CRANFIELD UNIVERSITY

MOHAMMAD ALI SARKANDI

DEVELOPMENT OF A COST REDUCTION METHODOLOGY FOR START-UP SMES DEVELOPING A NOVEL PRODUCT

SCHOOL OF AEROSPACE, TRANSPORT AND MANUFACTURING

PhD THESIS
Academic Year: 2011 - 2017

Supervisor: Dr. Paul Baguley and Prof. Ashutosh Tiwari
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This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

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ABSTRACT

This thesis is concerned with identifying cost engineering requirements of start-up SMEs in the manufacturing sector and developing a solution to address a number of their major requirements. The focus of the thesis is on cost reduction at the product development stage of a novel product. The aim of the thesis is to develop a cost reduction framework for SMEs developing a novel product in order to transfer necessary cost engineering knowledge to an SME in a structured way.

A literature review has been completed to identify potential areas for cost reduction and build an understanding of SMEs' characteristics in cost engineering requirements. The review confirmed the finding that SMEs lack cost engineering knowledge. Therefore, cost reduction best practices were identified through literature review and analysed for relevance for SMEs.

Collaborating with a start-up SME developing a novel product helped to identify SMEs cost engineering requirements. By close observation and participation of the SME, areas lacking knowledge were identified. In addition, potential cost reduction opportunities were examined. Due to the nature of cost reduction activities, it was required to study day to day activities of the collaborating company and become familiarised with development, production and business plans for the product.

The identification of the requirements and development of the AS IS model of the SME helped to build an understanding of characteristics and requirements of start-up SMEs. Based on these the cost reduction framework was developed. The framework includes best practice tools and methods which comply with start-up SMEs' characteristics. Where a suitable method could not be identified, the method was developed in this research to address their requirements.

The framework was implemented in the collaborating company and was validated by presenting the results to internal and external experts from industry and academia. Keywords: Start-up SME, Cost Engineering, Manufacturing, Novel product, production cost

ACKNOWLEDGEMENTS

I would like to express my special appreciation and thanks to my supervisors Dr Paul Baguley and Professor Ashutosh Tiwari for their guidance, support and encouragement throughout the project and also I would like to thank Professor Shehab for supporting me through the viva.

I also wish to thank Samad Power ltd for supporting this research and the management team, especially Dr Seyed Mohseni and Dr Esmail Najafi for their support and guidance.

Finally, a special ‘thank you’ to my wife Fatemeh who has supported and encouraged me in all the steps of my PhD and to my lovely son Hossein, who is a great inspiration for me in life. I am extremely grateful to my parents, Ahmad and Fahimeh, who have inspired, encouraged and supported me in all the stages of my life.

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LIST OF ABBREVIATIONS

AACE	Association for the Advancement of Cost Engineering
ABC	Activity Based Costing
ACS	Assembly Cell System
AHP	Analytical Hierarchy Process
ALB	Assembly Line Balancing
ALS	Assembly Line System
ANP	Analytic Network Process
BHN	Brinell Hardness Number
CAD	Computer-aided design
CEF	Cost Estimation Formulae
CEO	Chief Executive Officer
CER	Cost Estimating Relationship
CERT	Carbon Emission Reduction Target
CES	Cambridge Engineering Selector
CHP	Combined Heat and Power
CIM	Centres for Innovative Manufacturing
CNC	Computer numerical control
COTS	Commercial off-the-shelf
DECC	Department of Energy and Climate Change
DFA	Design for assembly
DFM	Design for Manufacturing
DFMA	Design for Manufacturing and Assembly
EPSRC	The Engineering and Physical Sciences Research Council
FA	Function Analysis
FAST	Function Analysis System Technique
FCS	Flexible Cell System
FEM	Finite Element Method
FW	Fixed Worker
GALB	General Assembly Line Balancing
GDP	Gross Domestic Product
GT	Gas Turbine
HEX	Heat Exchanger

ICMR	International Conference on Manufacturing Research
IDEF	Integration DEFinition
IMRC	Innovative Manufacturing Research Centre
ISO	International Organization for Standardization
JLR	Jaguar Land Rover
LCC	Life-cycle Costing
MAS	Manufacturing Advisory Service
MBA	Master of Business Administration
MCDM	Multi-Criteria decision making
MOST	Maynard operation Sequence technique
MTM	Methods-Time Measurement
NASA	The National Aeronautics and Space Administration
NPD	New Product Development
OEM	Original Equipment Manufacturer
PCE	Product Cost Estimation
PhD	Doctor of Philosophy
PRIMA	Process information map
PST	Parallel Single Task
QC	Quality Check
QFD	Quality function deployment
R&D	Research and Development
RBV	Resource-based view
SALB	Simple Assembly Line Balancing
SAVE	Society of American Value Engineers
SCAF	Society for Cost Analysis and Forecasting
SEER-MFG	Software Evaluation and Estimation of Resources – Manufacturing
SME	Small to Medium Enterprises
SMED	Single Minute Exchange of Dies
SPLP	Simple Plant Location Problem
SST	Serial Single Task
TC	Target Costing
TGB	Turbo Green Boiler
UK	United Kingdom

V&V	Validation and Verification
VA	Value Analysis
VDD	Value-Driven Design
VE	Value Engineering
WW	Walking Worker
XPat	eXpert Process Knowledge Analysis Technique

1 INTRODUCTION

1.1 Research background

Small and Medium sized Enterprises (SMEs) are an important part of a country's economics and contribute the most to a country's economic growth. Improving SMEs will improve the recovery of the whole economy. In 2017, 5.7 million SMEs have been active in the UK which form over 99% of UK businesses (Rhodes, 2017). SMEs contribute to 54% of the economic added value and account for 54% of employment in the private non-financial sector (Muller et al., 2015). In the UK, "37% of SMEs are active in high-tech manufacturing and knowledge intensive service sectors which are considered key for the future competitiveness of the country" (European Union, 15/10/2012).

In 2008, a great worldwide recession happened which was caused by a financial crisis in the US. "The UK economy went into recession during the second quarter of 2008 based both on declines in output and increases in unemployment. In this recession the labour market was not a lagging indicator. From peak to trough, real output fell by 6.4 per cent. By the second quarter of 2010 GDP had grown 1.9 per cent from the trough" (Bell and Blanchflower, 2011). As stated by a European commission (European Union, 15/10/2012) report the SME sector in the UK "is still struggling to cope with the crisis" and "of the key SME indicators, only the gross value added is now on a steady positive trend".

An annual series of surveys among the UK SMEs is done by the IFF research on behalf of the Department of business, innovation and skills. The report is published as "SME business barometer" and assesses how well or badly SMEs are performing. The latest report states that 39% of the employers reported approximately no growth in their last year turnover, 35% reported a decrease in their turnover and 25% said they had an increase in their turnover (Department of business, innovation and skills, 10/09/2012). The survey reports that "61 per cent of SME employers aim to grow their business over the next 2-3 years. Of these SME employers, 64 per cent plan to fund this growth through using internal finance only, 12 per cent through using external finance only and 22 per cent plan to use both” and 85% considered the economy to be the main obstacles to business success (Department of business, innovation and skills, 10/09/2012).

In the current challenging economic environment Small to Medium Enterprises (SMEs) are exposed to difficult and volatile financial situations. Changes in economic conditions have direct and significant effect on these companies and can cause profit reduction and lack of investment (Chowdhury, 2011).

Due to unavailability of many resources for small companies compared to large companies, they are in need of systematic and rigorous tools to assist them managing their costs and profits. Tools which should cover several aspects of costs. Forecasting cost can help in managing costs. Accurate and complete cost estimation will help the management in managing the future of the project and help them in decision making in order to control costs (Wilkinson, 2005).

By observing the global market, it can be predicted that in the near future giant enterprises will dominate the market, lead the market and will determine business parameters such as prices. SMEs without appropriate and on time business strategic decisions and resolving issues such as cost management and market competiveness can be excluded from the market (Fassoula and Rogerson, 2003).

Zengin and Ada (2010) state that in the current market conditions, SMEs are required to evaluate and implement cost management techniques to be able to stay in the market. But in order to implement such techniques, they are in need of financial and professional support.

Currently SMEs suffer from demand shock and shortage of credit. The SMEs are more dependent on credits than large industries and they are mostly affected by direct and indirect linkage effects. Especially enterprises linked with other countries (Chowdhury, 2011).

With the financial crisis in the world and the market competitiveness tightening everyday, every company and manufacturer is trying methods to save cost and increase its profit. As the competition is increasing, purchase power is reduced and due to factors such as low labour rates, inflation and economic crisis can cause increase in costs and reduction in prices. With the continuation of this trend, profit margins will merge to zero and finally there will be a negative margin and subsequently losses for companies. By employing value improvement and cost reduction methods in businesses it would be possible to control costs and prices and so manage the profit margin (van Dam and Pruijsen, 2008).

In this project a framework is being developed to assist the start-up SMEs developing a novel product in cost reduction for their production costs. This helps them to introduce a product to the market with low price which would be a benefit in the competitive market. The framework is intended for early stages of product development cycle where over 70% of costs are determined. The methods incorporated into the framework are cost estimation, 'Make or buy' decision making, factory design and costing, and design modification for cost reduction.

1.2 Research motivation

SMEs play an important role in economics, a large degree of high-tech technologies come from SMEs (European Union, 15/10/2012). Innovation and developing a technology on its own is not a guarantee for a business success, and one of the stages towards a successful business could be the introduction of the product to the market. The SME is required to compete in the market with large companies that have larger resources and can access all sorts of expertise, whereas SMEs are limited in financial resources which limits them in obtaining different levels of expertise. This has resulted in lack of Cost Engineering knowledge in start-up SMEs.

In addition, novel products need to be able to compete in the market with older technologies or similar products which have already matured and have reached their lowest production cost. So in order to be successful in the market the new products need to be cost effective to the customers. This is a critical determinant of success in the market and shows the importance of having low cost products.

Therefore there is a clear importance in addressing these requirements in SMEs. In addition, for any solution it is important to consider the specific characteristics of start-up SMEs. There are many available tools and methods in the literature or text books, but they don't have the exclusivity of simplicity and practicality and affordability for the level required by an SME. As a result of the research, practical methods for SMEs should be gathered and the already available methods should be made more practical for SMEs. It is necessary to transfer beneficial knowledge or methods to SMEs that is unknown to them. A 'Knowledge base tool' can help by making the knowledge required by SMEs available to them. Or a decision support tool to help in decision making by providing data and knowledge.

1.3 The collaborating organisation

The project is in collaboration with Samad Power Ltd. The project has been completed with close cooperation and involvement of the company. In particular, the case studies are developed during the research intensively with the company.

Samad Power is a research and development (R&D) company active in the micro CHP sector developing a new product for the domestic market. At the start of the research project, the product is at the technology demonstration stage and was developing towards a first working prototype. At the end of the research project the company is preparing their product for certification. In addition to the development of the current product, the company is working on other versions of the product with better performance and efficiency.

The company is a small start-up company based in Milton Keynes and consists of 10 employees and categorised in the Small to Medium sized Enterprises (SME) category in terms of the size of business. The company started up with the development of a domestic micro Combined Heat and Power (CHP) product called the Turbo Green Boiler (TGB) and aims at developing cutting edge environmentally friendly products.

The company was founded by a number of engineering research students studying at Cranfield University and added other specialities including marketing and finance staff to its team.

The product being studied is a domestic combined heat and power micro turbine which is named the turbo green boiler (TGB).

As the electricity prices are increasing, people are looking for alternative ways for cheaper electricity. For example, EDF has announced that it will increase electricity price by 4.5% in November 2011. The proposed CHP is intended to reduce the household energy bill by up to 25%.

Also according to UK Carbon emission reduction target (CERT), an 80% greenhouse gas emission reduction below levels of year 1990 by year 2050 is targeted (Department of energy and climate change (DECC), 2011). Therefore the necessity of moving towards reducing CO2 emissions is considered in every aspect of life, in houses or industries. The TGB (Turbo Green Boiler) has more than 20% improvement in overall efficiency and up to 40% of reduction in Carbon emission per household.

This product consists of a gas generator which is coupled with an electric generator in order to produce the electricity needed for domestic use. In addition to the produced electricity, there is additional product functionality through the high temperature exhaust directed into a heat exchanger. This transfers the heat from the hot exhaust air to water which can provide a house with hot water and heating. The product would have a size of a conventional wall hung boiler.

An additional configuration is also considered with the possibility of having a recuperator in the system, so it could be able to reach higher efficiencies which would result in lower fuel consumption. Due to space limitations, a smaller size heat exchanger which would result in lower heat output will be used in this configuration. Recuperators are internal heat recovery heat exchangers to improve electric efficiency by pre heating the air going into the combustor (Soares, 2007).

The company has aimed to manufacture the TGB with lowest capital requirement and lowest production cost in order to have competitive advantage against competitor products. The company has initially chosen the strategy to use Commercial off-the-Shelf (COTS) parts for most parts of the system in order to be able to achieve this goal. Some other parts may be designed and built in-store or be manufactured externally or some parts may be both designed and manufactured externally. The strategies will be evaluated and validated during the research project.

The company has mainly consisted of members with engineering background and benefits highly from their technical knowledge. The management of the company have engineering backgrounds and include an MBA degree. Due to limited financial resources, each member performs several roles in the company. Most of the work of the company is done in a workshop, consisted of different test rigs, tools and a monitoring computer with different sensors connected to it to be able to monitor different properties such as temperatures and pressures during tests.

The company is currently developing a working prototype. Different layouts and different types of parts are tested to reach an optimum working prototype producing the required amount of heat and electricity.

1.4 Research Aim

SMEs lack Cost Engineering knowledge and are in need for Cost Engineering knowledge to be transferred to them in the form of state-of-the-art tools and methods. Therefore, the research aim is as follows:

To develop a cost reduction tool for SMEs in the product development sector developing a novel product

1.5 Thesis structure and Summary

In this section, the thesis structure is presented and the chapters and contents of the final thesis chapters are discussed. The structure of the thesis is presented in Figure 1-1.

The first chapter of the thesis is an introduction to this thesis with the presentation of the background of the thesis title. A section is dedicated for introducing the collaborating company which includes a background about the company and explanation about their product.

Chapter 2 contains the results of a state of the art literature review. This chapter is structured according to the topics covered in this thesis and each main topic includes relevant sub-topics where more detailed study was required. At the end of the chapter findings of the literature review and discovered knowledge gaps are discussed.

In Chapter 3, the reader is introduced with the objectives of the research. In addition, the research methodologies used to fulfil the objectives are discussed. This chapter gives an overall view of the research strategy followed to reach the aim of this thesis.

The framework development is discussed in detail in Chapter 4 and the following sections in this chapter follow the steps to satisfy the objectives for the framework development.

The final Chapters 5 and 6 are validation and discussion which are written to fulfil the academic value of the thesis. The steps taken to ensure the validity of the findings and results of the thesis are discussed in Chapter 5. Then the findings are discussed in Chapter 6. How the findings contribute to knowledge is also discussed in this chapter. The research limitations are another topic discussed in this chapter.

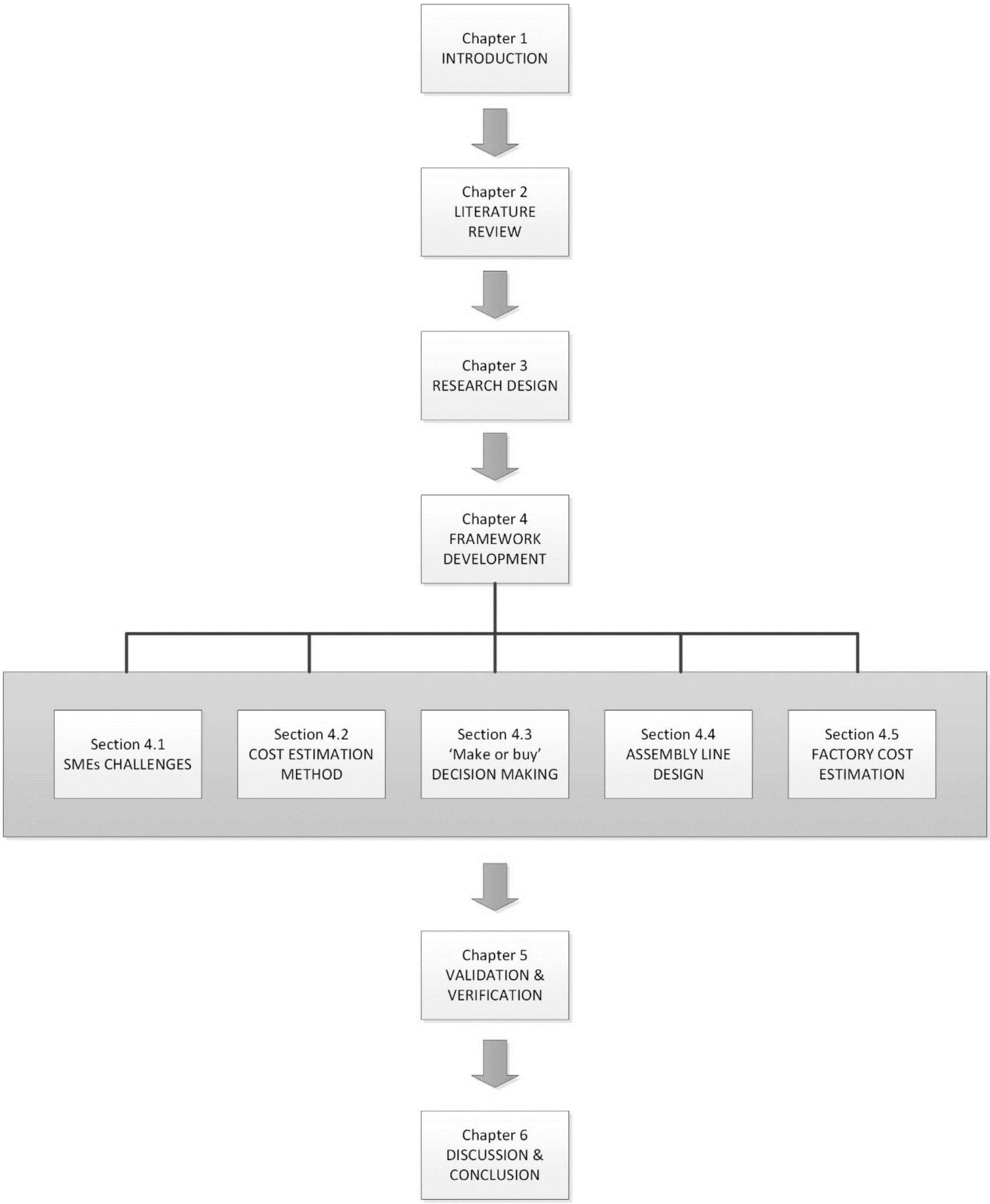

Figure 1-1 Thesis structure. Chapter 4 is divided into 5 sections based on the thesis objectives

2 LITERATURE REVIEW

2.1 Introduction

This chapter presents the literature review done for the main areas covered in this research with the focus on key subject of SMEs related cost engineering. The purpose of the literature review is to first develop an understanding of the main subject by exploring the published knowledge and identify what has been done and what has not been done in relation to cost engineering for SMEs and identify best practice methods and tools and state of the art methods that can to be used in the developed framework. Part of each section in this chapter has been allocated to outlining the ideas and theories related to the section topic and part of it is a critical review and evaluation of studies relevant to the section topic.

2.2 Literature review strategy

For the literature review, different books and papers from different areas were reviewed. The total number of references reviewed is over 250. The search was done through a number of electronic resources including Scopus, Web of knowledge and Google scholar. In order to have an effective search some keywords related to the research area had to be selected. The keywords were selected based on the specific area of review and the review was started with more general keywords and in order to focus the search results, more specific words were added to the general keyword.

The literature review process is illustrated in **Error! Reference source not found.**. The process was done after the subject area selection by keyword identification. The identification of keywords was done using three sources. The first source was self-brainstorming, using own knowledge of the researcher. The other source was mapping the field and identification of most used keywords of the field and the final source was consulting with supervisors and research colleagues. The next step was searching for keywords in Scopus, by reading through the title of the articles; the appropriate articles were opened in new tabs in the browser. Then by going through the opened articles in more details and reviewing the abstracts, the related articles were selected and the complete version of the article was downloaded into the relevant subject folder on the computer. If a full version was not available through Scopus, other data bases were checked for availability of the article. The final database to be checked was Google Scholar, which would obtain copies of one article in different websites. As searching for some keywords would result in a large number of results, the results should be filtered for optimum result. Filters such as subject area, document type and Source title were used. During the search, articles written after year 2000 were mostly targeted, apart from cases where basic knowledge and background reading of a specific subject was sought.

