architecture for a car audio head unit was selected for the case study at VES, while a helicopter engine was selected at R-R. An open questionnaire was used to collect data about the PD process for a historic case. The data collected allowed a gap-analysis to be performed between the historic case and the methodologies proposed for lean PD model activities. This allowed bespoke approaches for implementing the lean PD model to be proposed for the two cases. The author participated in the implementation of the lean PD model on both cases and the results of each applied activity are described separately.

The next and final chapter discusses the results presented in this chapter as well as the research project in general.

7 DISCUSSION AND CONCLUSIONS

The primary aim of this research was to construct an innovative model which supports the implementation of lean thinking in PD. As explained in chapter 2, the research was qualitative, and adopted a mixed methods approach. The study was organised into three phases. The first phase involved the exploration of lean PD theory and the industrial context, relying chiefly on literature, observation and interviews. The second phase is where the lean PD model was constructed based on principles and enablers extracted from literature, findings from phase 1, and workshops with both industrialists and researchers. The author guided the application of the model to two industrial case studies in the final phase of the study. A car audio head unit and a helicopter engine served as case studies, the results for which are presented in chapter 6. In this chapter the research outlined in earlier chapters is discussed.

The chapter is divided into 6 sections:

In section 7.1 case study results are discussed and findings from each case study are extracted. This is followed by a cross-case study examination through which key findings are derived. Common themes and differences between the findings in the two cases are discussed, followed by additional key findings expressed by practitioners during reflective ‘lessons learnt’ meetings at the end of each case study. In section 7.2 the research presented in this thesis is evaluated. First the lean PD model is evaluated based on the identified challenges from the industrial field study in chapter 4. The research methodology is then evaluated retrospectively, and research limitations are discussed. The fulfilment of research objectives is then discussed. Key research contributions are highlighted in section 7.3. In section 7.4 research implications are drawn for practitioners interested in implementing lean PD. Suggestions for future research are provided in section 7.5. Finally, conclusions based on the research are presented in section 7.6.

7.1 Discussion of Research Results

In this section the results for each case study are summarised and research findings are derived. A cross case study comparison is provided and key findings are then interpreted in light of previous research. Research insights are also provided throughout the section.

7.1.1 Case Study 1

Case study 1 was setup to support the development of a new audio head unit (AHU) for an in-car entertainment system. The lean PD model was applied to develop the design of the electronic product architecture of the AHU. The author attended meetings with engineers at the company site throughout the course of this study to guide the application. Although it was envisaged that the majority of lean PD model activities would be implemented in this case, 4 of the initial 18 lean PD model activities were deemed unnecessary due to the sets being composed of ‘off-the-shelf’ electrical components. These components did not have to be designed by the project and their specifications are provided by suppliers so there is no need to test them individually. Eight of the remaining 14 proposed activities were implemented, while 6 activities were not implemented. This meant that complete application of the lean PD model was not possible in case study 1. Furthermore, convergence upon an optimal design was not possible because a single product architecture was prematurely selected due to project pressures. Five out of the seven tools developed for the lean PD model were tested, customer value was given special attention, sets of components were considered as well as alternative system combinations. The case was resource-restricted and priority was inevitably given to business pressures over research objectives. Moreover, the research was not given much room to influence project decisions. This is likely to have been due to the risks involved, especially with a live project.

A number of findings were derived from case study 1:

- Ample time was available for PD but very little time was allowed for ideation and innovation, despite being graded a potentially high innovation project
- The central purpose of the product is to entertain the end user, and while a plethora of requirements and specifications had to be considered from the OEM customer, it was concluded that the most critical value attributes are those that could compromise the purpose; any value attribute that compromises user entertainment should be prioritised over others
- By using the product value model, hundreds of requirements and specifications could be reduced to a list of 30 attributes to represent the product; this was considered to be an effective way of communicating what the product was trying to achieve (as compared to lengthy requirements and specification documents)
- The PD strategy matrix can be used to evaluate system combinations against strategic benefits; the matrix was developed to ensure that the project was aligned with company strategies from the onset and therefore an additional use was identified
- By associating value attributes with engineering metrics (and target values), alternative components could be evaluated
- If there is no formal mapping of the design space, there may be ambiguity in how the sets of solutions are determined; formally mapping the design space is likely to lead to a more thorough approach to identifying concepts and convergence
- The number of alternative system combinations was much larger than expected, and the probability of arriving at the best combination using the typical subjective approach was found to be incredibly low
- The bill of materials costs for possible system combinations has a high standard deviation; analysing the cost of a large number of system combinations can be easily automated and can support convergence when cost is a criterion; where components (or perhaps subsystems) can

be individually quantified against other metrics or criteria, similar analyses could be performed

- With a considerably large number of component (or subsystem) alternatives, subjective decisions may be necessary to reduce the number of system combinations that can be tested
- Project milestones may force subjective evaluation and the premature selection of a system solution

7.1.2 Case Study 2

Case study 2 was setup to support the development of a turbo-shaft helicopter engine. The lean PD model was applied to develop the design of the engine concept, and focused on three key subsystems: the intake, compressor, and the turbine. The author attended project meetings at the company site throughout the course of this study to guide the application. Due to the strong organisational support given to the research, there was a high degree of influence on development activities and project decisions. This resulted in a more complete application of the lean PD model. Thirteen of the 18 proposed activities were implemented, while five activities were not implemented. Four of these unapplied activities are at the end of the process, all of which are expected to be completed as the project progresses further. Convergence upon an optimal design was not possible as the final activities were not executed. A single engine concept was prematurely proposed due to project pressures, but was not approved at a second design review due to system targets not being met. Five out of the seven tools developed for the lean PD model were tested, customer value was given ample attention, subsystem sets were considered as well as alternative system combinations, and a good degree of convergence was demonstrated for the intake system. Many other tools were also employed to support the activities, including lean PD enablers. Although the case involved many company resources, there was a shortage in the number of dedicated project engineers. This was identified in the industrial field study to be a typical PD challenge: the concept phase is often under-resourced (see section 4.3.2). The project manager expressed that the project had suffered according to company milestones, despite achieving a significant level of success and validation for the process. This fact is not disputed, however it was proposed from the onset that the second design review be postponed until the final system is converged upon. The main output for the second design review is a single system solution, which is typically arrived at by subjectively deselecting alternative subsystem options. It was intended that this approach be countered through the application of the lean PD model. A number of findings were derived from case study 2:

- Ample time was available for PD but very little time was allowed for ideation and innovation, despite the intention to demonstrate new technologies in the project
- Product value attributes can be structured based on their stakeholders when there is no direct end-user interaction with the product
- The product value model proved very effective in combining a mass of information regarding customer needs and desires, benchmarking reports, and market studies
- By relating a new project to process enhancement, and corporate and business strategies, the project benefits can be increased, the project is better aligned with business strategies and the project can also influence the strategy
- By combining the product value model and QFD, new market opportunities and ideas were generated
- Visual representations applied as a result of the research were very effective during design reviews, and in general when communicating about the project
- The innovation classification diagram was well received by both the project manager and engineers; the representation helped to discuss design options and constraints
- Decomposing system targets into subsystem targets for an aircraft engine is a very challenging and formidable task

- Over a hundred requirements were reduced to a list of 8 key value attributes, and eventually 4 system targets to represent the key project requirements
- Constraints from suppliers and partnering companies can require careful consideration when applying SBCE
- Due to the nature of an aircraft engine, some senior engineers asserted that an engine cannot be designed by first considering modules in isolation due to the interdependence between subsystems, and the effects of changes to one subsystem on another; this was disproved by the case study
- The knowledge creation plan proved effective in guiding the evaluation of alternative intake subsystem components; schematics, limit curves and trade-off curves were used to characterise the options and facilitate convergence upon 3 alternative intake subsystems
- A cross-functional project team can be instrumental in engaging with functional groups and combining design alternatives
- The number of alternative system combinations was much larger than expected (as with case study 1), and the probability of arriving at the best combination using a typical subjective approach was concluded to be incredibly low; in a turbo-shaft engine there are thousands of components and therefore the number of possible systems is actually much higher
- All system combinations may be possible, and even easy to integrate, thus concept intersection may not help in filtering subsystem sets for every application; due to the limited testing of different system combinations in aerospace products, it is likely that the project team did not have extensive knowledge regarding integration and thus could not comment on the integration of potential systems
- With a considerably large number of subsystem alternatives, subjective decisions may be necessary to reduce the number of system combinations that can be tested

- Project milestones may force subjective evaluation and the premature selection of a system solution
- If system targets (or design requirements) are difficult to achieve using available technology, a set-based approach can help to determine whether it is possible to achieve them or not
- SBCE is in line with the systems engineering approach, but is also complementary, as it facilitates the progressive evolution of requirements and the development of multiple solutions

7.1.3 Key findings

7.1.3.1 Common Findings in Both Case Studies

As both case studies progressed there were a number of common themes identified. Company representatives began to talk about the lean PD model as though it is the right way to develop products. Furthermore, the initial debate around 'what types of projects the model was relevant to' changed to 'whether the model was relevant to all projects'. This is similar to a finding by Raudberget (2010) based on some industrial trials of SBCE.

There was a positive response to all of the tools developed to support the lean PD model. The focus on visual representations to support communication and PD decisions was supported by project leaders and engineers alike.

Both companies develop design solutions based on requirements; however 'requirements' is used as a catch-all term for different pieces of information. By applying the lean PD model, different 'requirements' were distinguished by using terms such as value attributes, system/subsystem targets, and design criteria. The terminology was met with some initial discomfort, but there was also considerable appreciation for multiple terms and better articulation in general.

Although both of the cases started off with the potential to incorporate a high degree of innovation, very little time was allowed for ideation and innovation. The innovation in both projects can be described as merely incremental enhancements to previous designs. One of the challenges put forward by practitioners to this stance was that live business projects were not where ideation and innovation should take place. However, it is through projects that innovative products are developed, and ideas and technologies are actualised. Time is therefore required on projects to consider new ways of solving engineering problems. Alternative solutions were considered during both cases, but the actual mapping of the design space did not appear to be formal or thorough.

The consideration of solution sets resulted in a large number of system combinations. As a result it was concluded that some subjective decisions may be necessary in order to arrive at a feasible number of system combinations that can be further explored. This finding must be appended with a caution, as it was also found that rushed subjective decisions are likely to have resulted in rework on both projects[29]. Such subjective decisions were found to be pressured by tight schedules and project milestones. This was one of the barriers to SBCE suggested in previous research (Raudberget, 2010). Another factor that must be mentioned here is the lack of commitment to a convergent approach found in both cases. Both projects rushed to get to a single system solution without exploring other system combinations that were deemed suitable. Augustine et al. (2010) report a similar finding during a case study of their ‘concept convergence process’. The preference for subjective decisions may have also been caused by the concept phase being under-resourced and a lack of dedicated project engineers to support the project.

In spite of the obstacles faced during the application of the lean PD model, both cases experienced positive outcomes. Both companies remain keen on further implementation, and one of them wishes to extend the model to the rest of the organisation. This is similar to a finding by Raudberget (2010), who suggested that the usefulness of an approach may be ascertained if companies intend to use it for future projects.

[29] It is difficult to establish a causal link here, but design changes or changes to requirements were noted in both cases

7.1.3.2 Differences Between the Case Studies

Some distinctions between the case studies became apparent as they progressed. Case study 2 was met with an exceptional level of organisational support, which in turn resulted in a more complete implementation of the lean PD model as compared to case study 1. This may have transpired due to a variety of factors including the synergy between the research and company objectives, the relevance of the lean PD model to specific projects or project types, organisational culture, or some other exigency to improve.

It was found that applying the lean PD model to a product system is much more complex than applying it to a subsystem. Alternative design solutions are present at both levels, but at the system level both subsystems and components need to be considered. For case study 2 it was initially suggested that components not be considered until a general system solution is decided, however as the case progressed it was necessary to consider components. At the component level sets may be larger, which inevitably increases the number of system combinations manifold as compared to subsystem alternatives.

The application of the lean PD model was simpler in case study 1 due to the modular design of the product architecture and the standard interfaces present. In case study 2 a different approach was required due to the 'functional-build'[30] approach adopted in the aerospace industry.

7.1.3.3 Other Key Findings

A number of additional findings have been included in this section. These have been formulated based on 'lessons learnt' discussions at the end of each case study.

There was a consensus between case study 2 project leaders that the lean PD model is in line with systems engineering. One systems engineering expert at the company highlighted that the model complements systems engineering as it facilitates the progressive evolution of requirements and the simultaneous

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[30] Functional build involves focusing on the completed assembly of a product rather than the individual parts

development of multiple solutions. Prior research suggested that lean principles, practices and tools enhances the delivery of value and reduction of waste in systems engineering (Oppenheim, 2008; Oppenheim et al., 2010).

In case study 2, standard company design reviews (or quality gates) were held in order to assess project progress. Although a shift in the criteria was deemed appropriate, and the timings of reviews required careful planning, the case proved that standard reviews could be incorporated into an application of the lean PD model.