International Journal of Advanced Manufacturing Technology, International Journal of Production Research, International Journal of Production Economics, Computers and Industrial Engineering and Computers, Industrial Engineering, International Journal of Computer Integrated Manufacturing and International Journal of Productivity and Quality Management are among the important journals publishing articles in relevant research areas.

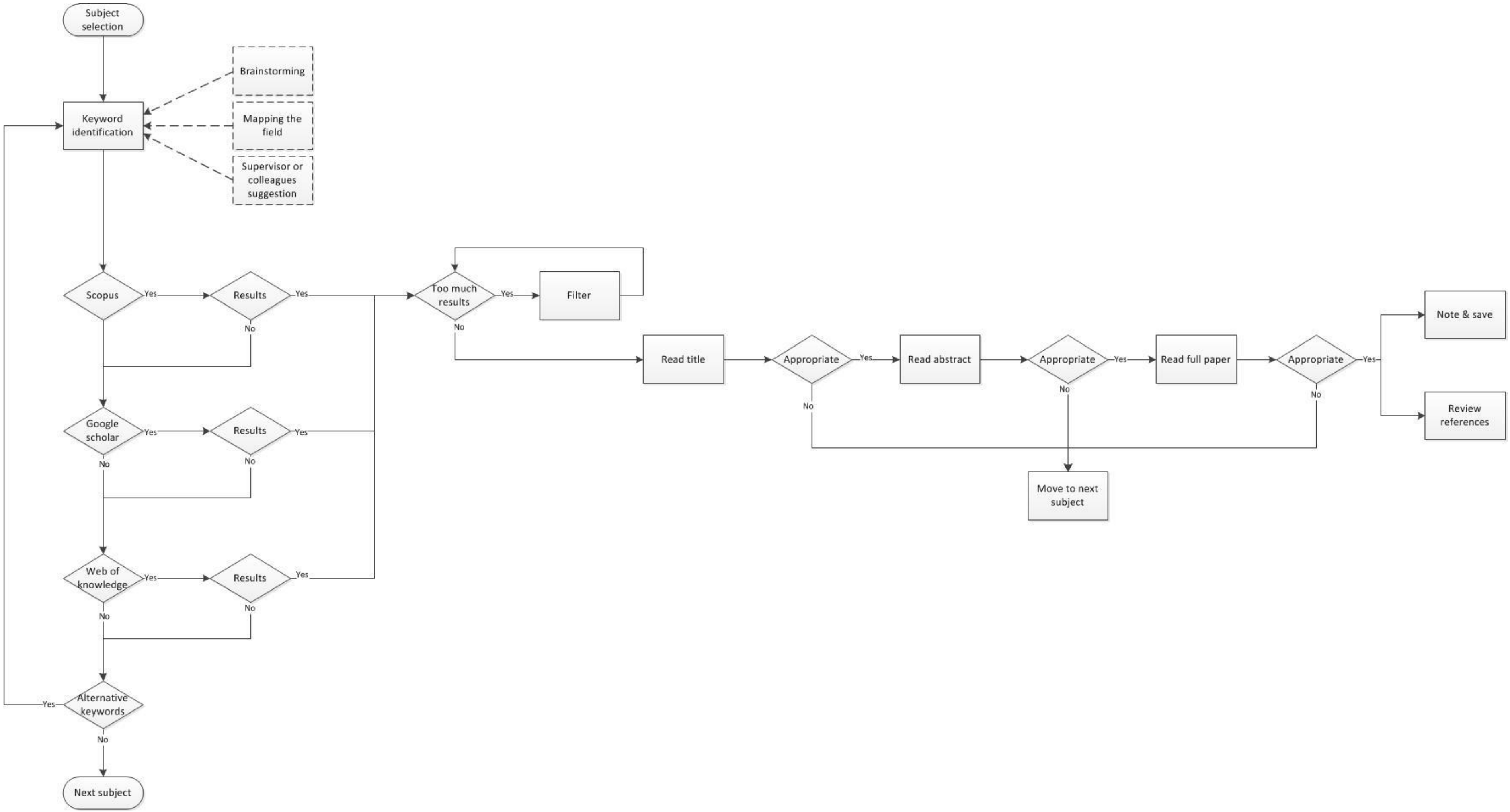

Figure 2-1 Literature review process

Some groups and universities have significant contribution to research in manufacturing and cost engineering. University of Bath, University of Southampton, Durham University, University of Manchester, University of Cambridge, Loughborough University and Cranfield University are among these groups in the UK. SAVE international, SCAF, ACostE and AACE international are some UK and international bodies that contribute to Cost Engineering research by mainly holding conferences and publishing papers.

The main research in the UK in the area of manufacturing and cost engineering was funded by EPSRC under the Innovative manufacturing research centres (IMRCs) program. A total of 18 centres at universities across UK were funded under this scheme until 2009. Figure 2-2 shows the centres and the area that they contribute to. It has to be mentioned that the figure was created in 2006 and other universities were added to IMRCs.

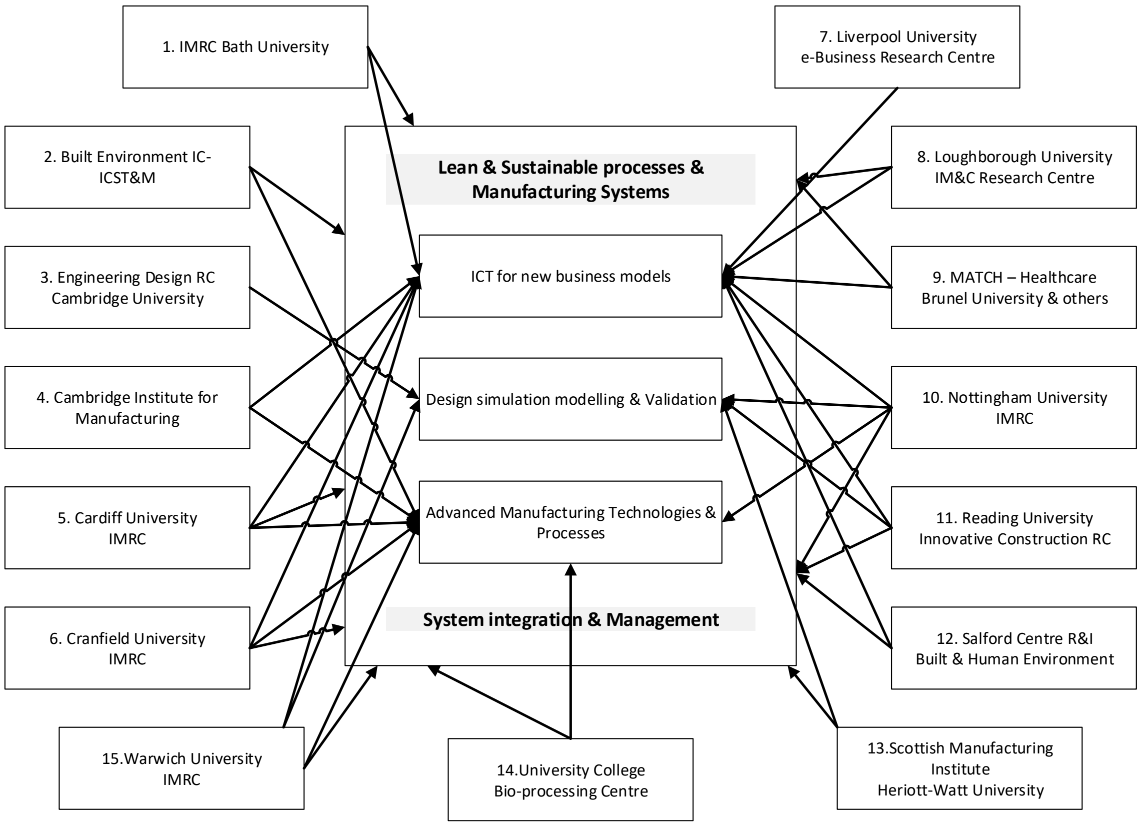

Figure 2-2 Innovative manufacturing research centres (EPSRC, 06/06/2006)

From 2009 onwards the funding model has changed and EPSRC centres for innovative manufacturing have been created. The change has happened to meet the changing business requirements. “There are now 16 EPSRC Centres for Innovative Manufacturing (CIMs) spread across the UK, tasked with enabling the commercial development of the key discoveries in university manufacturing research” (EPSRC, 10/2016). The centres focus on 16 specific manufacturing areas of composites, industrial sustainability, Emergent Macromolecular Therapies, Medical Devices, Photonics, Large-Area Electronics, Liquid Metal Engineering, Intelligent Automation, Additive Manufacturing, Advanced Metrology, Food, Continuous Manufacturing and Crystallisation, Laser-based Production Processes, Regenerative Medicine, Through-life Engineering Services and Ultra Precision (EPSRC, 2015).

The first step in the literature review was to identify the significant research areas related to the project topic and to identify what is state of the art. This area discovery formed different mind maps, so that each mind map covers a general topic of the research. These areas which have been explored using mind maps are Cost estimation models, life cycle cost, value driven design, manufacturing processes, factory simulation and simulation and Make or buy. The areas have been chosen as general topics related to Cost Engineering and SMEs for a broad argument to start an exploratory literature review and focus the research to the final aim. The mind maps are shown in Appendix B.

In Table 2-1 the subject areas reviewed and the number of references for each area is presented:

Table 2-1 Literature review subject areas and references quantity

Subject area	No. of Lit. materials
Standardisation	4
Activity based costing	7
Analogy-based cost estimation	2
Assembly line design	12
DFMA	2
Facility location	14
Factory cost estimation	3
Factory design	9
FAST	1
Integrated estimation methods	3
Integration cost reduction methods	6
Make or buy decision making	45
Manufacturing & cost estimation tools	5
Parametric cost estimation	4
Product cost estimation	20
Single minute exchange of die	2
SMEs	9
Target costing & Value engineering	10
Value-driven design	8

The literature review section is structured as following:

- SMEs and their important role in economics
- SMEs characteristics and requirements
- Methods to address SMEs requirements
- Conventional cost reduction methods
- Cost estimation methods and tools
- Make or buy decision making and outsourcing
- Factory design and cost estimation tools

2.3 SMEs

In this section, findings about SMEs characteristics in research literature are demonstrated and it is shown that why SME require help in terms of Cost engineering.

SMEs form 99.6% of UK's businesses and contribute to 49.5% of the economic added value and account for 54.3% of employment in the private non-financial sector. "37% of SMEs are active in high-tech manufacturing and knowledge intensive service sectors which are considered key for the future competitiveness of the country" (European Union, 15/10/2012).

As stated by a European commission (European Union, 15/10/2012) report the SME sector in the UK "is still struggling to cope with the crisis" and "of the key SME indicators, only the gross value added is now on a steady positive trend".

An annual series of surveys among the UK SMEs is done by the IFF research on behalf of the Department of business, innovation and skills. The report is published as "SME business barometer" and assesses how well or badly SMEs are performing. The 2012 report states that 39% of the employers reported approximately no growth in their last year turnover, 35% reported a decrease in their turnover and 25% said they had an increase in their turnover (Department of business, innovation and skills, 10/09/2012). The survey reports that "61 per cent of SME employers aimed to grow their business over the next 2-3 years. Of these SME employers, 64 per cent planned to fund this growth through using internal finance only, 12 per cent through using external finance only and 22 percent planned to use both" and 85% considered the economy to be the main obstacles to business success (Department of business, innovation and skills, 10/09/2012).

In the current challenging economic environment Small to Medium Enterprises (SMEs) are exposed to difficult and volatile financial situations. Changes in economic conditions have direct and significant effect on these companies and can cause profit reduction and lack of investment (Chowdhury, 2011). In the world's current financial situation where many of the top global companies have difficulty in just surviving and a high number of redundancies are observed daily, SMEs are fighting with many problems and without governmental aid and without special help they cannot survive.

By observing global market, it can be predicted that in the near future giant enterprises will dominate the market, and will lead the market and will determine business parameters such as prices. SMEs without appropriate and on time business strategic decisions and resolving issues such as cost management and market competiveness can be excluded from the market (Fassoula and Rogerson, 2003).

Zengin and Ada (2010) state that in the current market conditions, SMEs are required to evaluate and implement cost management techniques to be able to stay in the market. But in order to implement such techniques, they are in need of financial and professional support.

Due to unavailability of many resources for small companies compared to large companies, they are in need of systematic and rigorous tools to assist them managing their costs and profits, tools which cover several aspects of costs. Forecasting cost can help in managing costs. Accurate and complete cost estimation will help the management in managing the future of the project and help them in decision making in order to control costs (Wilkinson, 2005).

2.3.1 SMEs from Resource-based view

SMEs can be assessed in terms of resource-based view (RBV). By reviewing definitions of resources and capabilities Hewitt-Dundas (2006) results that they comprise financial, human and organisational resources and capabilities. SMEs as well as disadvantages have advantages compared to large firms. Large firms have strengths in terms of materials, which includes economies of scale and scope, financial and technological resources etc. whereas SMEs have more behavioural strengths such as entrepreneurial dynamism, flexibility, efficiency, proximity to the market and motivation (Rothwell, 1985).

Small firms have more difficulty accessing finance than large firms due to the weakness in ‘formal technical, commercial and financial appraisals’ compared to large firms (Roper and Hewitt-Dundas, 2001). This will result in less accurate financial analysis of their business which is usually necessary for fund acquisition. “Information asymmetries and the scope for moral hazard will result in general credit rationing or market failure in the provision of finance to small firms” (Freel, 2000).

One of potential SME’s sources of finance is business angels or venture capitalists, but they prefer to invest in large firms with more developed managerial competencies (Landström, 1990).

In terms of human resources, small firms have problems in employing skilled staff (Barber et al., 1989) and will “under-invest in continual employee training relative to larger firms” (Brown et al., 1990).

Organisational resources and capabilities refer to the ability of a firm to repeatedly integrate specialist knowledge to perform a discrete productive task (Grant, 1991).

Specialist knowledge of a firm may be covered by internal resources or external resources and from other organisations such as other plants within a group, suppliers, customers, private research labs and government labs etc. which may form partnerships or short or long term contracts (Hewitt-Dundas, 2006).

Ultimately external innovation links augment the pool of new information, ideas and possibilities as well as facilitating ‘inter-organisational interactions of exchange, concerted action and joint production (Robertson et al., 1996).

For small plants in particular, the bureaucratic burden placed on small firms by government policies may act as a significant barrier to innovation and growth (Henrekson and Johansson, 1999; Storey, 1994). Where firms are unable to comply with legislative and regulatory requirements this will indicate weaknesses in the internal resources and capabilities of the organisation which will negatively impact on innovation activity and success (Hewitt-Dundas, 2006).

2.3.2 SMEs management

“In SMEs ownership, board and top management overlap, with the same people, or people from the same family, involved at all levels” (Mustakallio et al., 2002; Nordqvist and Melin, 2002). They are mostly closely held and owner-managed (Bennedsen and Wolfenzon, 2000).

The concentration of ownership and the unification of ownership and management lead to managers being subjected to less pressure from outside investors and other monitors who demand accountability, transparency and strategic renewal (Carney, 2005). Ownership concentration among the top management of the firm can lead to risk aversion and lack of willingness to engage in strategic change activities such as corporate diversification, product innovation or entering new international markets (George et al., 2005; Hill and Snell, 1988; Hoskisson et al., 2000).

Moreover, in closely held firms, owner-managers typically develop the strategy at the founding of a firm. Due to their personal involvement, this commitment to the strategy often continues over time leading to unwillingness to change the original strategy (Boeker, 1989; Kimberly and Bouchikhi, 1995).

The longer ownership is concentrated to the same individual or a limited group of individuals, the more likely it is that owners unite around the same values, interests and strategic practices (Goodstein and Boeker, 1991; Tushman et al., 1985). ‘‘Over time, owners may become insulated from environmental and performance changes and fail to perceive and react to critical environmental and organizational changes’’ (Goodstein and Boeker, 1991).

Most SMEs, however, are closely held and owner-managed and owners thus have direct and detailed insights into internal processes of the firm (Cowling, 2003). As a result, there is less need for the control function of the board and many SME boards exist on paper only (Brunninge and Nordqvist, 2004; Ford, 1988; Huse, 2000). However, there are also examples of SMEs having active boards with outside members, using the boards of directors as a means for strategy development (Fiegener, 2005; Ward, 1991).

Roberts et al. (2006) have highlighted the risks they have identified while examining SMEs in Northwest England. The risks are illustrated in Table 2-2.

Table 2-2 SMEs business risks (Roberts et al., 2006)

Environmental risks	Social risks	Economic risks
Poor public transport infrastructure	Increased health and safety regulations	Lack of affordable housing and business properties
Waste disposal – increased waste disposal costs	Supply-chain pressures – increased demand from business customers to include social issues in tendering processes	Increased regulatory environment
Increased environmental regulations	Staff recruitment and retention	Delays in payment of contracts
Litter	Cost of living increases	Imposition of tax
Lack of recycling facilities and lack of information on the benefits on recycling	Social exclusion in local communicates	Lack of enforcement of regulation
Congestion	Retail crime	Supply-chain understanding of regulations
Lack of awareness of environmental risks and opportunities	Low-level crime, anti-social behaviour (e.g., vandalism)	Lack of competitive tendering opportunities
Pollution incidents	Lack of awareness of social risks and opportunities	Lack of awareness of economic risks and opportunities
Energy use – increased cost associated with energy use	Poor reputation within the local community	Impact of globalisation on small business – international completion has increased, creating an imbalance of power
Supply-chain pressures-increased demand from business customers to include environmental issues in tendering processes	Image and profile of the sub-regions. Media imbalance which do not present the NW in a positive light	Planning regime
Lack of facilities (e.g., parking spaces) in built up areas	Increased insurance costs and postcode discrimination	Poor IT infrastructure

In a survey of SMEs in Northwest England, 31% of respondents have mentioned staff recruitment and retention as the main risk of their business and 19% have seen impact of globalisation on small businesses as the major risk. The results of the survey are shown in Table 2-3 (Roberts et al., 2006).

Table 2-3 Risks highlighted by small businesses in a survey (Roberts et al., 2006)

% Response	Risk type
31	Staff recruitment and retention
19	Impact of globalisation on small businesses
17	Increased regulatory environment
16	Increased health and safety regulations
14	Delays in payment of contracts

Roberts (2006) mentions time and resources always as constraints for small organisations.

“SME behaviour is often understood in terms of the psychological characteristics of the entrepreneur or 'owner-manager'. These characteristics are bound to vary widely depending on individual personalities and differing ownership structures” (Jenkins, 2004).

Fombrun et al. (2000) describe small businesses as social entities that revolve around personal relationships, which are often short of cash, likely to operate in a single market, who find it difficult to diversify business risk and are vulnerable to the loss of customers. The SME manager may be responsible for several business tasks at once (Freeman, 2001) and awareness of issues beyond the day-to-day running of the business may be low (Friedman and Miles, 2002). SMEs can be difficult to regulate as they are both reluctant to adopt voluntary regulation but are also distrustful of bureaucracy (Fuller, 2003), and are less responsive to institutional pressures e.g. legal, competitor benchmarking, government agencies, public and private interest groups (Gibb, 2000). Even notions linked to SMEs, such as 'community' and 'small business owner' (Goss, 1991) have become more complex (Greening and Turban, 2000) suggesting a fragmented, far from homogeneous sector operating in numerous economic spheres, in a dispersed supply chain, with differing managerial styles and ownership structures (Jenkins, 2004).

2.4 Cost Reduction Methodologies

In the world market the price and cost of products are merging together, resulting in lower and lower profit margins. This profit squeeze is a result of low cost labour being used, advances in technology and market competition. If cost and net sale price are not managed, it will result in zero profit and finally a loss (van Dam and Pruijsen, 2008).

In order to be able to survive the current situation and to still have a profitable business, prices and costs of products should be managed, and this is called profit planning. By employing various techniques it is possible to prevent profit squeeze and maintain a stable profit margin (van Dam and Pruijsen, 2008). To be able to manage profit, either cost or price or both should be managed. Most techniques focus on one of the above. There are cost reduction techniques as well as value improvement techniques. There are a number of well-known techniques in the literature and used by industry such as value engineering, target costing, design to cost and Design for manufacturing and design (DFMA). (Michaels and Wood, 1989; Boothroyd et al., 2002; Webb, 1993a)

There are three characteristics which define a product. These are product's cost, quality and functionality. For having a successful product, the level of each of these three dimensions should be at an acceptable level to the customer (Cooper and Slagmulder, 1997). In order to have the highest value to the customer, the product must have the highest level of these characteristics related to the customer requirements.

Research and experimenting has been completed on the use of several methods together in an organisation. Utilisation of general, well defined methods and using cross-functional product development approaches have helped organisation to achieve more congruence and have a more systematic organisation and save time and cost in product development.