Constraints require careful consideration in the application of the lean PD model. Moreover, the types of constraints that need to be considered vary between industries, projects, and tiers of the supply chain. Constraints may be imposed by end users, OEM customers, partnering companies, suppliers, governments, institutions, as well as internal company subdivisions. This point was raised by Sobek et al. (1999) in their categorisation of principles for SBCE.

The system targets (or design requirements) in case study 2 were expected to be difficult to achieve using the available technology. By employing a set-based approach, the project team was able to swiftly determine whether it was possible to achieve them or not. This is quite different to the finding by Madhavan et al. (2008) that there is a lower risk of not finding a suitable solution with SBCE. Through this case study it was demonstrated that no suitable solution was found for a particularly challenging set of requirements.

Another key finding was that cross-functional teams may be essential for implementing the lean PD model. This is especially true in a large organisation where information needs to be quickly gathered from numerous functional and organisational groups. Dedicated multifunctional teams were put forward as enablers for lean PD by Ward et al. (1995) and Morgan and Liker (2006).

In both cases it was found that quality function deployment (QFD) is a valuable tool for the lean PD model. Sobek et al. (1999) suggested that Toyota rarely use QFD in projects based on their case study of TPDS. This may be because not all projects require the structured extrapolation of value attributes to system functions and targets, particularly in the case of modifications to modular systems. QFD is likely to be essential in new innovative projects where functions and system targets are obscure.

Some company representatives were sceptical with regards to considering more alternatives and the impact on project workload. Both cases demonstrated that this was not the case as no substantial increase was noticed prior to system testing. As multiple system combinations would require more testing, extra investment is likely. However these additional development costs are likely to be recovered by a reduction in late design changes, rework, and warranty costs as manifested in the industrial trials by Raudberget et al. (2010). Through the case studies it was found that getting projects to consider more design alternatives is not difficult, but to prevent them from making rushed subjective decisions and focus them on gradual convergence based on objective analysis can be immense. One possible reason for this may be that there is no incentive to gradually converge on an optimal solution, and it may not be the culture to do so. The same may be said about considering alternatives in the first place and also knowledge reuse, as mentioned by Raudberget (2010). In spite of this, participants in the study found that an objective and knowledge-based convergent approach was superior and likely to be less risky as compared to alternative subjective approaches, although the latter may be faster. A similar finding was made by Augustine et al. (2010).

It was concluded based on the case studies that an organisational transformation based on the lean PD model would require further engagement with senior managers as well as a long term commitment to the approach. Careful consideration of social, cultural, and political factors is also required in order to prevent resistance. Similar findings were suggested by Liker and Morgan (2011). Another key consideration is language and terminology. Unusual terminology was used in the lean PD model to differentiate activities from standard practices. This may require some finessing in the case of organisation-wide roll out.

7.2 Research Evaluation

In this section a reflective review of the research is provided. The lean PD model is scrutinised against industry challenges to assess its relevance, and evaluated as a design theory. The research methodology is then reviewed; strengths and limitations are identified and discussed. Fulfilment of the research objectives is also discussed.

7.2.1 The Lean Product Development Model

Through the industrial field study reported in chapter 4, a number of challenges were found to be present in industry. The challenges were reduced to 12 over-arching categories (refer to section 4.3.2). The challenge categories have been used to evaluate the relevance of the lean PD model. A summary of the evaluation is provided in Table 7.1 followed by a discussion of each category.

Table 7.1 The impact of the lean PD model on challenges faced by industry

Challenge category	Challenges addressed by the lean PD model	
	Expected	Observed
1. Design changes	✓	
2. Customer value		✓
3. Design specification		✓
4. Knowledge		✓
5. Process flow		✓
6. Communication		✓
7. Leadership	✓	
8. Management	✗	
9. Innovation		✓
10. Planning		✓
11. Time management	✗	
12. Process improvement obstacles	✗	

By applying the lean PD model it is expected that design changes will be reduced. This effect was not observed in the case study as the after-effects of the lean PD model were not studied, nor were the number of design changes measured. The flexibility of the model in dealing with changing requirements was noted.

Customer value is given significant attention in the lean PD model. The methodology provides recommendations for the capture and representation of customer value attributes. System and subsystem targets are defined based on these attributes and are included in the design criteria used to evaluate design options.

In the lean PD model, specification documents are not released until a final system solution is converged upon. The specification of the design solution is thus delayed. For case study 2 no specification document was created during the application of phases 1 – 4 of the lean PD model.

Due to the focus on knowledge incorporated into the lean PD model, decisions cannot be made without the relevant knowledge being present (such as test results). The application of the lean PD model resulted in the amalgamation of knowledge and the provision of various knowledge representations which supported decision making.

The lean PD model provides a logical roadmap for an engineering project. In case study 2 in particular, it was found that there was a high degree of obscurity regarding what should be done until the lean PD model was applied. The model does therefore enhance process flow.

In the case studies, visual representations served as communication mechanisms that engineers were happy to discuss. The cross-functional team employed in case study 2 was vital in engaging different organisational groups. Furthermore, consideration of sets of alternatives was welcomed by both engineers and functional groups, and it stimulated positive discussions.

The chief engineer leadership approach is key to the application of lean PD. This was not specifically addressed in the application of the lean PD model, but positive effects are expected in future applications. Although the lean PD model aids in managing the design process, management in general was out of scope.

The lean PD model urges more exploration of the design space and is supportive of innovation. Sets of design solutions are considered and evaluated based on simulations and other tests. By focusing on conceptual design the lean PD model induces front-loading and thus more innovation.

The lean PD model offers a staged process composed of activities with methodological steps. The first phase is predominantly a planning phase, and positive effects were witnessed during the case study. The project classification matrix in particular contributes to the early planning of projects.

The impact of the lean PD model on time and project durations was not studied. Application of the model may have both positive and negative consequences on time. Similarly the model did not address process improvement obstacles. That said, it is expected the sustained implementation of the model would result in continuous improvement of PD processes.

Having observed positive impacts on seven categories of challenges faced by PD in industry, and a further two expected, it can be concluded that the lean PD model is very relevant to its industrial context.

From a theoretical perspective, the lean PD model embodies the components of a design theory as shown in Table 7.2. Although a complete theory cannot be claimed, the fundamental components are present, and some are more mature than others.

Table 7.2 Design theory components of the lean PD model research (adapted from Gregor and Jones, 2007)

Design theory component	Description	Lean PD model research
Purpose and scope (the *causa finalis*)	"What the system is for," the set of meta-requirements or goals that specifies the type of artefact to which the theory applies and in conjunction also defines the scope, or boundaries, of the theory	The lean PD model supports the implementation of lean thinking in PD; the theory is relevant to the development of engineering products; the scope and boundaries of the theory requires further study
Constructs (the *causa materialis*)	Representations of the entities of interest in the theory	Define value; map design space; develop concept sets; converge on system; detailed design
Principle of form and function (the *causa formalis*)	The abstract "blueprint" or architecture that describes an artefact, either product or method/intervention.	A model is provided to aid in the implementation of Toyota PD principles and practices during the conceptual design of engineering projects
Artefact mutability	The changes in state of the artefact anticipated in the theory, that is, what degree of artefact change is encompassed by the theory	Suggestions for further work are provided and it is expected that applications of the lean PD model would differ depending on the context
Testable propositions	Truth statements about the design theory	It is claimed that the model is applicable to other PD contexts; goals include enhancing innovation and reducing rework
Justificatory knowledge	The underlying knowledge or theory from the natural or social or design sciences that gives a basis and explanation for the design (kernel theories)	The theory is developed based on case based research about Toyota PD principles and practices
Principles of implementation (the *causa efficiens*)	A description of processes for implementing the theory (either product or method) in specific contexts	Strong organisational support is required, in addition to a facilitator who is familiar with Toyota PD practice
Expository instantiation	A physical implementation of the artefact that can assist in representing the theory both as an expository device and for purposes of testing	Case study examples are provided with detailed descriptions of interventions

7.2.2 The Adopted Research Methodology

A systematic literature review was conducted in order to identify and analyse the published body of knowledge on the subject of lean PD. A number of research gaps were identified including the absence of a framework of lean PD enablers, and methodological guidelines for the application of lean thinking in PD. As a result, this study focused on both theoretical and methodological development to support PD practice. By combining theoretical and contextual analysis, the lean PD model was formulated. The model represents a staged process for implementing Toyota PD principles and practices during the conceptual design of engineering projects. The model focuses on conceptual design due to the results from analysis of the literature and findings from an industrial field study. Two case studies were conducted to test the lean PD model, yielding encouraging results. The research methodology adopted had several merits which will be mentioned in this section.

The research presented in this thesis was established upon a hybrid epistemological standpoint, combining social constructivism and pragmatism. The contribution to knowledge is thus a result of interaction between social phenomena and lessons from the executed interventions. This standpoint ensured a ‘real world’ focus, as opposed to an artificial or purely theoretical study. Developing a comprehensive understanding of the research setting was therefore a prerequisite to constructing the lean PD model. Five industrial companies were studied from three engineering sectors in order to understand current industry practices and challenges faced in PD. Company representatives and PD experts were involved throughout the research project. This prolonged involvement with multiple organisations meant that the research benefited through suggestions and feedback from many practitioners. Moreover, the research methodology itself was communicated to company representatives and was enhanced due to their feedback.

The aim of the research and research objectives were assigned from the onset, however, the adopted methodology allowed a fitting degree of flexibility. This allowed findings from the literature review and industrial field study to influence the research direction. The flexible design pervaded much of the research, including the interview strategy during the industrial field study and the case studies.

MS PowerPoint presentations and reports were used throughout the project to impart analysis of data collected for member checking. Researchers and practitioners provided feedback and necessary corrections. Misrepresentation and misinterpretation were both reduced through this measure.

Multiple methods were used to ensure research quality and triangulation throughout the research. The main research methods employed were literature review, observations, interviews, workshops and case studies. Data was collected via questionnaires, interview transcripts, meeting and workshop notes, coding matrices, and other soft documentation. Additional approaches used to reduce bias and ensure trustworthiness were peer debriefing and support, negative case analysis, maintaining an audit trail of research activities and research dissemination. Various meetings and workshops were held where research results were presented, and feedback was received.

As the research used a qualitative perspective, comparative analysis was employed throughout. This was true for the majority of the research conducted, including the two case studies. Two different cases were selected to maximise lessons from the implementation of the lean PD model, while also allowing for cross-case study examination. The case studies resulted in a rich understanding of the effects of applying the lean PD model.

All in all, the defined research methodology allowed a detailed study of both theory and practice and the development and testing of the lean PD model.

7.2.3 Research Limitations

Research limitations were identified in three areas: (1) the research design; (2) quality of results; and (3) the lean PD model itself.

The research design was qualitative, and therefore did not address the statistical significance of results. This issue permeated through the research, and as a result little metric-based analysis was possible. Had the research adopted a quantitative approach, it is likely that methods such as sampled surveys would have been present in the research. Adopting a quantitative approach however, may have jeopardised the richness of data collected regarding both the context and case studies.

For the case studies, an action research approach was adopted which meant that the author’s preconceived ideas, and opinions could have influenced the results. Researcher bias during action research was somewhat mitigated by involving multiple researchers and practitioners in the case studies. Action research is indeed a demanding research approach, and further cases are likely to have compromised the richness and reliability of results. Likewise, a limited number of case studies can be the basis for generalisation where the cases are central to theoretical development (Denzin et al., 2011).

The lean PD model focused on conceptual design, and hardly addressed detailed design or any further activities in PD. This was decided upon based on the research results. The focus on conceptual design was due to findings from the literature review and industrial field study. This decision helped to focus the research and ensure richness of data.

The usage of multiple methods for triangulation is very important in qualitative research. Due to the nature of qualitative research, the reliability of results and research validity must be given special attention, as analysis tends to be subjective and there is plenty of room for both researcher and participant bias. For example, interview results from the industrial field study were subject to bias due to participant judgements and opinions. There were some cases where inconsistencies existed between participant answers and what the researcher believed to be the case. As multiple interviews were conducted in the companies, incorrect beliefs and judgements became apparent during comparative analysis of results. In a few instances discrepancies were noticed by the author and results became clear by member checking and other triangulation methods.

During the case studies, some participants appeared to be a bit unwelcoming and resisted the research. The lack of support from some participants is believed to have had some affect in the case studies, but it is not expected that the results were compromised in any way. Research quality could have been improved in some areas, such as the unstructured approach toward observation. Although there may have been some benefits to the informal approach adopted, upon reflection it was felt that a more structured approach may have been more suitable.

7.2.4 Fulfilment of the Research Aim and Objectives

The primary aim of this research was to construct an innovative model which supports the implementation of lean thinking in PD. The resulting lean PD model provides a staged process that enables lean thinking to be applied during the conceptual phase of engineering projects. The lean PD model is presented in Figure 5.7. Five research objectives were composed to help guide the study. These objectives will be examined in this section.