Sharma, et al. (2006) developed a "synergistic management approach" (SMA). This method uses a combination of current methodologies as core component. Quality function deployment (QFD), Target Costing (TC) and Value engineering

(VE) are utilised to create a cross-functional product development approach in order to “maximise value creation”. This method will help to focus organisational energy to enhance the impact of various resources. The three well known methods employed in this methodology help to increase the three main defining characteristics of a product explained above. In the above research a case study of a small firm producing electronic equipment has been done. Although the method seems more effective for current product modifications and new products being developed based on previous products. For new products with no previous sale history, obtaining customer related information is a constraint.

Kumar, et al. (2006) studied integration of QFD and benchmarking. A real world study was done on a company. The combination of the two methods would result in improvement in product design and an increase in customer satisfaction which would lead to greater market share and more profitability. In the study it was shown that the combination of the two “strategic tools” has a “synergistic effect” both financially and strategically. QFD was used to design a product to maximise customer satisfaction, and benchmarking was used to identify most efficient process with lowest resource requirements (Kumar et al., 2006). From SMEs point of view, using benchmarking needs access to information related to similar products is the marker whereas in especially high technology industries most products are covered by confidentiality. Also when a novel product is involved, finding similar or close products is difficult. The author expresses the restriction for accessing internal technical information of a world class company in the paper.

Farsi and Hakimnezhad (2012) have studied the “integration of QFD technique, Value engineering and design for manufacture and assembly (DFMA) during the product design stage”. Although VE and QFD have differences in their methods, and VE uses cost reduction without lowering product quality and QFD uses increasing customer’s satisfaction for more profitability, they have been integrated in order to select an alternative to have higher value products to the customer without increase in the costs. Also DFMA was used in this process to optimise the design proposals. The results from QFD and VE processes can be used to evaluate the effect of optimisations done by DFMA on the performance and cost of the product (Farsi and Hakiminezhad, 2012). In this paper the integration of these methods have been presented in a general term and it seems that a further detailed analysis is necessary. Although the relationship and connection between QFD and VE has been presented in detail, a connection between the mentioned two methods and DFMA cannot be seen. Similar to previous methods, customer related information about the product is necessary for QFD and for a novel product; customer expectations cannot be easily obtained comparing to existing well developed products.

2.4.1 Value Engineering

Value engineering (VE) was first initiated during World War II and then it was adopted by General electric after the war. The popularity of it increased during 1960s and it was then when it first used in Britain. The use of VE was faded till late 1990s where company's competitiveness increased and an effective technique to help companies to remain in the market was required (Webb, 1993b).

In a competitive market one should provide a product or service so the value of them for the price paid is better or as good as other products and services out in the market (Webb, 1993b).

In Value engineering the functions of a system are analysed and by using creative techniques the product cost would be reduced for the same functions. This technique helps to prevent extra costs which are not related to the customer value of a product or service (Webb, 1993b).Value engineering helps with identifying the functions that are valuable to the customer and try to satisfy customers with the value of the product (Roy and Sackett, 2003).

The object of most Japanese VE programs is not to minimise the cost of product, but to achieve a specified level of cost reduction established by the firm's target costing system (Cooper and Slagmulder, 1997).

van Dam and Pruijsen (2008) have divided Value analysis (VA) into three steps:

1- Defining functions
2- Create and evaluate alternatives
3- Select best value options

The first stage in VE and VA is to define the functions of the product. Functions are what which give value to a product or service for customers. Some functions contribute more to the value for the customer than other functions. These functions are called Value drivers (van Dam and Pruijsen, 2008).

There are several defined tools for defining functions of a product or service. Function analysis (FA or function analysis system technique FAST) and QFD (Quality function deployment) are two tools used for defining functions (van Dam and Pruijsen, 2008).

For further detail about value engineering the books by (Cooper and Slagmulder, 1997) and (van Dam and Pruijsen, 2008) can be read.

Applying VE requires the involvement of multidisciplinary teams. People from design engineering, applications engineering, manufacturing, purchasing, management and even representatives from the suppliers and subcontractors should be involved (Cooper and Slagmulder, 1997).

van Dam and Pruijsen (2008) state that management approval is necessary for VA activities in a company. VA requires investment and involvement of many levels in the organisation, and without management endorsement, VA is likely to fail. Also the participant should be committed and have sufficient knowledge and power.

The points made by the above authors are applicable for medium and large firms, but for small firms with minimal people where many of the mentioned roles don't exist applying VE differs. From the point of view of availability of information, medium to large company have advantage over small firms. Small firms only produce and keep minimal data, so they require spending time to produce required data for implementing any cost engineering method. But on the other hand, SMEs have advantage in terms of ease of holding meetings and easier exchange of information and ideas due to availability of less people and physical approximation of people.

One of the steps after function analysis of VE is idea generation for finding solutions. Brainstorming is the first step in idea generation. Ideas should be assessed and ranked and then detailed solutions should be created. In order to achieve cost improvements van Dam and Pruijsen (2008) have recommended 4 standard methods. These are the six cost rules, design for manufacturing and assembly (DFMA), Single minute exchange of dies (SMED) and learning curve.

According to van Dam and Pruijsen (2008) six cost rules are:

- Eliminate the part
- Reduce number of parts
- Simplify the set up
- Make it modular
- Choose a standard solution
- Change the set up

DFMA is a combination of design for manufacture (DFM) and design for assembly (DFA). DFM means "the design for ease of manufacture of the collection of parts that will form the product after assembly" and DFA means "the design of the product for ease of assembly" (Boothroyd et al., 2002).

SMED is the popular name of Single-minute set-up. It was developed by Shigeo Shingo in 1950 and is based on performing setup operations in less than ten minutes. Two types of setups are considered in SMED, external setup and internal setup. In the former the setup is done while the machine is running and in the latter the setup is done while the machine is off (Agustin and Santiago, 1996). According to theory (Shingō, 1985), SMED consists of three stages and one preliminary stage. These are:

- Internal and external setup not differentiated
- Separate internal and external setup
- Shift internal setup to external setup
- Improve all elemental operations

Agustin and Santiago (1996) have stated that “it is evident that production flexibility has been improved with the supplication of the SMED concept. SMED had reaped us of benefits in terms of capital avoidance because of the additional capacity we gained from the reduction of setup time.”

Learning curve is one of the oldest cost reduction tools. Learning curve is based on the fact that the productivity of manual work increases as the output increases (Blocher et al., 2005).

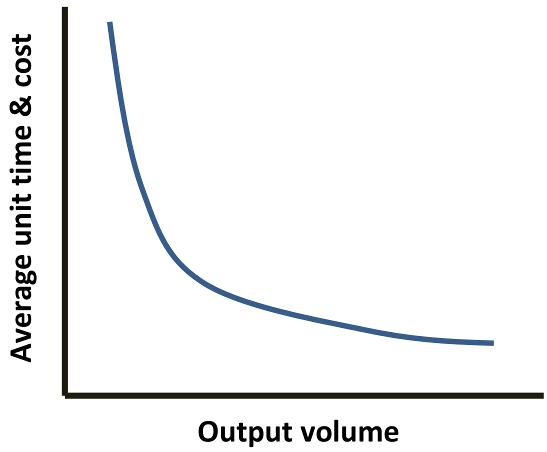

Figure 2-3 Learning curve

After creating detailed solutions, the solutions will be evaluated. Then best ideas will be selected and by doing a detailed review of the solutions, the best solution or a combination of solutions will be chosen. Finally, the outcome should be presented to the principal or the owner (van Dam and Pruijsen, 2008).

There are two phrases used in this section for the same tool. Value Analysis (VA) and Value Engineering (VE). The two are the same in terms of the methodology and tools, but the only difference is at the time they are used during the life-cycle of a product. VE is used during the product design and development and VA is used during the manufacturing and also for purchased part (Cooper and Slagmulder, 1997).

2.4.2 DFMA

DFMA or Design for manufacture and assembly is a combination of DFM which is “the design for ease of manufacture of the collection of parts that will form the product after assembly” and DFA which means “the design of the product for ease of assembly” (Boothroyd et al., 2002).

Over 70% of the final product costs are determined during design. By considering cost in the design stage, a great amount of cost can be saved (Duverlie and Castelain, 1999).

Traditionally “over the wall” design was used in businesses, and the design team had no communication with the manufacturing team. In DFMA, manufacturability and assemblability of a product is considered at design stage. So by ease of manufacture and assembly, cost reductions can be achieved. Boothroyd, et al. (2002) have stated that by considering DFMA, 40% time can be saved in design time, compared to conventional design process.

According to a reader poll (Computer-aided Engineering, June 1993) presented in (Boothroyd et al., 2002) the advantages of applying DFMA at the design stage are as following:

- Time-to-market improvements 39%
- Improvements in quality and reliability 22%
- Reduction in manufacturing cycle time 17%
- Reduction on assembly time 13%
- Reduction in part counts/costs 9%

Boothroyd, et al. (2002) also state that one of the advantages of DFMA is that it defines a systematic procedure for analysing a proposed design in terms of assembly and manufacture. “This procedure results in simpler and more reliable products that are less expensive to assemble and manufacture.” (Boothroyd et al., 2002)

In addition to the direct cost reduction gained by reduction in number of parts and simplification of parts, other related cost reductions such as reduction in number of drawings, reduction in the number of vendors and elimination of specifications that are no longer needed are achieved (Boothroyd et al., 2002).

The most important barrier for implementing DFMA is human nature of resistance to new ideas and unfamiliar tools. DFMA changes the traditional design procedures and takes more time than old design methods, but people ignore the fact that more time and cost saving can be achieved during the whole life cycle of a product.

One of the first steps of DFMA is material and process selection. Designers usually have limited knowledge about materials and processes. They tend to only consider their knowledge in the design process which would result in ignoring other possible materials and processes which would be more economical (Boothroyd et al., 2002). In order to perform materials and process selection at early concept design of new product, some general requirements are needed. General information about the new product should be provided, such as: product life volume, permissible tooling expenditure levels, possible part shape categories and complexity levels, service or environment requirements, etc. At the concept stage, an economical evaluation of the processes should be done. The estimates wouldn't be accurate due to uncertainties at the conceptual stage, but they are useful for economic comparison (Boothroyd et al., 2002).

Other DFMA step is to design a part in terms of the process and material selected for the part. The functions of different processes are different, so ease of a process won't result in ease for other processes. If a part is designed for automatic assembly, it wouldn't be efficient for manual assembly.

Selvaraj, et al. (2009) have used DFMA for parts count reduction using integration of parts and studied the impact on time and cost of manufacture and assembly. In the study it is resulted that high percentages of time and cost reduction can be achieved, mainly due to reduction in the number of parts, tooling and fabrication time and also tasks related to computer aided design.

For a novel product at the design stage, uncertainties about the design of the product and frequent design changes make applying DFMA difficult. Some products make use of off the shelf parts which would be a constraint for implementing DFMA. For any design changes to the product, the off the shelf parts should be considered as reference parts and design changes to other parts should happen by considering those reference parts.

DFMA benefits SMEs in terms of the giving them well defined process for modifying product designs to follow. DFMA has simple principles and guidelines that can be followed by designers and requires less customer or market related information compared to other cost reduction methods which would be a benefit start up small firms.

2.4.3 Target Costing

Target costing and value analysis are complementary methods.

Target costing is one of the ways to manage product costs. It is a structured approach to determine the profit goal of a certain product with a certain level of functionality and quality. By estimating the selling price of a product and knowing the profit margin, the required product costs can be obtained (Cooper and Slagmulder, 1997).

Cooper and Slagmulder (1997) present three levels in the target costing process. Market-driven costing, product-level target costing and component-level target costing.

Market-driven costing consists of studying the market for similar and competitive products, evaluating customers regarding the value of the product to them and their economic environment. These elements help to predict the market price of the products which would result in knowing its costs. In this stage the competitive pressure should be transmitted to the design team and suppliers (Cooper and Slagmulder, 1997).

In the product-level targeting, the focus is more on the product itself. An achievable target cost should be set and the product should be evaluated in order to find ways to satisfy the target cost in product-level. Cooper and Slagmulder (1997) have broken product-level target costing into three steps:

- Setting the product-level target costing
- Disciplining the target costing process by monitoring progress, applying the cardinal rule of target costing, and allowing for extenuating circumstances;
- Using value engineering and other techniques to achieve the product-level target cost.

Component-level target costing narrows the focus on components of the product. By using the achievable cost, selling price for the components will be set and transferred to the suppliers. The suppliers should find ways to meet the required selling price. Cooper and Slagmulder (1997) have divided this level of target costing into four steps:

- Set target costs of major functions
- Set the component-level target costs
- Select the suppliers for the components
- Reward suppliers for their creativity

In order to successfully implement target costing in a company, 5 criteria are defined by Khozein and Royaee (2011). These are organisational criterion, managerial criterion, environmental criterion, technical criterion and project team criterion. To have an effective target costing process in an organisation all the departments should be involved and management involvement is crucial.

For a successful target costing, a project team should be defined with representatives from all the departments including finance, technology, human resources and even all supply chain segments. Participation of an external consultant will help with effectiveness of the process. Implementing target costing would result in fewer failures in the system, as more evaluation is done on products (Khozein and Royaee, 2011).

Everaert and Bruggeman (2002) have resulted that target costing results in cost reduction of a new product if design engineers face low time pressure. If the design engineers are facing high time pressure, target costing would result in an increase in development time. Having a cost target won't have a significant result in design quality.

Zengin and Ada (2010) have explored "the role of target costing in managing product costs while promoting quality specifications that will meet customer requirements". Also Zengin and Ada (2010) have tried to simplify implementing target costing in SMEs by developing a target costing module, so SMEs are encouraged to use it. He has studied the implementation of target costing combined with QFD analysis and VE (called QFD-TC) in a small manufacturing company a company which has an assembly-oriented production and aims to survive in the market competition by managing costs using target costing, QFD and VE. Zengin and Ada (2010) have found that QFD-TC, despite being a time and money consuming and specialised process, can effectively be employed by SMEs.

Determining target cost requires market research and with the existence of similar products on the market, it is easier to determine the market value of a product. Whereas for novel products determining market value requires more extensive market research.

Zengin and Ada (2010) have implemented the method in a manufacturing SME that produces a product. The process is applied on a product under production to manage costs. For novel products lack of cost data would be an obstacle for implementing target costing.

One of the problems could be faced by SMEs applying such methods is the required cost and accounting information and databases. Lack of enough cost data requires a large amount of resources to gather the required data. For SMEs which outsource accounting tasks and lack internal accounting skills, obtaining the required data would have a great cost impact.

But on the other hand Cresse (2001) states that target costing is used by some manufacturers as a price setting process to reduce supplier cost. SMEs could also apply target costing to achieve cost reduction from their suppliers (Creese, 2001).

2.4.4 Value-driven design

“Value-driven design (VDD) is an improved design process that uses requirements flexibility, formal optimization and a mathematical value model to balance performance, cost, schedule, and other measures important to the stakeholders to produce the best outcome possible” (Value-Driven Design Institute).

“VDD optimizes all stakeholder values expressed in a single mathematical function. The function’s inputs represent attributes important to the stakeholders. Capabilities-based approaches + Robust design may augment VDD (or vice versa)” (Value-Driven Design Institute).

Collopy and Hollingsworth (2011) believe that the developed tools, methods and processes have not had any avail for the industry. Value Driven Design (VDD) is a frame work designed to assess other tools and methods against it. In VDD no directive is given to the design engineer about the cost requirements, instead a scalar function is set, so that the team’s full set of attributes is converted into a score. ”The design team’s task is to create a design that yields the highest score whilst meeting all the requirements on the non-extensive attributes” (Collopy and Hollingsworth, 2011).

According to Collopy and Hollingsworth (2011) the benefits of implementing VDD in engineering design teams are:

1) VDD enables and encourages design optimisation for the whole system during early design phases and for each component during detailed design
2) VDD prevents design trade conflicts, and thereby prevents dead-loss trade combinations
3) By eliminating requirements for extensive attributes at the component level, VDD avoids the cost growth and performance erosion caused by requirements.

In Figure 2-4 , a design process based on VDD for a system component is shown (Collopy and Hollingsworth, 2011). This cycle is scalable to components, sub-systems and a system.

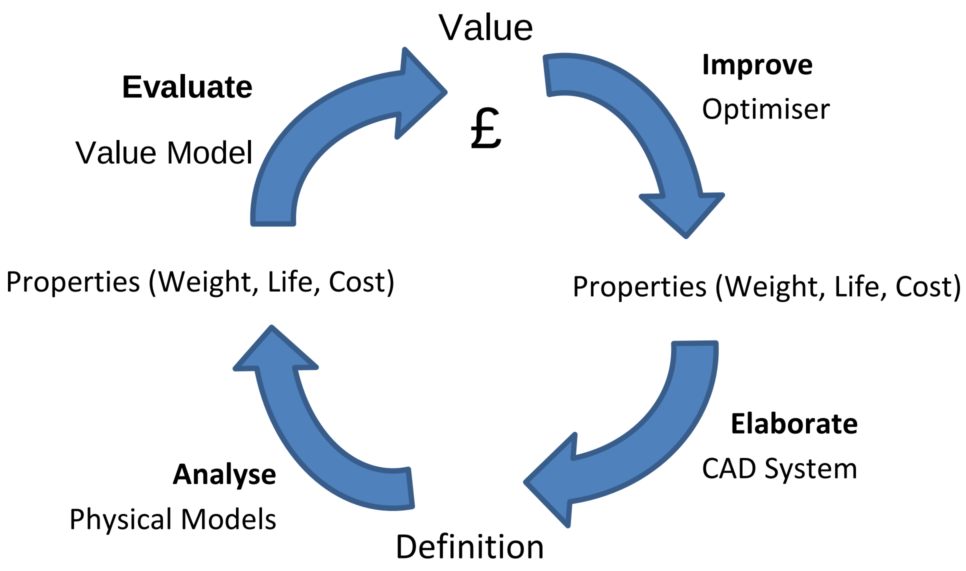

Figure 2-4 Design process based on VDD (Collopy and Hollingsworth, 2011)

Castagne, et al. (2009) have designed a methodology to implement VDD at an early design stage. This methodology was used for optimisation in design in order to achieve minimum weight, minimum manufacturing cost and maximum profit. The VDD optimisation utilised an objective function which related manufacturing cost and manufacturer’s profit.

Curran, et al. (2010) in a study have concluded that “the VDD approach simply promotes the sustained application of the main utility values that are always originally recognised and understood by the expert engineers in these world-class OEMS but which, due to the complexity of the product and enterprise, tends to be disaggregated into isolated requirements that result in a loss of control on managing the desired systemic output. Ultimately, this leads to optimisation at a sub-system level and that is especially unacceptable for a complex system”.

By reviewing research and studies done on VDD and the implementation at different industries, it can be observed that there is a lack of research on the implementation of VDD in SMEs and less complex systems and the impact on their cost and performance. It should be evaluated if this method can have any value for SMEs and whether with minimal resources it is implementable.

Meanwhile, it can be observed that the idea of VDD can be used as a general strategy in design without the need of detail implementation of the methods for SMEs.

2.4.5 ISO implementation

One of the possible cost reduction methods being studied is standardisation in companies and implementing ISO standards in a standard approach to standardisation. Ilkay and Aslan (2012), Bayati and Taghavi (2007) and Aarts and Vos (2001) have studied the impact and effect of implementation of ISO 9000 certification on the performance and costs of SMEs.

According to (International Organization for Standardization) web page “The ISO 9000 family addresses various aspects of quality management and contains some of ISO’s best known standards. The standards provide guidance and tools for companies and organisations who want to ensure that their products and services consistently meet customer’s requirements, and that quality is consistently improved”. The standard contains a set of principles and guidance including a strong customer focus, the motivation and implication of top management, the process approach and continual improvement.

Aarts and Vos (2001) have studied the effect of implementation of ISO in New Zealand firms, and the study counters the existing hypothesis that ISO certification can improve the performance of firms. One of the reasons is the cost of going through the process and registration for ISO. Also it has been seen that many ISO certifying authorities give incentive to firms to sell their service and the difficulty of issuing criteria is different between the certifying authorities.

Bayati and Taghavi (2007) observed the impact of ISO 9000 certification on firms in Tehran, Iran and the study confirms the existing hypothesis in the literature that acquiring ISO certification would improve SMEs performance. Although no significant effect of ISO implementation on cost reduction was observed in this study. Due to high cost of implementation and certification, usually all or most of the cost reduction achieved by certification would be covered by ISO costs.

By studying a survey of 255 SMEs in Turkey Ilkay and Aslan (2012) resulted that there was no significant difference between the performance of certified and non-certified companies and no direct effect on performance was seen. But in terms of quality practices, certified companies were higher than non-certified companies. Although due to high costs of implementation and certification, SMEs need to have enough financial resources and they need to perform a cost-benefit analysis before applying for certification.