The first objective was to review lean PD approaches and examine the current state of literature on the subject of lean PD. A systematic review was carried out, analysing research trends, representations, enablers, and case studies conducted. This allowed the researcher to gain a specialist understanding of the subject and identify research gaps. Research gaps included the need to classify lean PD enablers, and the absence of methodological guidance for the implementation of lean PD in engineering projects. These gaps were addressed in the research conducted.

The second objective was to explore whether or not lean PD has a presence in industry and identify current PD challenges faced. An industrial field study was conducted to gather data from practitioners primarily through semi-structured interviews. The results presented indicate clearly that lean PD principles and practices have a presence in industry. Some of the lean PD enablers described in the literature, such as SBCE were not found to be present in industry. A variety of challenges faced by PD were identified and organised under 12 over-arching categories. The most prominent challenge appeared to be design rework resulting from poor conceptual decisions. This finding helped to steer the research to focus on conceptual design.

The third objective was to extract lean PD principles and enablers from literature and define a framework that combines them. By analysing previous research, core enablers, methods, and tools were categorised and represented in the form of a framework for lean PD enablers (Table 5.1).

The fourth objective was to develop a process model through which lean thinking can be implemented in PD. Based on the critical analysis of lean PD and SBCE in particular; a process model for conceptual design has been developed. This is referred to as the lean PD model. The model provides a workable flow of activities for a PD project that is principle-based and can also be supported by company practices. The process may also be customised for each company in which it is implemented.

The fifth and final objective was to test the model through industrial application. Two real engineering projects were used as cases to test the lean PD model. Cases included a helicopter engine, and the audio head unit for an in-car entertainment system. An action research approach was adopted to support the implementation of the lean PD model in the two cases, which resulted in a number of key findings. Both cases experienced positive results, including the enhanced consideration of design alternatives and innovation. Both companies remain keen on further implementation, and one of the companies wishes to extend the model to the rest of the organisation. It was concluded based on the case studies that the model addresses 9 of the 12 categories of challenges faced by PD in industry, and thus is very relevant to the context.

7.3 Key Research Contributions

The research presented in this thesis contributes to human knowledge in many ways. It is believed based on the author's awareness of literature related to lean PD (and the systematic review carried out), that four key contributions have been made.

1. A framework which classifies lean PD enablers has been put forward; in prior research the enablers of lean PD were scattered across various publications
2. A generic lean PD model was developed based on Toyota PD principles and practices; the model supports the implementation of lean thinking by providing a workable flow of activities for the conceptual design of an engineering project

3. A number of novel tools have been developed and implemented to support the lean PD model; these include: a project classification matrix, innovation classification diagrams, the product value model, a PD strategy matrix, the knowledge creation plan, and the concept intersection matrix
4. Challenges that are currently faced by PD in industry were captured and organised under 12 over-arching categories; the challenge categories have been used to review the relevance of the lean PD model but can be extended to other research endeavours

Additional contributions to knowledge include the following:

- Approaches towards lean PD have been categorised and reviewed; the author argues the superiority of focusing on TPDS as the foundation for lean PD
- Through an industrial field study the presence of lean PD principles and practices was ascertained; the need for generic research-based methods to support the implementation of lean PD enablers, as well as integrated lean PD approaches was also uncovered
- The lean PD model has been tested on two live case study projects; the cases provide rich qualitative descriptions and analysis which is likely to benefit future applications of lean PD in industry; this case-based research shows that Toyota principles and practices when combined can have positive results on the local environment

7.4 Implications for Practitioners

Researchers and practitioners have approached lean PD in different ways. None of the approaches are wrong. But focusing on TPDS and taking a comprehensive 'systems' approach may be more suitable for the development of a lean PD theory and perhaps more beneficial to industry. The lean PD model facilitates the combination of Toyota PD principles and practices with contemporary engineering best practice. The implementation of individual TPDS tools and methods is likely to have a positive impact on engineering practice; however it is the philosophy and principles of Toyota that led to the creation of these tools and methods (Ohno, 1988; Liker, 2004). Furthermore the philosophy and principles attributed to Toyota are based on the progress of engineering throughout history; from the ancient civilisations of Egypt, China, Greece, Spain, and India, to the industrial revolutions in the UK, Western Europe, the USA, Japan, and later the rest of the world.

Lean PD as a theory must go beyond TPDS if it is to be successful in the future. The lean PD model provides a staged process that enables lean thinking to be applied during the conceptual phase of engineering projects. The model can be used to guide a project, as was achieved in two cases presented in chapter 6. One of the companies that implemented the lean PD model intends to extend it to the wider organisation. This symbolises the success of the model in practice, and companies are welcome to test the model further.

Based on this study, a number of lessons have been learnt which would benefit future implementation of the lean PD model. Firstly, organisational support may be key for successful implementation on projects, including the backing from senior management. Project leaders must be committed to the convergent approach so that sufficient resources and time are allocated for ideation, innovation, and analysing and testing alternative design solutions. This may also require some incentives so that engineers do not backtrack to point-based approaches. Rushed subjective decisions should be avoided, but a balance between subjective and objective decisions is acceptable.

Companies wishing to trial the lean PD model should experiment with a number of flexible projects before applying the model on projects with tight schedules. Implementing the model on modular designs is simpler than functional builds, but complex applications are not unsuitable. As the understanding of the process matures the model can be tested on more demanding projects. Standard quality gates or design reviews may be used to assess project progress but some shift in criteria and timing will probably be required. Dedicated cross-functional project teams can be instrumental in implementation of the lean PD model, as was noted in this study.

7.5 Suggestions for Future Research

Based on the findings from this study, a number of suggestions are put forward for further research.

First of all, it is recommended that the lean PD model is tested through further implementation in industrial cases through action research. The lean PD model is expected to produce various benefits and such research will help to refine the model further.

Secondly, research is required to extend the application of lean thinking to detailed design and the rest of the product lifecycle. In this research conceptual design was the focus, and it is suggested that future research should focus on specific areas of the product lifecycle while keeping other engineering activities and disciplines in mind.

Thirdly, research undertaken to combine lean PD and lean production (or manufacturing) is highly recommended. The lean PD model does address this to some extent, but the combination with lean production is expected to be synergistic.

A fourth area of research that requires attention is obliging ideation, innovation, analysing and testing alternatives, and convergence. The motivation of designers and engineers, controlling projects, communication between design teams and participants, and leadership towards correct implementation of SBCE are elements for further study. A framework for balancing between subjective and objective analysis and decisions would also prove helpful to this process.