By reviewing the literature, it was observed that due to high cost of implementation and certification of ISO standards, obtained cost reductions would have to be spent to cover ISO costs, although the effect of implementing ISO standards on the performance of the company, without just the aim to gain the certification could result in long term cost reduction and performance improvement effects in SMEs. It is observed that studying long term effects of implementing ISO standards requires further investigation and the effect of the intention of the firms for ISO registration on the outcome of the registration needs to be considered in the studies as well.

2.5 Cost Estimation

Cost data are the base of any cost reduction method and cost estimation methods are the main source for acquiring cost data. For any cost reduction activities, cost data are required and the initial costs of production should be known. Cost of any alternative solutions found through cost reduction methods should be known for evaluation.

It should be clarified at this stage that there is a difference between terms ‘Costing’ and ‘Cost estimation’. Cost estimation is the predicting the cost of a future process or activity like manufacturing or construction based on previous cost data or past experiences. Cost estimation requires technical knowledge. Costing is the methodology of determining actual costs of a product or service by recording and evaluating the actual incurred costs. Costing requires accounting knowledge and is usually done by accountants (Creece, 1992).

Cost estimation is to use available information to predict the cost, which this prediction might be deviated from the actual costs, but will give guidance to the designers or the planners (Ou-Yang and Lin, 1997). Cost estimation can be performed for each stage of the life cycle and a total cost estimation of the life cycle can be obtained. As mentioned earlier, over 70% of the total production cost is determined at the conceptual design stage, which shows the importance of considering cost as a design element in the early stages of the project(Duverlie and Castelain, 1999). So by correct decision making and considering cost, potentially a large impact on the cost reduction can occur.

A more specific form of cost estimation is total production cost estimate or total manufacturing cost estimate. The total manufacturing cost can be classified in different ways. They can be classified into material or production costs, or direct costs which can be directly assigned to the product, such as material and labour costs or indirect costs or known as overhead costs which are not directly associated with products such as heating and lighting of the factory or rental costs (McLaney and Atrill, 2012). Furthermore, the costs can be divided into variable costs and fixed costs. Variable costs consist of direct costs and variable overhead costs such as material cost per unit or direct labour cost, whereas fixed costs would remain constant over a period of time, costs such as set-up and tooling costs (McLaney and Atrill, 2012).

There is a general process for cost estimation. This process consists of six steps. The first step is to define the cost object. Cost object is the specific cost that needs to be estimated. The second step is to determine the cost drivers. Cost drivers are factors which affect the cost and cause changes in cost of an activity. Step 3 is collecting data about cost object and cost drivers. The data must be accurate and consistent. In the next step the data should be evaluated. The best way to assess the data is to graph them and identify unusual patterns in the graph. Step 5 is selecting and employing an estimation method. The method should be chosen according to the system conditions, the data available and the accuracy they provide and the final step is to assess how accurate the cost estimation is, considering the errors (Blocher et al., 2005).

Stewart (1995) has divided a complete cost estimation process into 12 steps shown in Table 2-4.

Table 2-4 Cost estimation steps (Stewart, 1995)

1	Develop the work element structure
2	Schedule the work elements
3	Retrieve and organize historical data
4	Develop and use cost estimating relationships
5	Develop and use production learning curves
6	Identify skill categories, skill levels and labour rates
7	Develop labour-hour and material estimates
8	Develop overhead and administrative costs
9	Apply inflation and escalation (cost growth) factors
10	Price or compute the estimated costs
11	Analyse, adjust and support the estimate
12	Publish and present the estimate so that it can be utilized effectively

To study a system two types of experiments could be done, either experiment with the system or experiment with a model of the system. There are two types of models; Physical model or mathematical model and in mathematical model we can either have analytical model or simulation (Law, 2000). For experimenting with an actual system, the system should already exist, as for this project there is no factory or product existent. A physical model is real size or scaled down model of some parts or a whole system and mathematical model is to represent a system in terms of mathematical concepts and equations. Physical modelling to study manufacturing systems is less used currently and the vast majority of models built are mathematical. If the system is simple enough that can be represented by equations and relationships and an exact answer can be obtained, analytical models would be more desirable. But there are complex systems which would have a complex mathematical model and getting an exact solution is unlikely. For modelling these systems, simulation would be used. Law (2000) defines simulation as “numerically exercising the model for the inputs in question to see how they affect the output measures of performance”. Due to the complexity of manufacturing systems, simulations are more preferable to other modelling techniques.

There are two types of models, either static or dynamic. In a static model the system is modelled in specific points and the time flow in between the components in the system is continuous, on the other hand, in a dynamic model there could be waiting times and queues at each component (Jinks et al., 2010).

Duverlie and Castelain (1999) have presented a graph of different cost estimation methods and the stages during the life-cycle they can be used. The graph is presented in Figure 2-5.

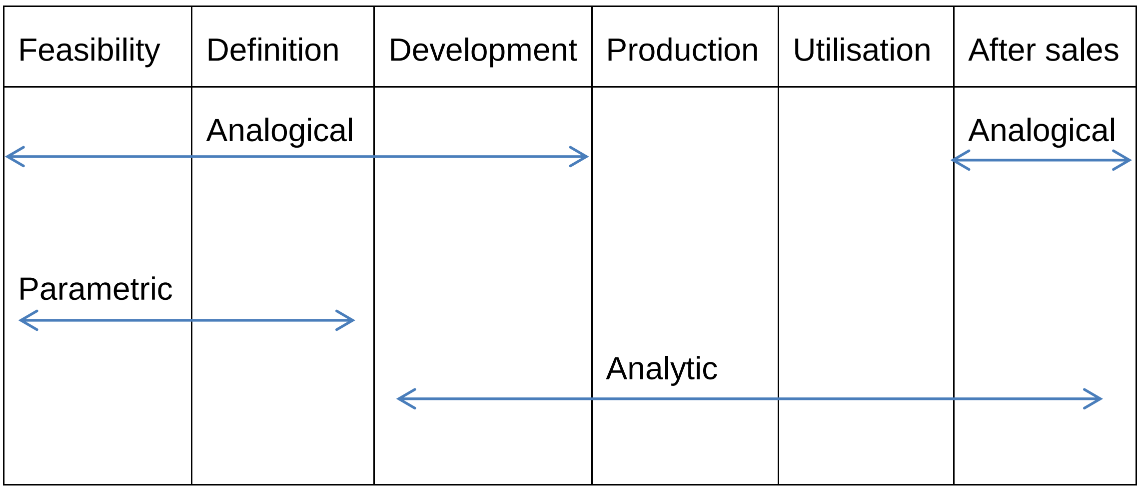

Figure 2-5 Cost estimation methods and relevance to life-cycle stage (Duverlie and Castelain, 1999)

According to NASA (2010), based on the phase of the project, NASA uses different methodologies. The methodologies that NASA examines are, parametric costing, analogy costing and engineering build up costing. Figure 2-6 shows which methodology is used for which phase:

	Pre-phase A	Phase A	Phase B	Phase C/D	Phase E
Parametric	⬭	⬭	▭	▭	⊗
Analogy	⬭	▭	▭	▭	⊗
Engineering build up	▭	▭	⬭	⬭	⬭
Legend:	⬭ Primary	▭ Applicable	⊗ Not Applicable		

Figure 2-6 Project phase and relevance to cost estimation method (NASA, 2010)

According to NASA (2010) the cost estimating process consists of three main levels which are project definition, cost methodology and estimate.

Kim, et al. (2012) have presented a diagram of critical elements needed for cost estimation which can be seen in figure 6.

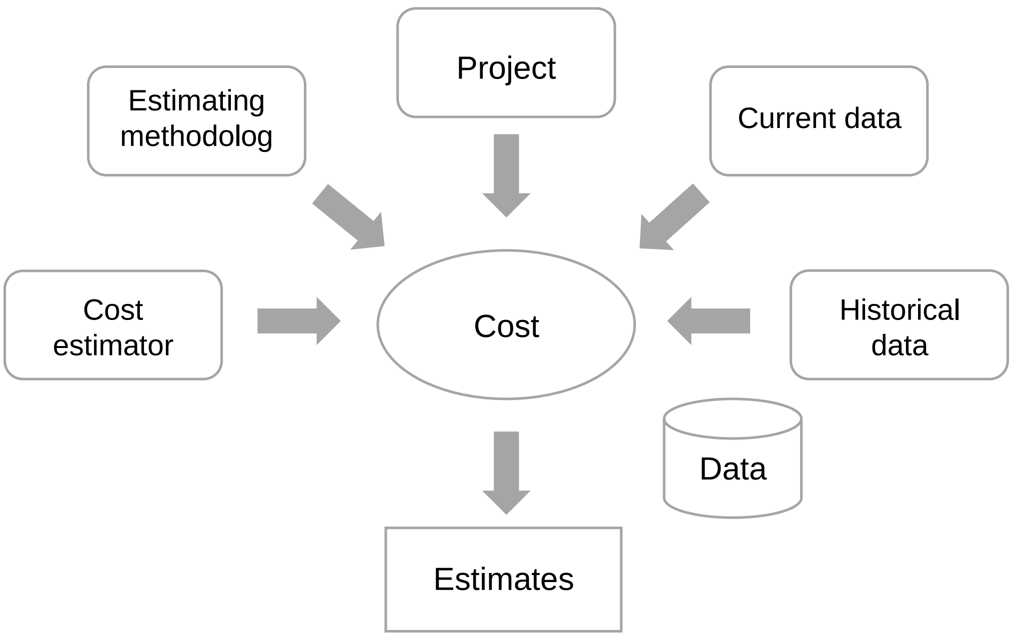

Figure 2-7 Critical elements for cost estimation (Kim et al., 2012)

Like many activities involving cost estimation, a consistent communication between the estimators and the managerial team should exist. Basic information related to the production and managerial policies for production should be known in order to be able start the estimation. This information dominates the estimation route. Output rate of the plant, shift hours, considered or possible locations, changes in output rate in future, required flexibility and production strategies are amongst the information needed to be obtained from the management. Also a continuous communication with the technical team of the company should be kept. A feedback loop should be made with the technical team in order to be able to update inputs to the tool (United States. Government Accountability Office et al., 2009).

2.6 Cost estimation Methods

There are many papers about product cost estimation (PCE) and lots of research has been done in this field. Niazi, et al. (2006) in a review of PCE techniques have categorised these techniques into qualitative and quantitative techniques. Qualitative techniques are further categorised into Intuitive techniques and Analogical techniques and Quantitative techniques are categorised into parametric techniques and Analytical techniques.

Expert judgement is a well-known method for cost estimation which is based on the experiences of the estimator. This method is one of the most widely used methods in the world although it has many disadvantages (Roy et al., 2011). This method depends on the cost estimators experience and judgement which would result in a subjective decision. The more the experience of the estimator would result in a wider cost database which would result in more accurate cost estimate. For SMEs due to lack of resources, employing an experienced cost estimation expert would be unviable, instead well-defined cost estimation processes which can be followed by less skilled staff with short training are suitable for SMEs.

There are other general cost estimation methods used currently in the world.

Analogy, parametric, activity and feature based methods are the main cost estimation methods used currently (Jinks et al., 2010).

Analogy cost estimation is a method comparing different products or features of a system. In this method the archive of a company should be reviewed to find similar projects to the project being estimated. Similar projects are ones that "feature similar project metrics or features" such as number of team members and level of expertise. For the times that reasonable databases are not available for a product, this method can be used. But for getting accurate results, highly experienced experts with good judgment abilities are required. This method is one of the popular methods for estimation (Auer and Biffl, 2004).

Auer and Biffl (2004) have described analogy estimation process as: Data collection from portfolio, the estimate proposal creation with a model and a rational check by the estimator.

Analogy estimation is a form of case-based reasoning. According to Shepperd and Schofield (1997) analogy estimation process consists of identification of a problem as a new case, collection of the data from company sources, reuse of the information from previous cases and suggestion of a solution for the problem.

Shepperd and Schofield (1997) have mentioned two problems regarding analogy estimation. These are how to characterise cases and how to measure similarities.

Analogy-based estimation is not an appropriate method for stages where there is high level of uncertainties, especially at early stages of product development (Azzeh et al., 2011).

Duverlie and Castelain (1999) mention that analogical method is not appropriate for SMEs as it needs "significant investment" as for manufacturing or mechanical parts, analogical method consists of defining codification for parts and usually multi-dimensional codification.

In parametric costing, the main factors that the life cycle costs are dependent on are sought and different statistical techniques are employed. This approach is useful at design stage where many details about the product and manufacturing operations are not known (Qian and Ben-Arieh, 2008).

For parametric estimations, technical or physical parameters of a product or part are sought and related to cost of that product or part. Duverlie and Castelain

(1999) have listed three types of parametric method which are the method of scales, statistical models and cost estimation formulae (CEF).

One of the disadvantages of parametric costing is the necessity for knowing all the parameters of a product. In early stages of the product development, all the parameters of a product are not known and the estimator has to estimate these parameters which would results in uncertainties (Duverlie and Castelain, 1999). One of the other disadvantages is sourcing the final costs to their origin is difficult in this method (Duverlie and Castelain, 1999).

Parametric estimating is usually used in early stages of projects where there is little information known and a detailed estimating is not possible. In parametric estimating the most important areas are generation and formation of the cost estimating model and development of a database (Hamaker, 1995).

One of the other widely used cost estimation methods is activity-based costing (ABC). ABC was originated in 1980s. ABC is a management accounting technique. In this method costs are associated with the activities that generate the cost. This method helps to allocate costs, usually overhead costs to activities (Cooper and Kaplan, 1988). The most important task in this method is to identify the cost drivers. As this method needs extensive activity cost databases, it cannot be used for novel products. It is resource intensive to use and there are potential difficulties for new products when they are using new processes or where there is still lack of product definition at the early stages of design (Korpi and Ala-Risku, 2008).

Analytic costing is bottom up detailed costing. Analytic cost estimation uses analysing a product and production activities to come up with a detailed cost (Duverlie and Castelain, 1999).

Knowledge based cost modelling is one of the analytical cost models used in the design stage of a product. In this model the knowledge variables such as features, operations, weight, material, physical relationships and similarity laws are integrated into the cost model (Shehab and Abdalla, 2001). The problem with knowledge based modelling is that it has a limitation. Because it is a static model so it cannot model dynamic systems. Dynamic models can model multiple components with different queuing times, but static models can represent waiting times in queues (Jinks et al., 2010).

According to Gupta and Gunasekaran (2005) the cost measures used over time are as following. For the period of pre-industrial, average cost was an approach. Until 1940s, total manufacturing cost focus. From 1940s till 1980s, direct costing (fixed vs. variable) was the measure used. During 1940s, opportunity costing was introduced and also transfer pricing was used. At 1980s ABC, 1990's market driven and 1990s product life cycle were used. During 1990s, throughput costing (JIT) was used and from 2000 onwards, value base costing is the dominant measure. Value-based costing is integration of market driven and life cycle approach and mostly focusing on highlighting the value creation.

Hundal (1997) has compared traditional costing method with ABC for product costing. He has resulted that ABC is more useful for allocating overhead costs when there is a mix of products in production. Also a comparison of the two on the change in part cost showed that ABC results in more realistic and rational costing.

In a study Qian and Ben-Arieh (2008) have developed a cost analysis model that links ABC and parametric cost estimating. Also Qian and Ben-Arieh (2008) have compared the results from various parametric cost estimates with ABC costings and have resulted that ABC is a more accurate method than using traditional cost estimates. In this model ABC is used to determine the actual costs of a current product and parametric is used in congestion with ABC to estimate the cost of new parts based on activity cost driver obtained through ABC. The last stage of the model is a cost reduction analysis based on cost data to eliminate non-value-added activities.

2.7 Cost Estimation tools

Many commercial cost estimation tools have been developed based on the mentioned above cost estimation methods. The tools try to capture data in a systematic way, automate many of the cost estimation processes and have visual modelling tools for design selection. They incorporate sidelong tools for ease of data capture and decision making. They ease the process of trade-off analysis. Significant tools used for cost estimation are as following.

Vanguard studio is a hierarchical cost modelling tool which is now being used in Rolls- Royce for unit cost modelling. Vanguard studio is a visual planning and analysis tool and by Cheung, et al. (2010) is used to model Surplus value which is one of the terms used in manufacturing. Collopy (1997) has defined Surplus value as “the difference between reservation price and manufacturing cost.” Surplus value was introduced as a model to include the impact of design on price and manufacturing cost at early stages of design in aircraft industry. The way the tool works is that because most manufacturing systems are complex, so the system is divided into a hierarchy. The hierarchy is divided into different levels and each level is categorized by the horizon of planning and the kind of data required in the decision process (El Adl et al., 1996).

Another cost modelling software is SEER-MFG (formerly SEER-DFM) which is developed by Galorath Inc. and is mostly used in aerospace industry. This software helps to “evaluate process options and trade-offs impacting such factors as ease of fabrication and assembly, number and availability of parts, materials selection, and failure and repair rates” (Galorath Inc., 2011). SEER-MFG is a process based detailed cost estimation tool which includes a data base of cost data. An extensive list of pre-defined manufacturing and assembly processes are available in the software. About 80 processes including conventional machining processes, casting, finishing, electrical assembly, composites making, sheet metals processes and mechanical assembly.

A number of tools facilitate cost estimation process by capturing data and information in a systematic way. IDEF3 and XPat are two widely used data and process capturing tools. Process mapping is a tool used early in the cost estimating process.

IDEF3 is a process modelling technique which captures knowledge about the operation of a particular system or organisation which “includes the capture of assertions about the objects that participate in the process, assertions about supporting objects, and the precedence and causality relations between process and events in the environment" (Mayer et al., 2010).

XPat which is abbreviation of expert process knowledge analysis tool is a knowledge elicitation tool to gather and analysis expert knowledge (Roy et al., 2011).

2.8 Make or Buy decision

Outsourcing has always been proposed as a method for cost reduction. However in addition to direct view of cost, other factors are involved in the decision making which could affect cost in short and long term indirectly (Ellram and Maltz, 1995).

Some manufacturing plants have only assembly lines and some have fabrication lines too. The first group outsource components and subassemblies and only assemble them in the assembly line. But some companies manufacture some parts as well and have fabrication lines in there plant too. Manufacturers rarely make all the parts themselves. Parts like bolts and nuts and screws would be cheaper and faster to be bought in bulks from suppliers than being manufactured by the company. The important thing to look for is what way is the cheapest way to provide a part to assembly line. This could be either to buy the part from suppliers or to make the part ourselves (Meyers and Stephens, 2005).

"Make or buy" is defined by Zenz (1994) as the decision of whether to make a product in-house or buy from suppliers. Probert (1997) defines "Make or buy" decision as whether to carry out a process or activity in your own business or to assign it to suppliers. "Make or buy" decision is not only limited to cost or to speed to the market of a product. Dale and Cunningham (1984) have mentioned other factors other than cost in the decision making and evaluated their importance. Suppliers' capabilities and quality are among the decision making elements. Also "Make or buy" decision making not only can be a cost saving decision, but is a strategic activity that can affect the future of company's' activities (Fine, 2000). Dale and Cunningham (1984) have concluded that "Make or buy" decisions can be "very complex, time consuming, interactive and affect many departments within a company".

The first theoretical “Make or buy” decision making model was developed by Ronald Coase in 1937 and further development can be found in Oliver Williamson’s (1975) research in 1975. Coase (1937) introduced the “idea of transaction cost” in economics and developed the economic theory of the firm which was the basic model for “Make or buy” decision. Amenudzi (2009) in a structured review of “Make or buy” related research stated that “most of the decision making frameworks identified in the literature are not regarded as a standard tool or mechanic for making “Make or buy” decision, but had been used as an aid in decision making”.

The literature related to “Make or buy” decision making can mostly be classified into two types. Part of the research have been dedicated to development of decision making methodology and part of the research have identified factors and criteria involved in the decision making process which surveys are the dominant method used in this type. Few samples have been mentioned in this section. Further detailed literature review related to the decision making method development is presented in Section 4.3.2.

Many researchers such as Slack et al. (2007) mention that other than the short term effects of outsourcing, long term and strategic effects of outsourcing should be considered too.

Anderson and Anderson (2000) mention three “outsourcing traps”:

1. A company loses its market dominance when its supplier acquires its proprietary technology and diffuses it to its competitors.
2. A company relies too heavily on a single supplier, which weakens its ability to negotiate favourable purchase agreements.
3. A company outsources a component or service to a vendor to reduce costs, only to encounter higher expenses or reduced functionality when putting the final product together”

Also Anderson and Anderson (2000) suggested 5 points to avoid outsourcing problems:

1. Long term considerations
2. Avoid outsourcing “core capabilities”
3. Partially outsource other critical capabilities
4. Use of more than one supplier
5. Strategic alliance development with suppliers

Due to the nature of SMEs and their vulnerability to environmental changes, many experts believe that SMEs should choose partnerships or strategic alliances in their business strategy to spread investment costs and possible risks and to be able to overcome resource and capability shortages (Li and Qian, 2007).