A number of research gaps were identified during the literature review, but were not specifically addressed in this research. These include: the interaction between lean PD and other PD approaches (e.g. systems engineering), the suitability and impact of TPDS enablers, and cultural implications of the various Toyota PD principles and practices. All of these gaps are suggested for further research.

7.6 Conclusions

The intellectual proposition in this study was that engineering product development (PD) could benefit from the application of lean thinking. This claim has been made by a number of academics, but prior research focuses on principles and rationale, as opposed to methodological development. In order to substantiate this claim methodological research was required to determine how lean thinking should be applied to PD. A model to support the application of lean thinking in PD has been constructed and tested in this research. The main conclusions from this research are:

1. Lean PD has been approached in different ways, however, lean PD should refer to PD theory based on Toyota PD principles and practices
2. Conceptual design appears to be where Toyota PD is unique through the set-based concurrent engineering (SBCE) process
3. The five core enablers of lean PD are the process of SBCE, chief engineering technical leadership, value-focused planning and development, a knowledge-based environment, and a continuous improvement culture
4. For PD models to be effective they should be simple, flexible, enabling, and not coercive
5. Lean PD principles and practices have a presence in industry, however some lean PD enablers, such as SBCE were not found to be present as described in the literature
6. By implementing the lean PD model, design rework is expected to be reduced
7. Practitioners were initially sceptical about lean PD principles and practices, however the lean PD model was effective in communicating and facilitating a different approach
8. The application of lean thinking in the conceptual phase of PD addressed various industrial challenges including customer value, communication, and innovation

The conclusions presented above are based on research results presented in chapters 3, 4, 5, and 6. Conclusions 4-8 are reflective of the specific companies involved in the research; however it is likely that they are extendable to other engineering applications as well.

Although the focus of this research has been on engineering and in particular PD, the theory could benefit the development of systems in general. It is hoped that this study will contribute to future research and in turn benefit the world.

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APPENDICES

Whilst Heading 1 to Heading 6 can be used to number headings in the main body of the thesis, Heading styles 7–9 have been modified specifically for lettered appendix headings with Heading 7 having the ‘Appendix’ prefix as shown below.

Appendix A Automotive Industry Articles

A.1 Article 1: Toyota quarterly profit quadruples on recovery

By Yuri Kageyama (Tokyo)

The Associated Press May 9, 2012, 07:09AM ET

Toyota's January-March profit more than quadrupled to 121 billion yen ($1.5 billion), and the automaker gave upbeat forecasts, marking a solid recovery from a sales plunge caused by a tsunami in Japan.

Japan's No. 1 automaker forecast Wednesday its profit soaring to 760 billion yen ($9.5 billion) for the fiscal year through March 2013, after plunging 30 percent to 283.6 billion yen ($3.5 billion) for the year ended last month.

The annual results were better than the company projection for a 200 billion yen ($2.5 billion) profit, as well as the FactSet estimate at 279 billion yen ($3.49 billion) -- a sign of a turnaround from last year's tsunami that hobbled Toyota production around the world.

Toyota's profit for January-March the previous year had been dismal at 25.4 billion yen because of the damage from an earthquake and tsunami that hit March 11, 2011. The flooding in Thailand, which disrupted supplies, added to the decline.

Toyota President Akio Toyoda acknowledged the hardships, but also pointed to the strong yen, which erodes the overseas earnings of Japanese exporters like Toyota.

"Our vision is to establish a strong business foundation that will ensure profitability under any kind of difficult business environment," he said.

"But thanks to the concerted efforts of our employees, suppliers and dealers, we were able to recover production and sales faster than anticipated and achieved a strong result."

Toyota, which makes the Prius hybrid, Camry sedan and Lexus luxury models, saw its vehicle sales grow in Japan, Europe and Africa, although not North America. However, it is regaining market share there.

Toyota is expecting to sell 8.7 million vehicles this fiscal year, 1.3 million more vehicles than the nearly 7.4 million vehicles sold for the year ended March.

The rise in gas prices and concerns about global warming are major plus factors for Toyota and other Japanese automakers that excel at producing compact fuel-efficient models.

Toyota's image suffered in North America over a series of massive recalls since 2009, and its USA sales fell last year. But its sales and market share in the USA have almost recovered.

"It's no secret that Toyota had a tough year last year due to the production fallout from the Japanese earthquake. In the last few months though, Toyota has made big strides to regain the USA market share it lost to its competitors," said Edmunds.com senior analyst Jessica Caldwell.

But she warned Toyota needs to keep coming up with new products to maintain its recovery momentum amid intense competition.

Toyota faces an increasingly powerful Hyundai Motor Co., a resurgent General Motors Co. and Volkswagen AG, which remains hard to beat in key growth markets such as China.

Toyota's sales for the fiscal year ended March 31 totaled 18.58 trillion yen ($232 billion), down 2 percent on-year.

January-March sales rebounded to 5.7 trillion yen ($71.3 billion), up 23 percent from 4.6 trillion yen the same period a year ago.

The comeback at Toyota is playing out at other Japanese automakers.

Last month, Honda Motor Co. reported its January-March profit jumped 61 percent on robust car and motorcycle sales, and forecast record global sales of 4.3 million vehicles for this fiscal year.

Toyoda, the grandson of Toyota's founder, vowed to lead a full turnaround, promising a range of products targeting emerging markets, in addition to established markets.

"In recent years, we have suffered periods of hardship," he said. "This year, I am determined to show tangible results."

Toyota shares closed unchanged at 3,145 yen ($39) in Tokyo, shortly before earnings were announced.

AP Auto Writer Tom Krisher in Detroit contributed to this report.

A.2 Article 2: Record Profits, but Still Mixed Success at GM

By Diane Brady

July 22, 2012 11:28 AM EDT

The term "record earnings" tends to enhance the mood of all who hear it. On one level, General Motors' record annual profit is clearly good news. America's largest automaker earned $7.6 billion on $150.3 billion in sales in 2011, just two years after taxpayers bailed it out. Moreover, its once-weak compatriots in the USA auto sector—Ford Motor and Chrysler Group—reported profits for the year, as well. That's the first time the Big Three, as old-timers fondly call them, have all been profitable since 2004.

But those profits have come at a cost. After years of watching companies build up cash even as the overall economy was in decline, Americans know all too well that the bottom line is only part of the picture. Not only has GM won back its financial health by closing plants and reducing wages, it's not yet thriving in some areas that matter.

Consider what's happening on the actual assembly line. While sales rose across the board, Americans bought only about 12.8 million cars and trucks last year. That's quite a comedown from the industry average of 16.8 million in annual sales from 2000 to 2007, according to researcher Autodata. The good news is that GM was able to boost its total while also reducing the incentives needed to get people to buy. But it still made less profit per vehicle, as Americans bought fewer high-margin trucks, and GM lost market share from December through January.