Minh (2011) has studied Japanese automobile companies and he has observed that most firms base their make or buy decision on experiences and various discussions and no specific scientific model was used. A model was proposed from an empirical point of view using Analytic Hierarchy Process (AHP) method and in order to develop this model, interviews with Japanese automotive companies from various automotive sectors with different sizes from medium to large size companies were done. The aim of these interviews was to identify main criteria and sub-criteria for the decision making and the importance of each criterion among the vast selection of industries. The developed AHP model including the main and sub criteria are shown in Figure 2-8.

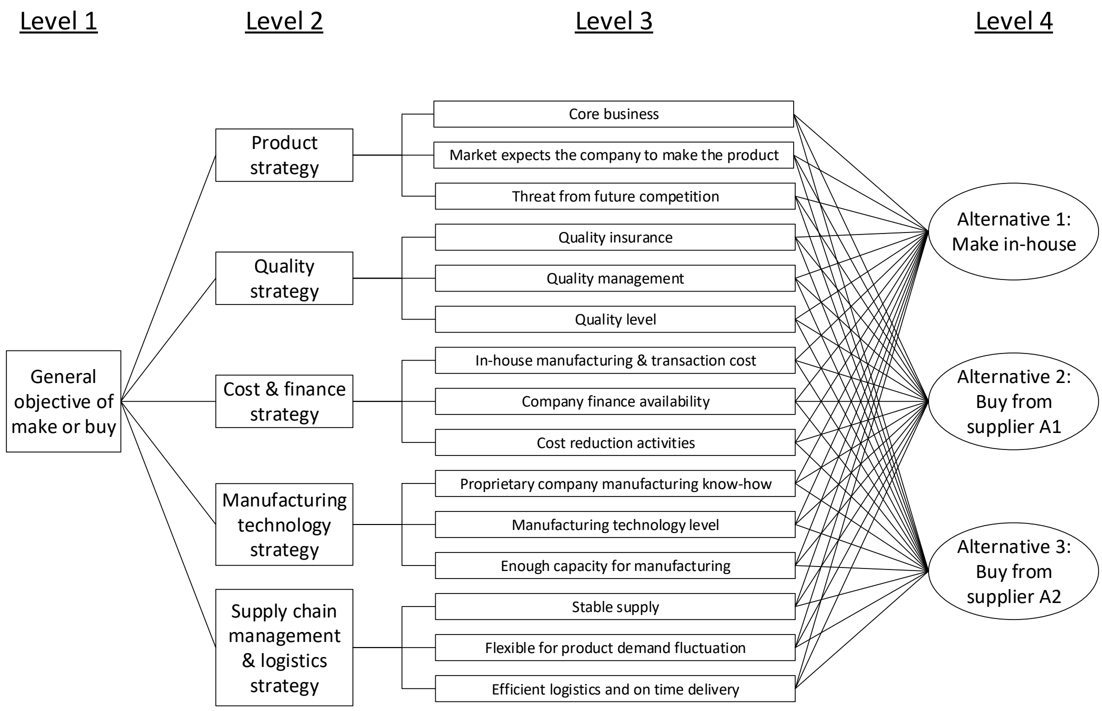

Figure 2-8 The Proposed AHP model for Make or buy decision making by (Minh, 2011)

Five main criteria have been identified by Ming (2011) for the “Make or buy”. These are product strategy, quality strategy, cost and finance strategy, manufacturing technology strategy and supply chain management and logistics strategy.

The main factors and methods involved in a ‘Make or buy’ decision making process identified by McIvor (2005) and Benton (2010) are shown in Figure 2-9. The factors are divided into two groups. The first group of factors are related to the ‘Make or buy’ decision making and the second set are related to vendor selection. According to the findings, there are two main decision making steps for “Make or buy. The first step is the decision to whether make or buy and the second step is vendor selection or supplier selection. Similar to the criteria mentioned for “Make or buy” decision making, there are criteria for vendor selection. These include but not limit to cost and financial matters, supplier capabilities, supplier reliability, logistical strategy and geographical location.

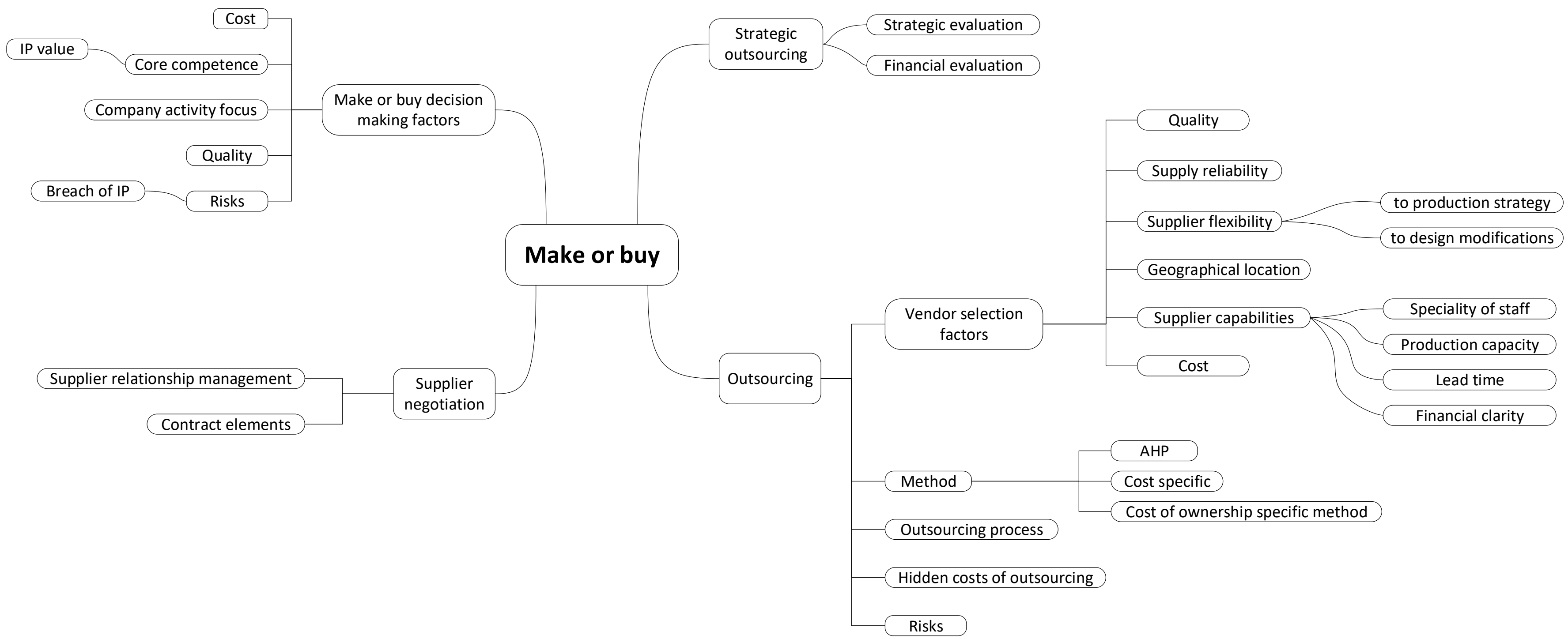

Figure 2-9 The methods and factors included in 'Make or buy' decision making (McIvor, 2005), (Benton, 2010)

2.9 Factory Cost Estimation

Factory's rental or ownership cost contributes to the overhead costs of a product. In order to have a low cost product, factory's rental or ownership costs should be low. So estimating the cost of a future production plant and knowing the minimum space requirements would help in planning to obtain a factory with lowest capital requirement.

Li, et al. (2005) have mentioned three groups of cost models that can be used for buildings:

1) Element-based floor-area models
2) Probabilistic models
3) Regression models

From these groups of models, the first two are not widely accepted due to their outcomes. In the element based model, factors other than the floor area influence the cost and Probabilistic models as implied by the name don't have deterministic outcome. The most popular and useful technique is regression analysis and in more detail is multiple regression analysis (Li et al., 2005). Regression analysis is a statistical estimation model where mathematical models are defined to best describe the available data, and each formula shows the relation between two or more variables (Weil and Maher, 2005). According to the purpose of estimation, level of detail and the stage of a project, different methods can be chosen. But for any chosen methods, the input elements should be available.

Factory rental cost is one of the biggest contributors of the overhead costs. In order to find out about the rental cost, two important factors should be obtained. Factory area size and factory location are two important factors which highly affect the place rental costs. Land prices defer from one place to another. Rental cost is a function of area size. Knowing the minimum area required, can help forecasting rental or buying prices of a plant (Pratt, 2011).

Equipment and machinery should be selected proportional to the activities done in the plant. The equipment list should include all the apparatus, machinery, equipment and accessories to run the production activity in the plant. In order to be able to specify the number, amount and type of equipment and accessories, listing of the equipment should be done after designing production lines. These should be decided in meetings with technical members of the company. Costs should be determined using available cost databases. In this case this can be historical data or data gathered from vendors.

Li et al. (2005) has developed a cost model for estimating pre-design construction costs of office buildings in Hong Kong. The cost model is developed using regression analysis and data from previous building constructions in Hong Kong have been used for this cost model. The data include cost data and statistical data related to average floor area sizes, average building heights, average storey heights and etc. The sources of data are cost consultants and construction companies.

For a method that would be done internally in a SME, detailed cost and construction data of other companies cannot be accessed easily. However, some public domain data such as purchase or rental costs of various available buildings on the market can be obtained. These data can be used to obtain a general view of the relationship between cost and size and location of a building which in the case of this study would be a large workshop or a factory.

2.9.1 Factory Area estimation

In order to perform area calculations, necessary facilities and locations in the factory should be identified. A factory not only consists of a production line, but it is in need of many other areas and facilities to be able to run. Output rate and activity volume of each facility determines the area needed for that facility. Parking and loading areas, employee services area, offices, warehouses and storages and production areas are facilities required in a typical production plant (Hiregoudar and Reddy, 2007). For each area the capacity needed should be estimated in order to obtain the minimum area needed. Meyers and Stephens (2005), in their book, have mentioned 15 steps for developing total space requirements. These steps include determining what will be produced, production volume, make or buy decision, process planning, assembly line balancing and determining Takt time.

In the previous steps, by identifying manufacturing processes, the workshop areas could be identified. In this step, area required for different departments should be obtained. This process is called Area allocation.

Production area is the key area in the production factory. The focus of activities of the factory are on this area. The type and number of equipment depends on the type of activity performed in that area. In this section of the factory raw materials and parts are entered and one or several types of products are produced under different processes. The area size of this section mainly depends on area size occupied of the equipment or work station and work area needed for each equipment or work station. An allocation should be left for non-productive areas such as aisles. In order to know what types of equipment are needed and how many work stations should be available, production process should be determined and manufacturing lines should be designed (Hiregoudar and Reddy, 2007).

Assembly area consists of a number of work stations which are responsible to assemble a product. There are different layouts available for assembly areas and selecting a layout will depend on different factors. Number of workstation is important in the area size calculations. Number of workstations depends on the number of assembly process. Assembly process planning and line balancing are required for obtained this information. The painting area and packaging area can be included in the assembly area (Meyers and Stephens, 2005).

Schenk, et al. (2010) have listed the general elements of factory/production facilities as:

Personnel/workforce

- number, gender
- qualifications, skills

Machinery and equipment:

- manufacturing and assembly equipment: machinery/workstation including fixtures/ auxiliary equipment and tools
- logistics facilities: transport, handling, storage and order picking facilities including auxiliary warehouse and transport equipment
- quality assurance equipment: measuring and testing equipment, jigs and fixtures/ auxiliary equipment
- control, information and communication systems
- safety, emissions and interference suppression systems
- supply and disposal systems for utilities, power; raw materials and auxiliary materials; waste and residual materials

Technical systems (in conjunction with their structures):

- structural equipment: supporting structures, foundations, pillars, beams, roof structure
- envelope: facades, roofs including windows, doors, gates
- interior: flooring, ceilings, dividing walls, openings
- building systems: heating, ventilation, air conditioning, sanitary facilities
- supply and disposal systems for utilities: power, gas, water (drinking and industrial water), electricity, raw materials, auxiliary, waste and residual materials

Operating materials:

- liquid materials (fluids, media): water, oils and greases, coolants, acids and bases, solvents, cleaners, polishing materials and abrasives, fuels, paints, biological materials
- gaseous materials: technical gases, technical fuel gases, gas mixtures, steam
- solid materials: fuel, paper and cardboard, glass, administrative equipment

Meyers and Stephens (2005) have mentioned that for this step a total space requirements worksheet should be prepared for each department. The required departments according to Meyers and Stephens (2005) are, the manufacturing space, production service space, employee services space, office space and outside area space. Other spaces needed to be considered are under the floor (Basement) area, overhead or clear space areas (8 feet above the floor to the ceiling), truss level and the roof.

2.9.2 Factory Location

Location selection is one of the strategic decisions for an enterprise to make and can highly effect the operation cost of an activity. Poor location decisions can result in subsequence such as high delivery cost, shortage of qualified labour, lack of customers, high operating cost and loss of competitive advantage. For a manufacturing company several location selection criteria are more important in the decision making; elements such as relevant location to suppliers and customers, availability of cheap labour and transportation system. In a location selection decision both quantitative and qualitative factors exist. Three main areas of factors influence the location decision. Market attraction, consumer characteristics and location qualifications are these three areas (Yang et al., 2008).

Zanjirani, Farahani and Hekmatfar (2009) define facility location problems as "Facility location problems locate a set of facilities (resources) to minimize the cost of satisfying some set of demands (of the customers) with respect to some set of constraints". They state that in location selection decision not only the current state of the location has to be considered, but the future state of the location for the lifetime of facility should be considered. Also future scenarios should be evaluated with the changes in factors such as environmental factors, population shift and market trends evolve.

Stevenson (2009) in his book 'Operations management' has mentioned a general process for location decision:

1) Decide on the criteria to use for evaluating location alternatives
2) Identify important factors
3) Develop location alternatives
    A. Identify the general region for a location
    B. Identify a small number of community alternatives

C. Identify site alternatives among the community alternatives

4) Evaluate the alternatives & make a selection

Yang, et al. (2008) have developed a decision making model based on AHP/ANP. In this model the location characteristics will be evaluated to support managers with decision making. Yang, et al. (2008) have mentioned four ways to make a location decision. These are:

- Focusing on group opinion
- Expert opinions
- Management decision models
- Mathematical programing

Based on (Yang et al., 2008) findings using experts opinions, the important criteria for location selection decision making are shown in Figure 2-10.

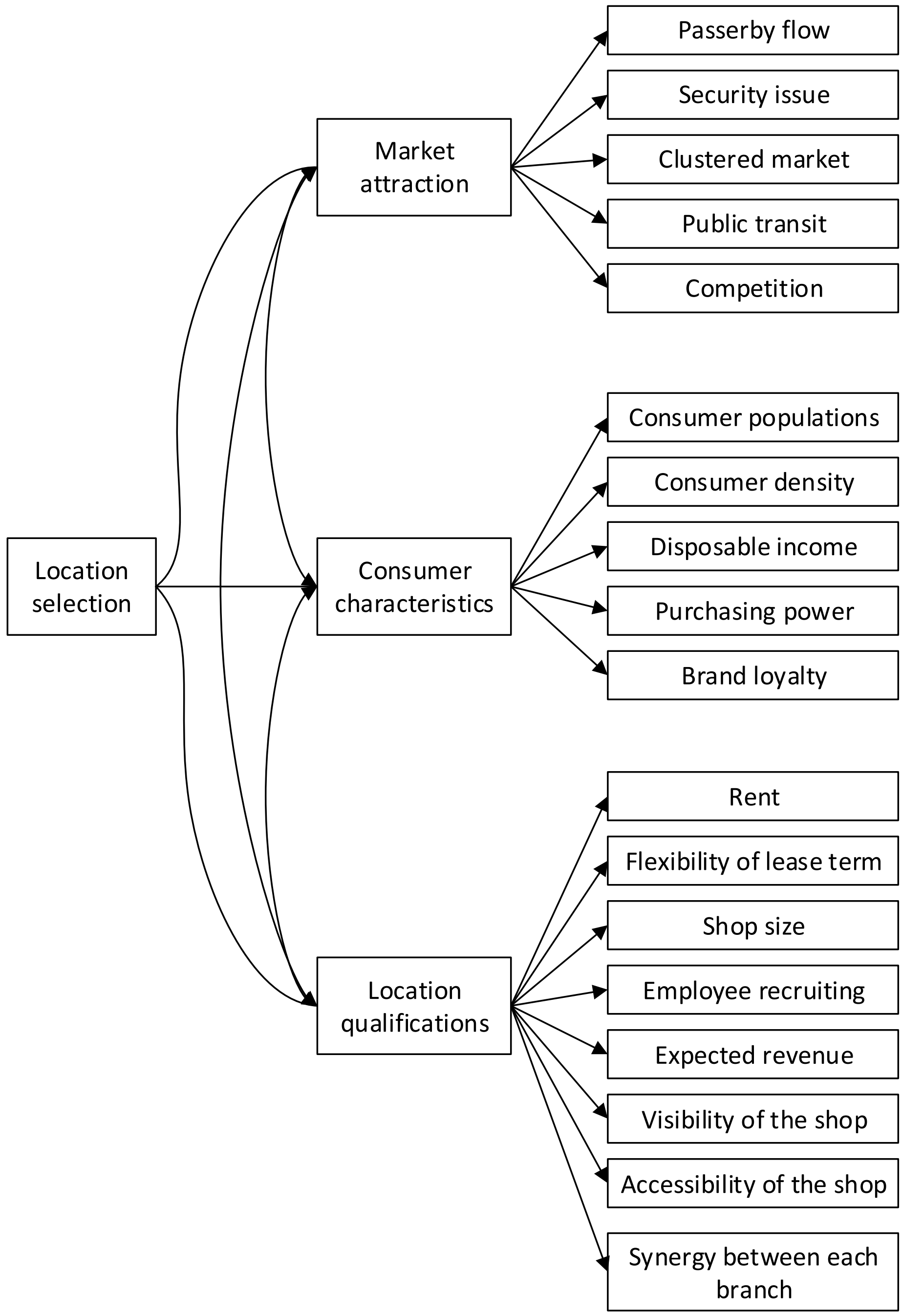

Figure 2-10 – Identified criteria for shop location selection based on experts opinions (Yang et al., 2008)

Early locations problems, 1-Median and 1-Centre have been raised since 1600s and 1857 and the most discussed four location problems in the literature are p-Centre, p-Median, Simple plant location problem (SPLP) and Quadratic assignment. But according to the author, SPLP has been mostly evaluated in research and is more applicable to real life decision making (Krarup and Pruzan, 1983).

In SPLP the main criterion is to minimise the total cost of serving clients in locating the facilities and it can give results in terms of the number, size, design, location and service pattern for plants and in this problem, neither the number of plants to be located, nor the transportation or communication patterns are predominant (Krarup and Pruzan, 1983).

In traditional cost-based location problems the focus was generally on minimising the plant costs, but in current models the focus is mainly on competitions between supply chains (Weng and Fang, 2011). Weng and Fang (2011) have developed a new cost-based location decision model from the view of the entire supply chain. In most of the papers in the literature, the models mainly consider minimum transport cost, maximum profit, minimum operating cost which all are from the view of the plant itself, but Weng and Fang (2011) have developed a model in order to minimise the cost of the entire supply chain.

In the model, data from different locations were collected and compared to each other. The basic data are listed as, different types of insurances, credit rates, rental prices, average construction costs, average salary, electrovalence, utility prices, waste disposal prices, transport price and land price. In a case study the data from six locations in China were compared using a mathematical equation. The model uses a simple mathematical equation for summarising cost of the above cost for each location and comparing them. The disadvantage of the model is that it considers the weight of each factor the same. Although it has the advantage of considering a wide range of factors across the supply chain.

Melo, et al. (2009) in a literature review paper state that due to the increase of supply chain management importance and the influence of factory location of that area, factory location models are being integrated into supply chain context. In the paper, they have looked at the role of factory location models in supply chain management. The factory location problems can be divided into two categories, discrete and continuous. In discrete location models, the number of locations to be selected from is restricted to some finite set of pre-specified points. In continuous plant location problems, instead of considering point locations, area locations are considered (Francis and White, 1974).

In addition, Melo, et al. (2009) have reviewed literature related to reverse logistics, where the return of goods from customers and the processes following the return of goods are considered. Reverse logistics is one of the areas that can be considered in a location selection decision, especially where collection and recovery/remanufacturing centres exist.

Zarinbal (2009) states that in the classical locational studies, the models are divided into four categories: Analytic models, continuous models, network models and discrete models. Analytic models are mainly based on "simplifying assumptions such as the fix cost of locating facility". Continuous models are the oldest location models and the classic model of this type of problems is Weber problem. Network problems are consisted of nodes and links. Famous models in this area are Absolute 1-median, un-weighted 2-center and q-criteria L-median. Well-known models of discrete type location models are discrete N-median, un-capacitated facility location, and coverage models.