For most Americans, the bigger concern is jobs. The Center for Automotive Research has estimated that more than a million jobs were saved by the USA auto industry bailout. The actual number of workers once employed in the sector, though, may never return. From 2000 to 2009, the number of people employed by the auto *industry fell from 1.13 million people to 500,000. While that number is expected to creep back to more than 750,000 if sales continue to rise, the reality is many of the remaining jobs may be history.*

More important, perhaps, those jobs that do come back will pay less and carry fewer benefits. USA automakers have adopted the two-tier pay system that is also credited with helping the airline industry. New workers are being hired at $15.78 an hour, or about half the rate of those hired under older union agreements. Of course, few can argue for the sustainability of pay-and-benefit packages at two to three times that level in today's global economy. (Journalists and politicians cited autoworker pay rates as high as $75 an hour around the time of the bailout, though some $15 of that was from retiree benefits, and others dispute the calculations.) But it's a stark reminder that the auto industry is no longer a reliable ticket to a middle-class life. While GM's 47,500 blue-collar workers will now get a $7,000 profit-sharing bonus, that's a fraction of the money worker groups have lost under new contracts.

It's not just labour that's yet to experience the full fruits of GM's earnings rebound. GM shareholders, who are still waiting for shares to regain their $35 initial public offering price, might argue that what's needed now is even more cost-cutting, especially in sagging markets such as Europe. And taxpayers who opposed giving the company $50 billion in support and $15 billion in additional tax write-offs also may balk at the fact that they still face billions of dollars in losses from the bailout.

Appendix B Numbers of practitioners who contributed to the research

Table B-1Research engagements and the numbers of practitioners involved

Research engagements	No. of practitioners involved
LeanPPD Consortium members	12
Field study interviewees	37
Additional interviews not reported in this thesis	20
Participants of the LeanPPD value survey	72
Case Study 1	8
Case Study 2	50
Additional personnel from RR	10
Additional personnel from VES	3
Additional personnel from VW	3
Additional personnel from Indesit	2
Additional personnel from Sitech	3
Additional personnel for Getrag	30
Practitioners from Caxios do Sul University who attended the LeanPPD value workshop in Cranfield University, UK, January 2010	10
Practitioners who attended the LeanPPD workshop at Cranfield University, UK, September 2011	25
Practitioners who attended the LeanPPD workshop at Rey Juan Carlos University, Madrid, February 2012	30
Total	315

Appendix C The Stage-Gate® Model

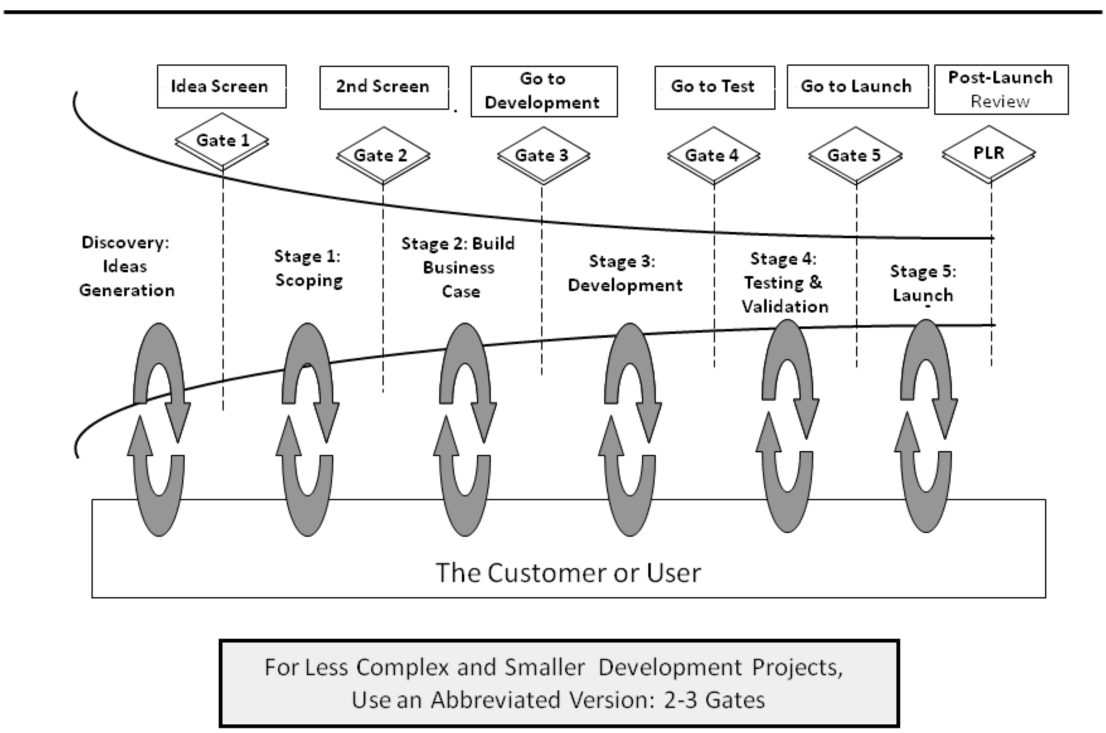


Figure C-1 A Typical Five Stage Idea-to-Launch Stage-Gate Model (http://www.stage-gate.com/newsletter/images/Figure-1.png)

N.B. Loops indicate a series of design-test-feedback-and-revise iterations

Appendix D Product Development Model Example

Figure D-1 Example of a product development model with stages, activities, and checkpoints/gates (http://img.docstoccdn.com/thumb/orig/11760168.png)

Appendix E The LeanPPD Industrial Field Study Questionnaire

Semi Structured Questionnaire for LeanPPD Field Study

Grant Agreement number:	NMP-2008- 214090
Project acronym:	**Error! Unknown document property name.**
Project title:	Lean Product and Process Development
Funding Scheme:	Large Collaborative Project
Date of latest version of Annex I against which the assessment will be made:	20.02.2009
Academic Supervisor names, title and organisation:	Dr. Ahmed Al-Ashaab & Dr Essam Shehab Cranfield University
Project website address:	www.leanppd.eu, www.leanppd.org, www.leanppd.net
Authors:	Muhammad S Khan; Rahman Alam, Maksim Maksimovic; Wasim Ahmad
Start date of the project:	01.02.2009
Duration:	48 months
Responsible of the Document	Cranfield University Team a.al-ashaab@cranfield.ac.uk
Due date of deliverable	n/a
Document Ref.:	*Questionnaire for field study*
Version:	1
Issue Date:	29/February/2010

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

E.1 Product Development Process

E.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 administer 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			

E.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?)

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

E.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 engineers share some responsibility			
	A chief engineer with a team of engineers have responsibility for the entire development of a product			

E.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 & 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

E.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 with 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.)

E.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

E.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 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

E.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

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

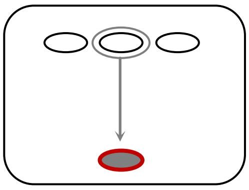
Options	
	Project initiation is dependent on customer requests and projects often run late
	Project initiation is dependent on customer requests, but projects rarely run late
	Projects start at regular intervals, but do not have consistent standard durations
	Projects start at regular intervals, have 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

E.2 Product Design

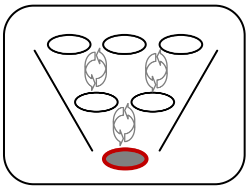
E.2.1 Which of the following tool/techniques have you formally implemented and utilise as an aid during the design of the product?

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:						

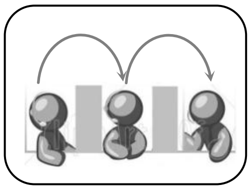
E.2.2 From the diagrams below can you indicate what method(s) of product development do you currently follow and rate its effectiveness?



Concurrent Eng



Set-Based Concurrent Eng



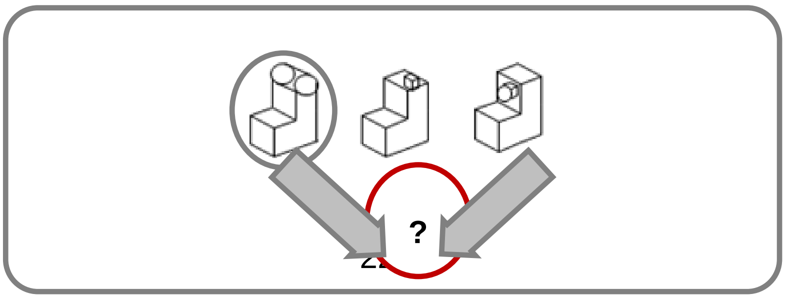
Sequential Manner

Method	**Frequency of use**			**Effectiveness**		
	Never	*Sometimes*	*Always*	*Never*	*Sometimes*	*Always*
Concurrent Eng						
Set-based Concurrent Eng						
Sequential Manner						

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

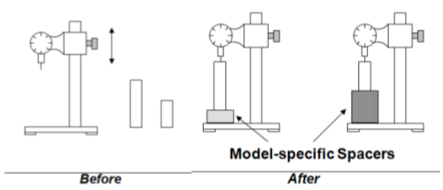
User	**Incorporation**		
	Never	*Sometimes*	*Always*
End User			
Prototyping			
Manufacture			
Assembly			
Testing			
Packaging			
Storage			
Distribution/sales			
Delivery			
Disposal			
Recycling			
Service/Maintenance			

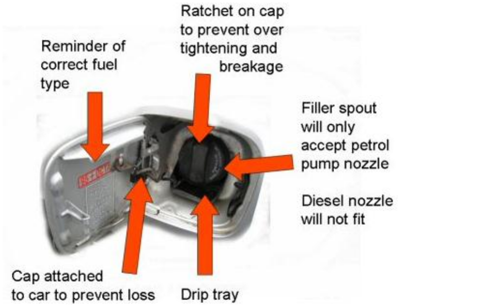
E.2.4 During concept selection which of the following criterions do you consider in reaching a final solution? (select applicable)



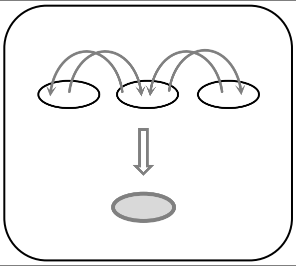
Criterions	Considerations			**Criterions**	Considerations		
	Sometimes	*Always*	*Never*		*Sometimes*	*Always*	*Never*
Function				Safety			
Critical to quality				Sustainability			
Durability				Ease of Manufacture			
Technology				Portability			
Cost				Enhanced Capability			
Performance				Usability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

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

Example		Consideration	
		Yes	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>Poke-Yoka (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			

E.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:*

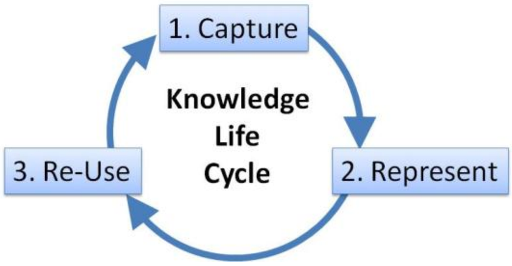
E.2.7 What sources do you use to ensure the following are considered your design? (Select applicable)

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	☐	☐	☐	☐	☐	☐	☐
	☐	☐	☐	☐	☐	☐	☐
	☐	☐	☐	☐	☐	☐	☐
	☐	☐	☐	☐	☐	☐	☐
	☐	☐	☐	☐	☐	☐	☐

E.3 Knowledge Based Engineering & Environment

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 re-used within an organisation to support engineering decisions in product design and development. These procedures are defined as a Knowledge Life Cycle.



Knowledge Capturing

E.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					

E.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					

E.3.3 Currently what are the implemented mechanisms to capture knowledge in your organisation and how efficient do you asses 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						
We have no implemented mechanisms to capture knowledge in our organisation						

Knowledge Representation and Re-Use

E.3.4 What technologies or functions are used in your company to realize that captured knowledge is re-used and shared during the product development process and how frequent it is used? In addition, do you think the knowledge content of the provided technologies are 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 judgment by Experts in your Organisation						
	Wikis						
	Web Servers / Intranet						
	E-Books						
	Reports						

E.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

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

The routine tasks are standard and done for all products; as most of the product 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.

E.3.6 Please estimate in percentage how much of your work is related to routine or innovative Tasks?

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

E.3.7 Please estimate how much, in percentage, do you rely on knowledge from previous project when designing a new product? *(Select one)*

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

E.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			

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

	Importance		
Activities	*Not Important*	*Important*	*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			

E.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		

E.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				

E.3.12 How and which of the following data is stored at your company for a specific product during the entire product life cycle? *(If used select one or multiple 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							

E.4 Cost Estimation

E.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)

E.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*			

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

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			

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

Finance personnel	
Design engineers	
Cost engineers	
Other	

E.5 Additional Questions

E.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

E.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 passed optimised designs that require significant modification or redesign?

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

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

E.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

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