The factors involved in a location decision depend on the scope of the location problem. Location problems can be international, national, and state-wide or community wide, and depending on the extent of the problem, the factors vary. Factors such as political stability, foreign exchange rates, duties and taxes are determinant for international decisions, but for community wide problems, community services, local business climate, local governmental regulations and local governmental grants are more remarkable (Moradi and Bidkhori, 2009).

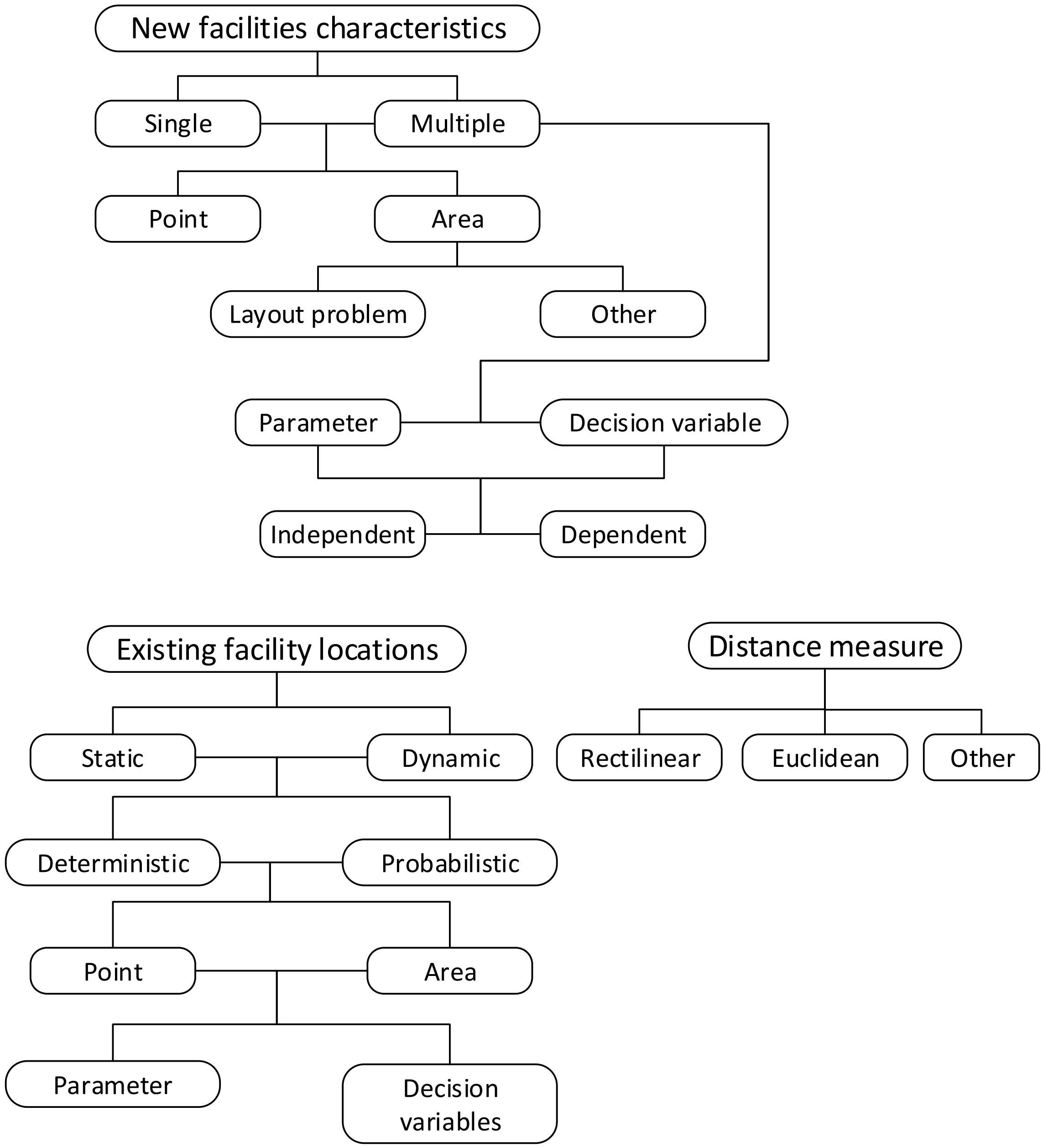

Figure 2-11 Classification of location models (Francis and White, 1974)

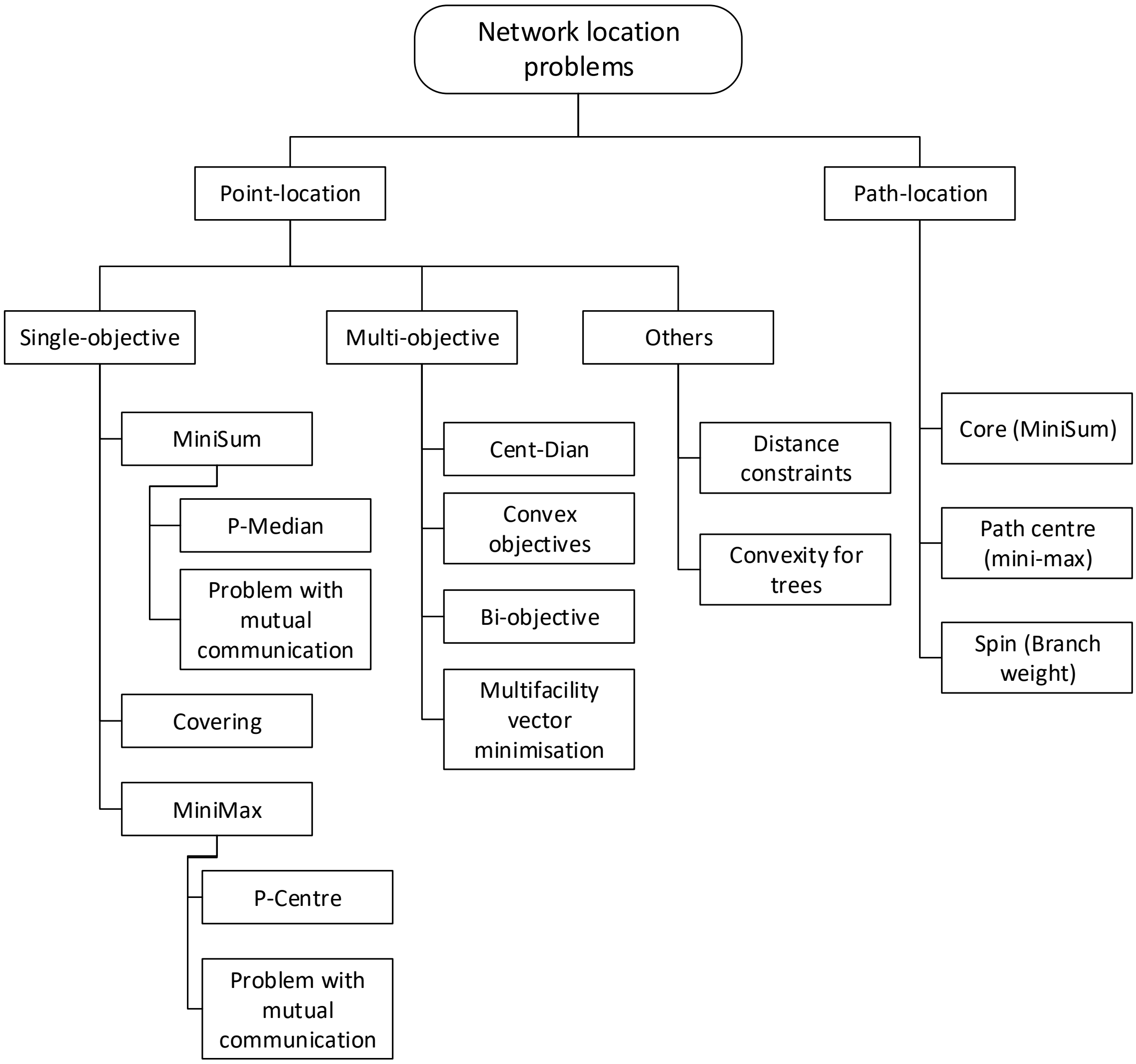

Figure 2-12 Tree structure for network location problems (Tansel et al., 1983)

Canel and Das (2002) in a review have concluded that the common factors influencing the facilities locations abroad are:

- Labour and other production inputs
- Political stability
- Host governmental attitudes towards foreign investment
- Host government tax and trade policies
- Proximity to major markets
- Access to transportation
- Existence of other competitors

2.10 Factory Design

As mentioned in Chapter 2.9.1, in order to estimate the size of the assembly area, it is needed to determine the type and quantity of equipment and machinery and the layout of assembly line. In addition, to have low cost product, a low cost assembly line should be designed.

2.10.1 Assembly line design

In assembly line design problems, the two factors which are important are line balancing and sequence (resource) planning (Rekiek et al., 2006).

Assembly lines are categorised by the number of different type of products being assembled on the line. The assembly line can be a single-model line, multi-model line or a mixed-line. In a single-model line, only a single model is assembled or different products use identical processes. A mixed-model line uses the same production system for manufacturing varying models and the processes have high similarity so the setup times are zero or negligible and in multi-model line different batch of products are processed which for each batch setup is required (Boysen et al., 2007).

Each of the mentioned types can be divided into two different types of problems. Either can be Stochastic or Deterministic.

The Stochastic problems are defined as “given a finite set of tasks, each having a performance time distributed according to a probability distribution and a set of precedence relations which specify the permissible orderings of the tasks, the problem is to assign the tasks to an ordered sequence of stations such that the precedence relations are satisfied and some measure of performance is optimized.” (Erel and Sarin, 1998)

Deterministic problems are “given a finite set of tasks, each having a fixed performance time, and a set of precedence relations which specify the permissible orderings of the tasks, the problem is to assign the tasks to an ordered sequence of stations such that the precedence relations are satisfied and some measure of performance is optimized.” (Erel and Sarin, 1998)

Any manufacturing process including assembly lines can have different types of layouts and these layouts are chosen according to the objectives that the layout is trying to achieve. Process layout means how equipment are positioned relative to each other and how tasks are allocated to the recourses.

The basic process layouts are fixed-position layout, functional layout, cell layout and product layout (Slack et al., 2007).

In fixed-position layout the product is largely stationary and the equipment and resources are moved around. An example of this kind of layout is shipbuilding

In Functional layout similar processes are located together with regards to the functions and needs. For example, all machining processes are located together in one area.

Cell layout is the layout in which all the equipment with common purpose are located in same locations, so for each part family a specific set of machines are considered.

Product layout is locating the workstations entirely for the convenience of the product. In this layout the equipment are located according to the sequence of operations for a specific product. An example of this layout would be a television manufacturing line or most automatic assembly lines.

There are mixed layouts as well which are combinations or hybrids of the mentioned layouts (Slack et al., 2007).

An assembly line is consisted of workstations which are arranged along a conveyor system. At these stations operations is done on the work pieces by man and machines.

Precedence constraints determine the order of the tasks to be done. A Precedence graph represents the ordering and is consisted of nodes and arcs as shown in Figure 2-13. Nodes represent the tasks and arcs show the precedence relationship.

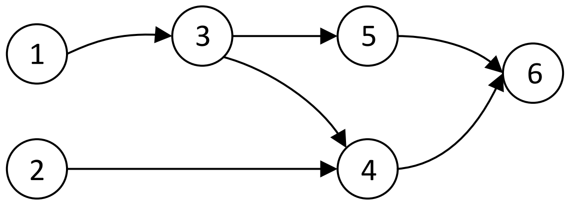

Figure 2-13 Precedence graph (Rekiek et al., 2006)

The number of basic operations essential to assemble a work piece is called tasks and the time to perform a task is called the task time.

The time span between the exit of two products is called the cycle time (*C*). The work load of a station is the Station load and the processing time is Station time (Boysen et al., 2007).

Assembly Line balancing (ALB) is levelling all workloads across the workstations. And there are two main different types of ALB, Either simple assembly line balancing (SALB) and General assembly line balancing (GALB). SALB is when many simplifying assumptions are used. In GALB more practice relevant aspects are integrated into the problems. The ALB problems can be categorised into more detail. For example Boysen, et al. (2007) have distinguished SALB into four types presented in Table 2-5.

Table 2-5 SALB problem types

SALBP-1	For a given cycle time, minimizing the sum of station idle times is equal to minimizing the number of opened stations
SALBP-2	If the number of stations is given, then minimizing the cycle time guarantees minimum idle times
SALBP-E	Maximizing line efficiency E minimizes idle times
SALBP-F	The problem of finding a feasible balance for a given number of stations and a given cycle time

2.10.2 Factory simulation tools

One of the types of simulation is discrete event simulation. This simulation is for modelling systems which the state of the system changes over time and the changes in the system happen at discrete events and not continuous. They happen suddenly at each time point (Law, 2000). This type of simulation can be used for modelling the assembly line in this project and simulating the Assembly and flow of components and parts around the factory.

The famous factory simulation software currently used are introduced in this section.

One of the popular off the shelf simulation tools currently being used in industry is ARENA which is developed by System modelling and acquired by Rockwell automation. ARENA is a discrete event simulation software (Kelton, 2010). In ARENA a model is built by drag and drop of the modules into the model window. ARENA allows an infinity number of hierarchy levels and it has 2D animation. ARENA contains Activity-based costing too (Law, 2000).

One of the 3D factory simulation software is Witness which is developed by Lanner. This software provides 3D factory process model and can model discrete and continuous elements. The 3D simulation allows visual appraisal of the shop floor environment. AutoCAD files of shop floor plan can be imported into Witness (Markt and Mayer, 1997).

Flexsim is another factory simulation tool. This software is an object oriented, discrete event simulation tool which models, analyses, visualises, and optimises any imaginable process. Flexsim can visualise the manufactory process in tree view, 2D, 3D and virtual reality simulation.

In Object oriented simulation all the components which form the model are active or passive objects. Active objects are processes and passive objects show behaviour when requested by other objects (Nordgren, 2003).

2.11 Knowledge gap

The literature review was completed in the three main areas of cost reduction, cost estimation and factory design being in the interest and scope of this project. Literature review was done using online databases and university library resources and over 150 literature items were reviewed. The review of each subject can be extended into a wider review of the area. Each subject itself can be reviewed in more extensive form and from different perspectives, but due to the scope of the project, they were limited to boundaries of the interest of the research.

It was observed that there are a high number of articles in the main areas of cost reduction, cost estimation, factory design and Make or buy and currently lots of research being conducted in these areas. The focus of most of the research in all four areas is on large companies and firms, but little research has been conducted on SMEs. Due to the important role of SMEs in the world's economy, more research focus is being drawn to SMEs and providing and transferring academic knowledge to them.

There are a number of cost reduction methodologies in the literature which have been studied and used for many years in the academia and industry. Some of these methods have been subjected to more focus, such as Value Engineering (VE) and some attracted less attention such as Value Driven Design (VDD). Due to lack of resources and attention, not many of these methods have been used and implemented by SMEs, especially in the Research and Development section. Some studies are done on the impact of the implementation of some of the previously mentioned SMEs such as VE, but the studies are done on specific types of SMEs and cannot be generalised. As mentioned in section 2.4 few articles were found that have used a combination of the methods in the industry such as Farsi and Hakiminezhad (2012) which an integration of VE, QFD techniques and DFMA was used during the product design stage. Some limited case studies were performed on some components or a product, whereas no in depth implementation of the method and the analysis of the impact on a firm were done.

The same behaviour is being observed for Cost estimation and factory design areas. SMEs possess a very low number of research topics in these areas compared to larger and more complex firms. Most of the available tools and methods are applicable to SMEs as well as large companies, but studying the impact of using such methods on SMEs hasn't been of much interest.

It was observed that no research was found to suggest a coherent process to help a small firm in make or buy decisions. The lack of suitable processes and knowledge about the state of the art methods and tools was observed during the experiment of working with an SME and reading the literature.

Most cost estimation methods used have been researched and developed for a long time and these methods are well defined, although using the methods in different contexts and at different stages are being studied in more detail by researchers (Section 2.5). By observing the SME requirements and reviewing the literature, it was realised that a process for set-up of new plant or factory is required by SMEs, although by reviewing the literature, no specific complete process was developed to estimate the cost of setting-up a plant and define a process to include location selection and factory design.

One of the major novelties of the research would be in the novel application of the conventional methods for a novel product and the results obtained from the implementation of these methods. The product which the company is developing is a novel product and also because of the situation of the company which is a start-up SME, the results obtained from the implementation of framework would be novel.

3 RESEARCH DESIGN

In this chapter the objectives of this research are presented. The objectives section follows with explanation of research methodology theory and background and in the next section the research methodology development is explained. The chapter continues with the description of the research strategy and the chapter is closed with the description of final research methodology.

3.1 Research Objectives

The objectives are as follows:

1. To identify challenges that SMEs are facing introducing a new product to the market
2. To develop a cost reduction framework based on the identified industrial requirements
3. To develop a process for 'Make or Buy' decision which would include a detailed estimating tool for total manufacturing cost and outsourcing
4. To develop a process for identifying best manufacturing processes and designing manufacturing and assembly line
5. To develop an estimating tool for factory set-up cost and a method for plant location selection
6. Validate the results with academic and industrial experts and perform a case study

3.2 Research Methodology Development

Research methodology includes three forms of study according to the purpose of research: these are exploratory, descriptive and explanatory. These will now be explained (Robson, 2011).

In descriptive research an accurate profile of people, events or situations is provided. In this type of research, a wide historical knowledge of the situation should be researched, thus the researcher could plan data gathering based on the previous knowledge.

In explanatory research an explanation of a situation or problem is sought in the form of casual relationships. In this form of research, it is attempted to explain patterns relating to the researched phenomenon.

Exploratory research is usually used for new less known situations. The base of this type of research is to seek new insights and to ask questions about new problems.

There are mainly three perspectives for research; "a qualitative perspective (Denzin & Lincoln, 2005), a quantitative perspective (Shadish, Cook, & Campbell, 2002), or a mixed methods combination of the two perspectives (Tashakkori & Teddlie, 1998)" (Dellinger and Leech, 2007). The main differences of qualitative and quantitative research is shown in Table 3-1.

In qualitative research, anthropologic methods are applied to study relevant social phenomenon. In this type of research, the researcher tends to get close to the phenomenon and qualitative research is much more subjective than quantitative research. Observing, interacting with people, interviews, constructing case studies and analysing existing data are methods of data collection for qualitative research (Steckler et al., 1992).

On the other hand, Quantitative methods are derived from physical sciences. These methods tend to collect numerical data and the data analysed using mathematical methods. Experimental and quasi-experimental designs are the basis for data collection. The aim of quantitative methods is to maximise objectivity which is done by distancing from people and social phenomenon (Steckler et al., 1992).

In Table 3-1 specification of qualitative and quantitative research approaches have been compared.

Table 3-1 Comparison of qualitative and quantitative research approaches (David and Sutton, 2011; Gray, 2009)

	Qualitative	Quantitative
Data	Soft data (Words, sentences, photos, etc.)	Hard data (Numbers)
Basis	Interpretive and critical	Positivist principles
	Constructivist	Objectivistic
	Verify or falsify already existing relationship or hypothesis	Generate new hypothesis and describe details of causal process or mechanism
Planning	Before data collection	On going
Method	Inductive	Deductive
	Non-hypothesis driven	Hypothesis driven
	Unstructured or semi-structured	Structured
	Semi-structured & unstructured interviews, Participation/Observation, documents and data review	Experiment, survey & measurement
Focus	Meanings	Facts
Purpose	Exploratory	Conclusive
Results	Contextual, open to interpretations & evolving	Objective, valid & replicable

In quantitative design, the main measurement technique selection and planning is done before data collection starts. But in qualitative research all the thinking and planning happens simultaneously with data collection. Qualitative research has a fluid nature whereas quantitative is structured and fixed.

There are qualitative and quantitative measures in all research. In any research, in order to ask a research question or to make a set of observations, distinctions should be made and recorded. This is done in the form of identifying boundaries between gradations, classes or types. Any quantification requires these qualitative measures (David and Sutton, 2011).

Any qualitative research requires some sort of measurement. Measurements can be done in various levels, nominal, ordinal, interval and ratio levels. The difference between the levels is in being scalable and orderable. Quantitative data makes statistical methods possible (David and Sutton, 2011).

One of the differences between qualitative and quantitative research appears in the positioning of the literature review. In quantitative research, literature review is done in the beginning of research, whereas in qualitative research literature review happens throughout the research in different types. It can happen in terms of theoretical literature which would help in the development of the study or it can be empirical literature which comes from empirical study and also in the form of methodological literature which concerns about how research is conducted (Gray, 2009).

For this study a mixed method is used. Due to the nature of the study which is multi-disciplinary, qualitative and quantitative methods have been employed.

Using mixed methods would help to understand a phenomenon from various aspects. It helps to have rigorous and valid results (Gray, 2009).

Gray (2009) has mentioned four models for mixed methods. The methods can be used in different sequences and independently or interdependently. The models are shown in Figure 3-1.

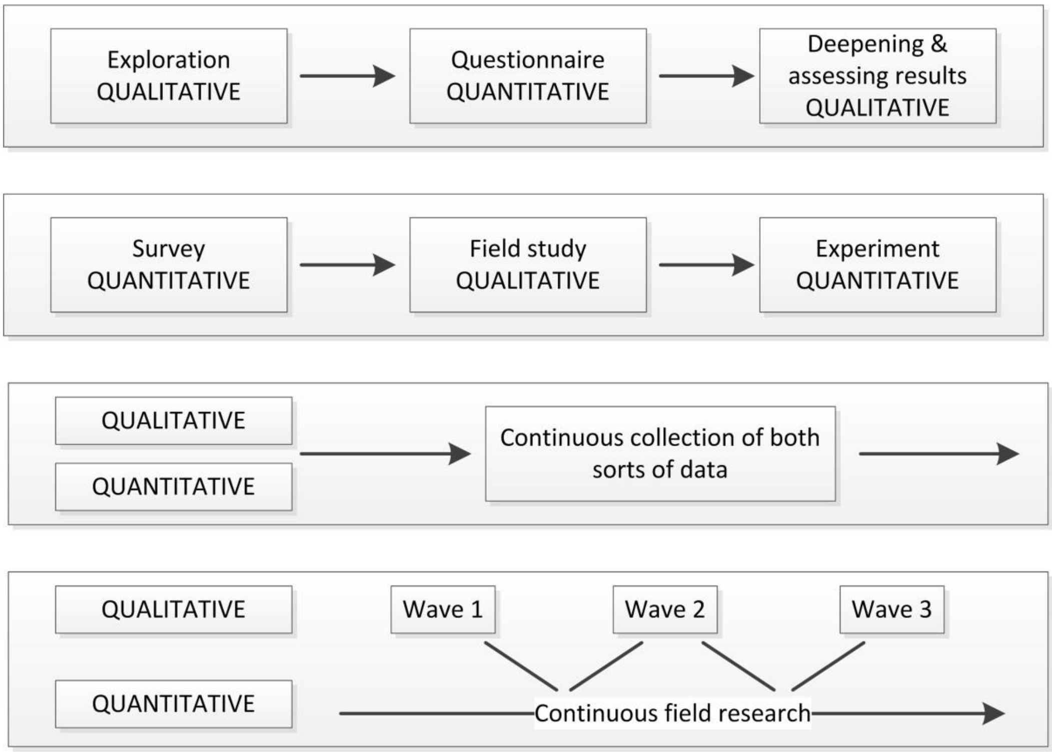

Figure 3-1 Mixed method models (Gray, 2009)

Case studies are an important part of qualitative research. They help to develop multiple perspectives of a phenomenon which this would help to develop deep and wide understanding of a context (Gray, 2009).

3.3 Research Methodology Adopted

This project was based on the participant observation data collection methodology. The researcher spent a large amount of the PhD time in the collaborating company. The researcher participated in various activities and roles in the company while it opened the opportunity to observe different layers of an SME in detail. Due to the nature of small businesses, there were more opportunities to contact the management and other employees directly and without waiting. Also accessing different levels of data was without difficulty as all the data could be accessed directly by the researcher or through the management team.

Because of the participation of the researcher in the design tasks, a complete understanding of the developed product was obtained. For example, Computer Aided Design tasks in solid modelling using the Solid Works product allowed an in-depth understanding of geometry, function, design intent and assembly level details to be understood.

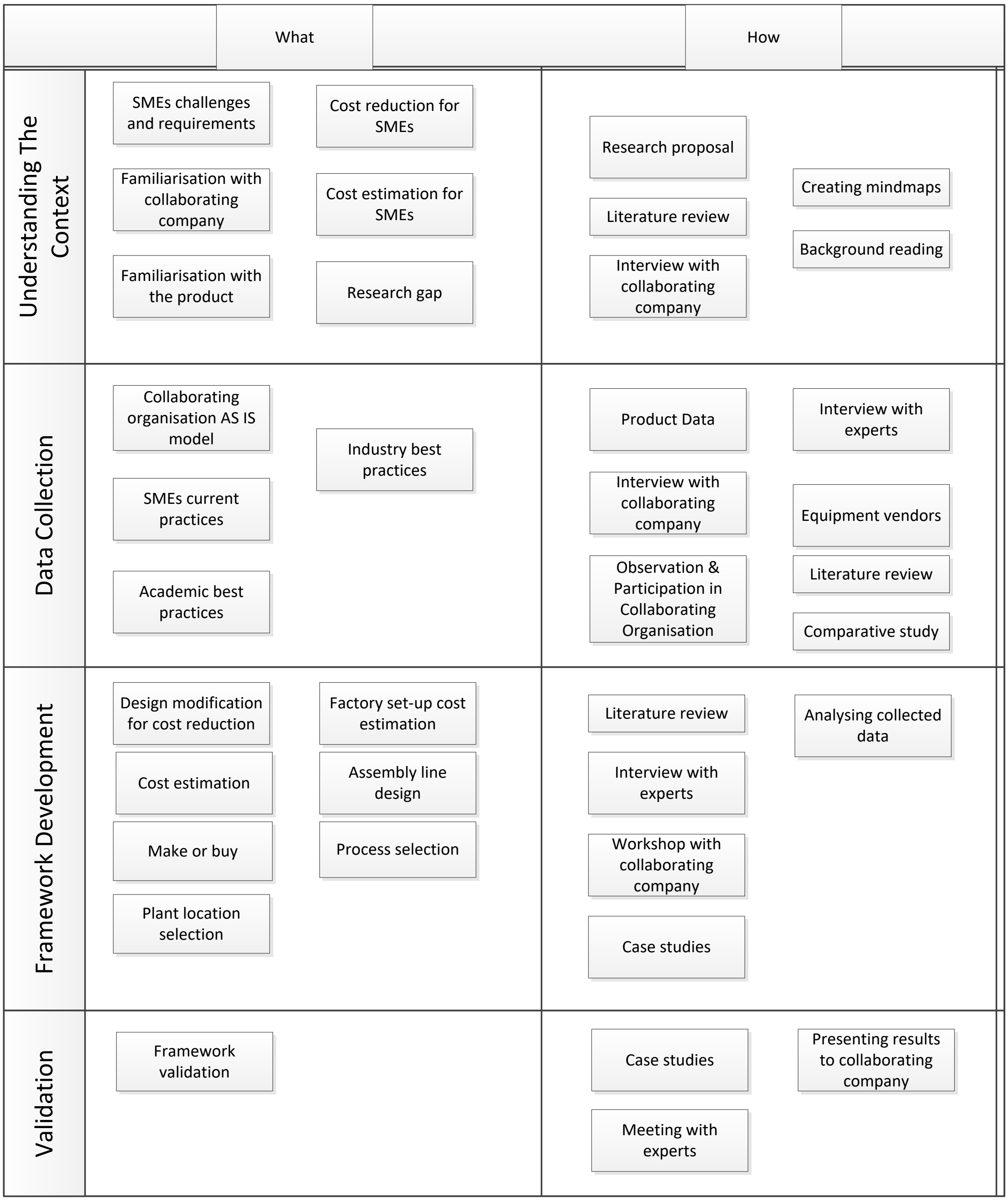

Figure 3-2 Research methodology overview

In addition to hours of informal contact with the company, more than 40 hours of formal meetings have been held with the managing director, technical manager and general manager of the company during the research. The aim of these meetings was firstly to develop an understanding of the requirements of an SME and to get familiarised with the developing product. Further in the project, the aim of the meetings was to present the findings to the company as well as getting feedback about the results and progress of the work. The meetings were used as an opportunity to collect the required data regarding the company, the product and requirements of the organisation. The connection of the project with a real world company and the feedback received throughout the project resulted in an iterative element in the research methodology which caused adjustments to requirements and hence adjustments to data collection during the project.

In this project two types of case studies were completed. The first type of case study was done by holding short workshops with the company members and by the participation of the researcher in the company which has been running during the time line of the project. The final case study was commenced during the third year and involved the implementation of the developed framework in a step-by-step plan on the product.

During the first year, a few cost reduction workshops were held for the management of the company. The focus of these workshops was on DFMA and value analysis. These workshops helped the researcher to develop an understanding of the product and also helped to identify further opportunities for cost reduction in the company. Although, it was later decided that due to the nature of the product development process in the company and the development stage that they were at, there were little design modification opportunities at that stage. A report about the workshop can be seen in Appendix C. At that stage the focus was on proof of concept and the design was not gone into detail and was not intended for production purpose. In addition, most of the product parts were outsourced through COTS. Using COTS had specific design constraints and there was limited knowledge at that stage about the parts in the design which also was constraint for any modifications. Therefore, the focus was moved to other cost reduction methods.

In addition to the meetings held with the company, meetings were held with experts from the university and externally. The list of the meetings is presented in Section 3.2. Similar to a meeting with the company, these meetings were held at different stages of the project and with different topics and different aims. As shown in Table 3-2, meetings were held with different objectives. A number of meetings were held for presenting the developed framework to experts in companies for obtaining views from industry about the framework. A few other meetings were more specific about sub-topics of the framework, and these were intended for data collection and review of results. The experts were selected based on having expertise views from both academia and industry. Expert 6 and Expert 5 had the experience of working with a wide number of SMEs and could review the framework based on SMEs characteristics and requirements. Expert 1 and 2 contributed through their expertise view on more specific topics of the framework that needed further consultation from experts in method development. Experts 7 and 8 were representatives from a commercial package and as experts in Cost Engineering themselves discussed the potential of commercialisation of the developed framework, in addition to reviewing the framework based on their expertise view in the field of Cost Engineering.

Table 3-2 List of meetings

Expert	Expert number	Company	Role	Date	Topic
Dr Patrick Mclaughlin	1	Cranfield University	Senior lecturer	19/03/2012	Factory layout
Reg Isherwood	2	JLG	Senior cost engineer	30/03/2012	Factory cost estimation
Justyna Spurtacz	3	Cranfield University	Research assistant	24/08/2012	SME research
Prof Richard Weston	4	Cranfield University	Consultant professor	24/10/2012	SME analysis
Angus Brummitt-Brown	5	National grid	Process Improvement Manage	05/03/2013	Framework
Chris Perry	6	MAS	Consultant	26/03/2013	SME networking
David Simms	7	Galorath	Business Development Manager	10/04/2013	Framework
Steve Robinson	8	Galorath	Business Development Manager EMEA	10/04/2013	Framework
Bob Mills	9	JLR	Senior Manager Cost Estimating		Framework
Yuchun Xu	10	Cranfield University	Lecturer in Cost Engineering		Framework

3.4 Research strategy

The research strategy is explained in this section.

3.4.1 Understanding the context

The first step in any research is to understand the context of the research. In this research reading about background knowledge and exploring the relevant subject areas was the first step in understanding the context. Part of the research context is understanding the studied company as an SME. Holding meetings and running initial workshops such as Value Engineering helped to get familiarised with the studied company and their product. Having an interview with the managing director of the company and using exploratory questions was the main technique for understanding the context. The workshops helped to explore the product configuration and understand the product in terms of its functions and values. Further, the VE workshops helped to develop understanding of value and cost in the researcher as well as the company.

As the researcher had a background different to the research area and the research topic is multi-disciplinary, some portions of the research time was spent to learn and explore the new areas. These were mainly done by reading text books. In addition, attending a short course with the title of Cost engineering for the oil and gas industry, helped in developing the background knowledge.

Background readings in the areas of Cost estimation, Value analysis, Cost reduction techniques, manufacturing processes, factory layout, Make or buy, outsourcing, manufacturing processes and materials and engineering, to understand the product better, developed concepts in the potentially wide field of Cost Engineering. Also, as this project involves working with computer software, related training was sought. The software used was mainly Microsoft Office, Visio and Project, Mindjet MindManager, Dassault Systèmes SolidWorks, Lanner Witness and Galorath SEER-MFG.

In this stage, the initial aim and objectives of the project were determined and they were discussed and confirmed in meetings with parties involved in the project.

In order to gain information about the research done on topics related to this project and to be familiarised with the journals, published papers and the top researchers in this field, a review of the literature was done. The first step of the literature review was to explore and scope the areas related to this project. In the next step the review was gone into detail and the knowledge gaps were identified and furthermore it was found out what potential contribution to knowledge could be made. Also state of the art techniques and methods were identified. During the literature review the findings of other researchers were evaluated and a critical analysis was completed.

Furthermore, a basic understanding of the product and the company's plans was formed and an AS IS model of the company was developed. This was achieved by having several meetings with the company members and holding a number of workshops.

At this stage of the project it was necessary to determine what objectives and tasks are in the scope of the project and what is out of scope.

Table 3-3 List of events attended

Events attended
SCAF conferences and workshops
ACostE annual conference
ICMR conference 2012
ICMR conference 2013
SMEs networking event
Research methodology course – University of Cambridge
Cost Engineering in the Oil and Gas Industry short course

3.4.2 Data collection

Data collection involves collecting data needed to develop the methodology. These data can be collected through meetings with the product manufacturers or different data bases. The manufacturer has the most accurate data regarding the product.

The data collection was done mainly through observation and participation in the studied company. The researcher spent 10 months full time and 12 months part time in the company. The company was first located at Cranfield University, but later moved to Kiln Farm in Milton Keynes for which the travel to the company was one of the obstacles for the researcher. This meant larger office and workshop area which was required as the company was expanding.

During the stay of the researcher in the company, observation of day to day activities of the company and being involved in the development process of the product, helped to identify the current practices in the company. In addition, being in the company allowed for familiarisation with the development process of the product and the collection of the required data for developing the model and running case studies.

Being in direct contact with the employees was a significant advantage in obtaining information with the shortest possible delays. Although for having a productive stay at the company, having a plan of actions was critical.

Important data required to be collected from the company were detailed information about the product, current practices in terms of product development, product development plan and general information about the company.

As the case study was running throughout the research period, the data required for running the case studies were collected, in addition to the data required for the model development.

Depending on the phase of the case studies, specific related data was required. As an example, during the case study of the factory set-up cost estimation, in addition to data related to the product, data about the future production plans such as time shifts, supply chain management and delivery method were required.

One of the other sources for collecting data for the model development was the use of literature items. Analysing literature items such as journal papers, conference papers and reports helps to collect data about the state of the art methods and best practices in academia and industry.

For example, literature review was used to identify what cost reduction methods have been developed in the academia, what methods are being used in the industry and which are more suitable for the company being studied.

3.4.3 Data analysis

Raw data have no value unless analysed. The data gathered in the previous step are analysed in this step. The data are either quantitative or qualitative and each has specific methods of analysis. The data gathered during the data collection stage were a blend of quantitative and qualitative data. IDEF mapping, Process maps and Excel were tools used during this stage.

In this stage the model is being developed based on the data gathered both regarding the AS IS model of the studied company and the best practices.

Due to case studies running parallel to data collection and analysis, the feedback from the result of the case studies was used to modify the model and to develop it into more detail. In addition, during the model development, further data collection was required.

3.4.4 Validation

In this stage, the chosen methodology and results would be validated to make sure no mistakes have been made and to determine the accuracy of the methodology. In addition, results should be validated to show if they meet academic requirements of valid research. Also the results should be verified by the sponsor at this stage.

Some validation tasks have been started at this stage of the project. The most important task to do in this step is to run a case study and define suitable scenarios. Checking the results with experts in this field and also company members would also help the validation. As the project has two aspects of academic and industrial, two sets of validation are planned during the project. The validations are done by presenting results to experts from academia as well as experts from industry.

In this project two types of case studies are done. A case study is done by holding short workshops with the company members and by the participation of the researcher in the company which has been running during the time line of the project. The final case study has been commenced during the third year and involves the implementation of the developed framework in a step-by-step plan on the product.

The company has a project plan and has deadlines and more importantly has design freeze points. In order to help the company to achieve the requested cost reduction requirements, workshops with the company during the early stages of the PhD project were necessary.

Qualitative validation of the framework is another step taken to validate the research results. In this step the methodology and results were presented to experts in the field to verify the quality and credibility of the research. For this step, meetings with experts in industry were organised. The list of the meetings is presented in Table 3-2.

The research methodology steps including validation steps can be viewed in Figure 3-3.

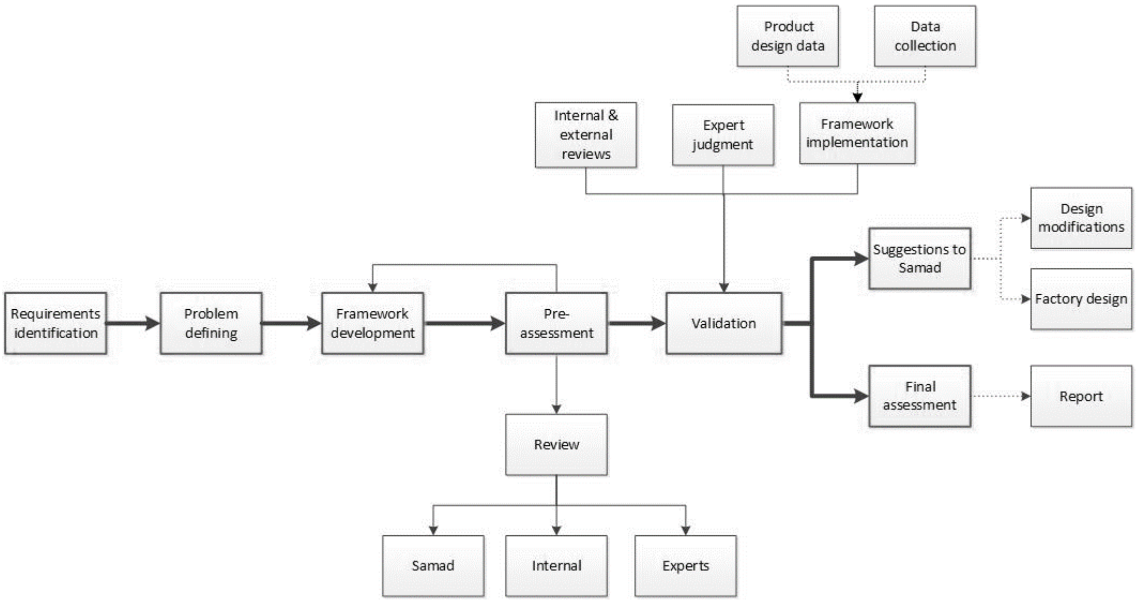

Figure 3-3 Research methodology process

3.5 Framework development

The framework development was based on SME requirements with focus on the collaborating company.

The development started with identifying cost reduction best practices. This was done through reviewing literature and background reading and creating mind maps of findings. Also expert opinion of supervisors and fellow researchers helped in identifying best practices.

In the next stage, some of the best practices appropriate for the collaborating company were selected and workshops were held with the studied company to implement these methods. The focus of the workshop first was on methods related to design modification for the purpose of cost reduction. Value analysis and value engineering, DFMA and target costing were the methods selected at this stage. But due to limitations in design changes because of mostly COTS parts and also because of the commercial priorities of the start-up SME, there wasn't enough opportunities to continue with these methods and the focus was moved to others methods.

One of the elements leading the framework development was the data requirement of the company. At different stages, the company required some data for the purposes of decision making or presenting to others. In order to obtain the data different methods had to be used.

One of the first data requirements was future production plant cost which was required by the individuals or organisations approached by the company for investing. Also, as one of the main identified requirements for SMEs was production cost estimate, knowing the production plant set-up cost was needed. This led to the development of a factory-set-up cost estimation tool. In order to have a low cost product, the production costs of the product should be kept low and this can be achieved by having a factory with lowest capital requirement and a low cost production line.

By evaluating the above requirements, it was realised that in order to design a factory, production line as the main area of a factory had to be designed. As the company was intending to use commercial off-the-shelf parts, assembly line would be the main area for production. Therefore, search for production and assembly line design methods started.

It was realised that for designing an assembly line, production processes have to be identified, and process selection is directly related to parts material selection.

One of the other identified requirements from the company was a ‘Make or buy’ decision making method. They needed a process to be able to select which parts to outsource and which parts to manufacture themselves and if they have made a decision, how to evaluate the decision against different factors. In addition, as the company had selected Outsourcing most parts as the production strategy, this method would be needed to evaluate their decision and to select suppliers. This led to the ‘Make or buy’ box of the framework.

One of the main requirements of the company itself and also as found in the literature, cost reduction activities require knowledge about a product’s future cost. The cost of a product and all its parts should be known in order to be able to reduce the cost. In addition, whilst developing the Make or buy cost, it was realised that the main core of the decision making process is to compare cost to buy a product to cost to make it. This led to the development of the cost estimation method.

In order to have a framework, all the required methods have to be ordered in a layout with logical connections together. Some methods were added because of the requirement arose from another method, but some like ‘Make or buy’ arose because of a requirement of the SME.

As an example, ‘Make or buy’ is positioned in the framework according to precedence in the work flow. The ‘Make or buy’ block needs some inputs and gives some outputs. It was realised that it needs cost data as input. And its output is needed directly by Production line design blocks. So it is positioned accordingly in the framework.

4 FRAMEWORK DEVELOPMENT

In this Chapter, the results of the framework developed are discussed in detail. The framework is developed based on the studied company requirements and the SME's requirements captured in the literature whilst addressing the requirements with best practices from literature and industry.

The framework is developed with a top-down strategy with the main focus on cost reduction of the production cost of a novel product developed by a start-up SME. Identification of the cost reduction requirements and opportunities was the next step of the framework development. The first level of identified methods is the top level of the methods.

In the next step and after validating the findings, the top level methods are developed into a greater level of detail. The scope of identified methods is limited to production cost reduction and limited to product development stages and production stages of the life cycle. The focus was kept on the developed product and production cost. The development was continued to the detail of each methods of the framework. The framework sections are presented in Figure 4-1.

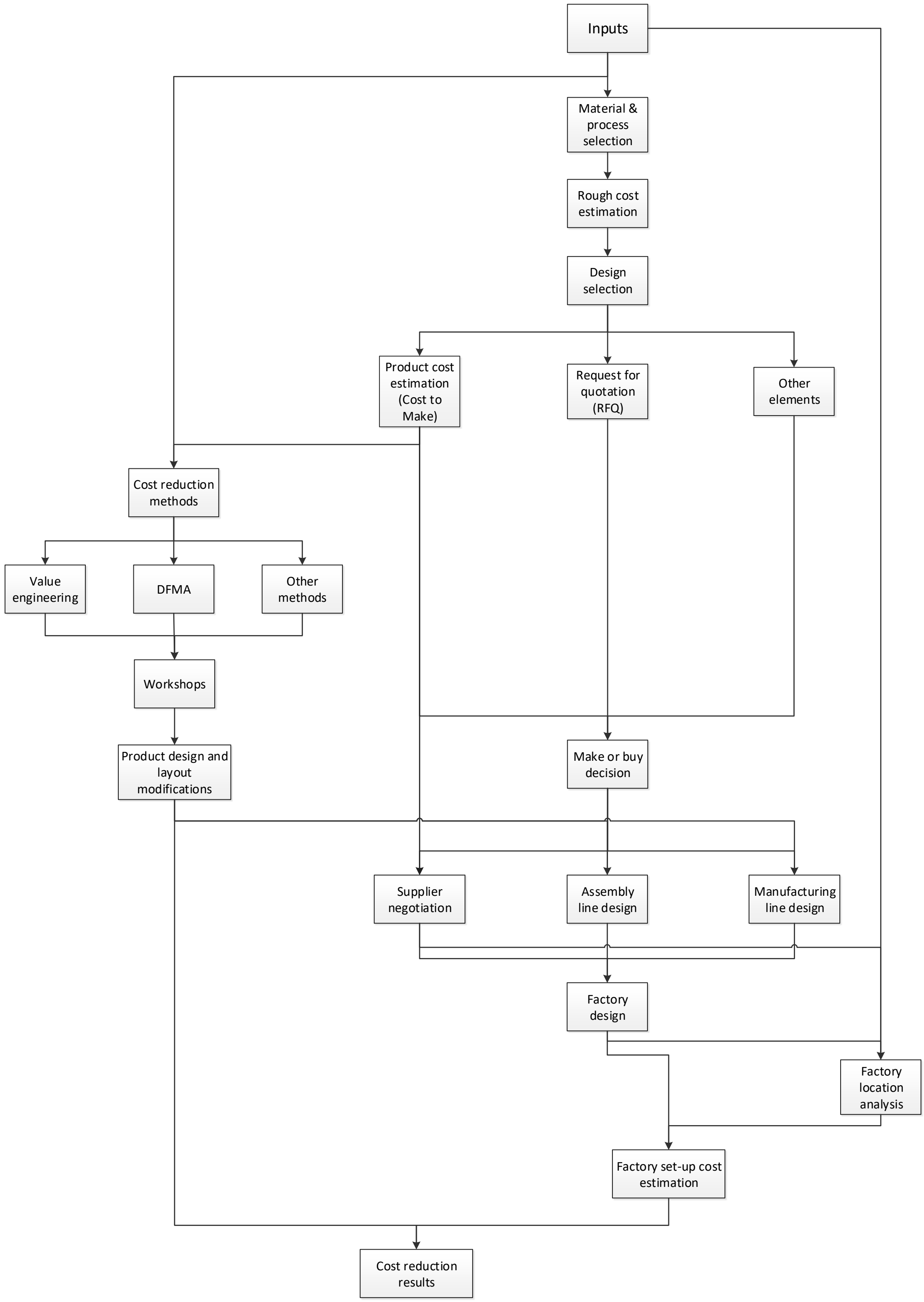

Figure 4-1 The developed framework in this research. Cost Engineering methods are shown in boxes and their logical relation is denoted with arrows.

4.1 SMEs challenges identification

4.1.1 Introduction

In this section the work done towards the objective ‘To identify challenges that SMEs are facing introducing a new product to the market’ will be discussed.

4.1.2 Method development

The results of this section are based on literature review, meetings with experts and analysing the collaborating company as shown is Section 3.5. The literature review gives a view of problems that SMEs face while introducing a novel product to the market. The results of the literature review related to SMEs characteristics and challenges is presented in Chapter 2.3. Surveys of large numbers of SMEs are mainly used to collect data about SMEs. In addition to the general view obtained through literature review, a more specific view is gained through observation and participation in the studied company.

For this section, most of the study was done by close analysis of the studied company. The data was collected through day to day observation of company activities and challenges. Majority of the researcher’s time at the company was spent by collecting data through engagement in various activities, as being engaged in the actual environment gives a better view of the actual challenges and better understanding of the data being collected, specifically activities related to product development. In addition, it had the advantage of being in close communication with the staff which gave the opportunity of quick data gathering directly from the staff and management.

Also the researcher has attended several meetings with investors and was aware of investment attracting processes of the management team. Three general assembly meetings were closely analysed by the researcher. In these meetings the progress of the company in a year were discussed and the business and technical plan for the upcoming year were presented.

A number of the meetings with the management of the company were specifically related to capturing the company challenges as an SME.

The minutes of the research related meetings were all recorded in a log book and for few the voices were recorded on audio. The voices were recorded with verbal permission of the attendees for research purposes.

4.1.3 Results

In this section, the results from studying the company will be discussed.

As mentioned earlier (Section 1.3) the company is a start-up organisation and in terms of maturity level it is in the managed level. According to European Commission's definition of SMEs (European Commission, 16/04/2012) and by considering number of employees, the company can be classified as a small enterprise, but by considering the turnover side of the definition, it can be considered a micro enterprise. In general, the company is on the margin of transforming from a micro organisation to a small enterprise.

It can be observed that resource constraints are a day to day challenge for the company. The resource constraints exist in terms of human resources and financial resources. It can be expressed that lack of human resources is a consequence of financial shortages. As most SMEs, the collaborating company started their business using personal finances. As they developed their product, they benefited from governmental grants. The nature of Samad Power's business required the use of external or internal investment due to lack of any turnover and the need of spendings on development costs and staff's salaries. Investor hunting is one of the CEO's roles. In order to convince investors, comprehensive business plan and product demonstrations are required. The use of director's personal funds is one of the financial resources of the company. Governmental grants and funds for technology development are another major source of funding the project.

Financial constraints have resulted in constraints in other areas, such as human resources. Lack of finances limits the organisation's will to employ required experts and skilled staff. These requirements have to be fulfilled by utilising current resources in other areas. Multi roles are assigned to employees and each employee has to cover different functions. As an example, the test engineer was dealing with administrative work and purchasing in addition to usual tasks of a test Engineer. Also whenever there was a need for extra help in other engineering tasks, he would get involved.

In such cases that the core members are co-founders of the company, the sense of responsibility of fulfilling multiple tasks and roles is even higher than later employed staff.

The multi-role responsibility of staff may result in role and tasks conflicts in the organisation. This would happen if the role borders are not well defined and lack of communication exists. Having a systematic and well defined organisational structure, reduces the risk of conflicts. In addition, maintaining continuous and cross section communications would help this and improve productivity.

As mentioned earlier, financial constraint is one of the main characteristics of SMEs. Also survival in the tight market competition requires competencies in different aspects in which price is one of the main competitive advantages. Managing profit is possible by managing cost and value. Utilisation of cost reduction and value improvement methods is a potential method to assist firms in reaching the desired profit margin (see Section 2.4). Different methods and techniques can be implemented at various levels of an organisation's activities and product life cycle and can result in short term or long term cost reduction and value optimisation. As an example, the implementation of Design for Manufacturing and Assembly (DFMA) methods during the early product development cycle would result in cost reduction at production and assembly stage. Over 70% of the total production cost is determined at the conceptual design stage (Pham and Ji, 1999).

It should be mentioned that due to nature of SMEs implementing such methods they may be confronted by various obstacles. Convincing the management team and changing their mind-set to implement such methods is a large obstacle in any organisation. Also lack of defined processes in an organisation's activities would cause difficulties during the implementation of these methods.

The studied organisation showed a frequent change in cost engineering requirements which caused difficulties in the process of implementing cost reduction and value improvement methods. The involvement of all of the staff in tense daily activities of the organisation, made it difficult to acquire free time for meetings and workshops to implement such methods.

In order to be able to study the company in more detail the process of activities in the company was monitored and a detailed process map was developed. The process map is illustrated in an IDEF0 diagram. The analysis is limited to activities related to the TGB project. This is due to the reason that other activities were added to the company's activities for the sole reason of income creating while the TGB has remained the core activity.

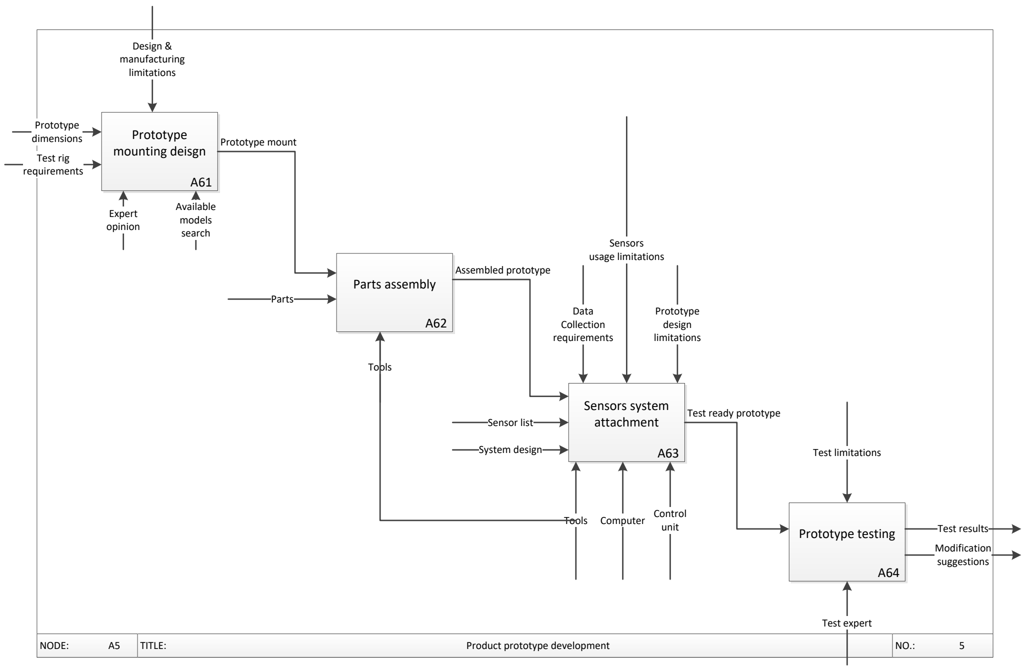

Figure 4-2 Sample of IDEF0 diagram showing function of product prototype development

The IDEF0 diagram helps to identify functions in a system as well as inputs, outputs, mechanisms and controls for each function. By using IDEF0, activities, decisions and actions in a system can be modelled. A sample of developed

IDEF0 diagrams is illustrated in Figure 4-2. All the IDEF0 maps developed as shown in Appendix A.1.

IDEF0 was selected out of a vast option of process modelling methods due to various reasons. IDEF0 focuses on function modelling which is the focus in the study of the company. This method through its graphical format gives a better view of the functions in the company compared to mathematical and textual methods. In addition to identification of functions, this method builds a broad view through showing the connection of function together and building a wide view of the system.

The findings from modelling the company helped to develop an AS IS model of current practices in the company which would lead to possible improvements in the system.

Using visual diagrams helps to compare the company AS IS practices to the best practices in literature and industry.

4.1.4 Discussion

The result from observation of the studied company is according to what is found in the literature in most aspects of management and development activities, although some characteristics were specifically due to manager's specific mind-set. In Table 4-1 the characteristics and practices of SMEs identified in the literature are compared to findings from the studied company. The table shows that the characteristic identified through literature review and characteristics identified through study of the collaborating company match completely which shows that the collaborating company is an appropriate selection for case studies of this research.

Table 4-1 Comparison of practices and characteristics of other SMEs to the collaborating company

	Other SMEs	Samad Power
Financial constraints	×	×
Lack of human resources	×	×
Owners managed	×	×
Board & management overlap	×	×
Manager multi responsibility	×	×
Motivation	×	×
Flexibility	×	×
Multi role of staff	×	×
Proximity to market	×	×
Operational agility	×	×

4.2 Cost Estimation method

In this section the development of a cost estimation method would be discussed. For definition of 'Cost estimation' see Section 2.5. This section would include an introduction, method explanation, results and discussion.

4.2.1 Introduction

A cost estimation method is developed in this chapter because a need for a suitable cost estimation method is identified for SMEs. This need has resulted from lack of Cost Engineering knowledge in SMEs, where Cost Estimation data are necessary for managing costs and therefore cost reduction tasks. The need was recognised through reviewing the literature which resulted in identifying SMEs characteristics. In addition, studying the collaborating company revealed their need of a cost estimation tool at product development stage. Furthermore, lack of Cost Estimation method development by other researchers in this area was seen through a literature review. In this chapter the development of 'a Cost Estimation method for start-up SMEs developing a novel product' is presented.

The development of the method began by thoroughly reviewing the literature related to the area of Cost Estimation. The review started at the wide area of production cost estimation and the search area was narrowed down to specific methods developed for start-up small enterprises involved in the design phases used in developing a novel product. The topics followed in this method are shown in Figure 4-3.

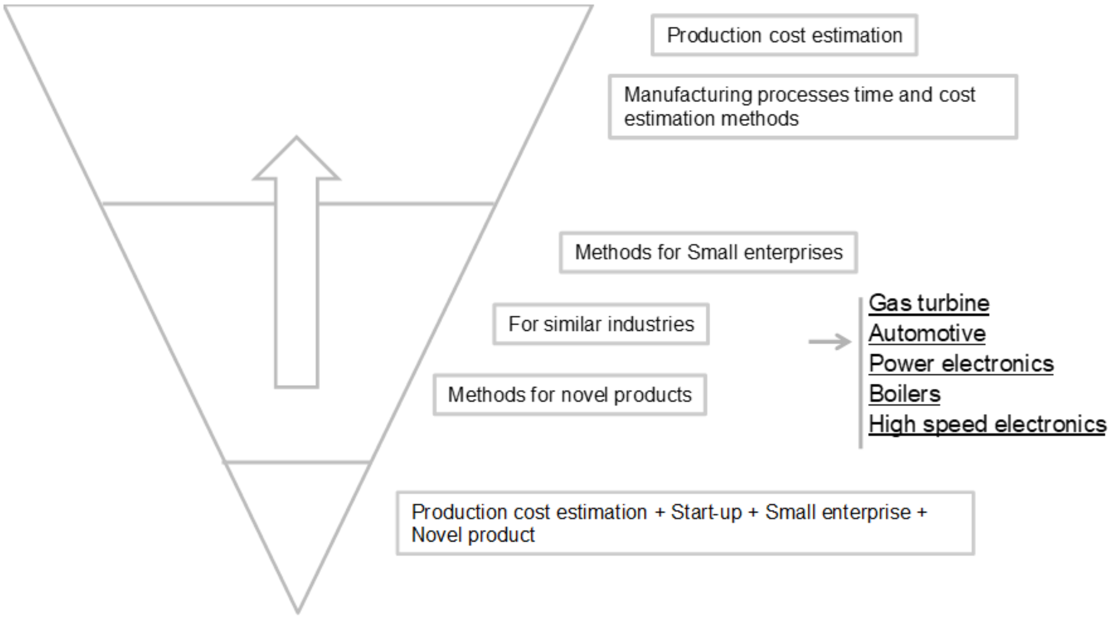

Figure 4-3 Focusing literature review topics for cost estimation

The main starting keywords used for searching in databases are as follows:

- Small business cost estimation
- SME cost estimation
- Small enterprise cost estimation
- Small enterprise costing
- Novel product cost estimation
- Start-up cost estimation

In relation to the research focusing of cost estimation methods for SMEs, most studies were related to implementing ABC in SMEs. The significant studies have been done by Roztocki et al. (2004), Needy et al. (2003), Bharara and Lee (1996) and Januszewski (2008). As discussed in Section 2.6, ABC is not a favourable method for SMEs developing a novel product. ABC is resource intensive and requires extensive activity cost databases.

By doing a further search it was realised that no significant production cost estimation method specifically developed for SMEs was found.

The focus of the review was moved to conventional cost estimation methods used by general industry. Curran et al. (2004) has listed the traditional estimating methods as shown in Table 4-2. Three main traditional methods have been listed in the table. Bottom-up costing, analogy costing and parametric costing are listed in the table. Bottom-up costing is a very detailed estimating method that requires expert knowledge and substantial detailed expert data should exist. For Analogical costing again expert knowledge is required and additionally an appropriate baseline should exist for the analogy. Parametric costing is the easiest to implement compared to the two former methods, but requires existing data for the development of parameters.

Table 4-2 Tradition cost estimation methods (Curran et al., 2004)

Approach	Advantages	Disadvantages
Bottom-up	Cause & effect understood	Difficult to develop & implement
	Very detailed estimate	Substantial, detailed expert data are required
		Requires expert knowledge
Estimate by analogy	Cause & effect understood	Appropriate baseline must exist
	More easily applied than the bottom-up method	Substantial, detailed data are required
		Requires expert knowledge
Parametric	Easiest to implement	Can be difficult to develop
	Non-technical experts can apply method	Factors might be associative buy not causative (i.e. lack of direct cause-and-effect relationships)
	Uncertainty of the forecast is generated	Extrapolation of existing data to forecast the future, which might include radical technological changes, might not be properly forecast
	Allows scope for quantifying risk	

In addition to the traditional methods, modern methods have been developed using advanced techniques such as:

- Featured-based costing
- Fuzzy logic
- Neural network

Fuzzy logic and Neural network are advanced methods that require extensive mathematical knowledge for development and can be considered too advanced for SME users. Featured-based costing is a modern method based on estimating costs based on feature parameters and requires substantial expert knowledge and existing manufacturing data to extract cost estimating relationships.

One of the most comprehensive method classifications has been suggested by (Curran et al., 2004). Curran et al. (2004) have classified methods into two groups:

1. Generative or Compilational costing: aggregating various identified costs.
2. Relational costing: comparative relation of product defining parameters.

The following methods are categorised as compilational costing:

- Activity-based costing (ABC)
- Absorption costing
- Bottom-up costing
- Life-cycle costing (LCC)
- Scenario-based reasoning
- Feature-based costing

Relational costing methods include:

- Physical process modelling
- Parametric
- Neural nets
- Analogous costing
- Case-based reasoning
- Fuzzy logic
- Financial modelling

Another categorisation is suggested by (Collopy and Eames, 2001). They have divided models into two groups:

- Parametric models
- Process cost methods

Lin et al. (2012) mentions that manufacturing process cost models are more accurate than parametric models, but need much more detailed information at the beginning of an estimation process. Also process cost models are owned by large aerospace companies and their cost databases are confidential. In addition the process cost models cannot be used for new design processes (Lin et al., 2012).

In addition to the generic cost estimation methods, the industrial specific developed methods have been reviewed. The focus of the review is on the industries similar to the product being developed by the studied company. The identified industries are

- Automotive
- Boilers
- Gas turbines
- Power electronics
- High speed electronics

Roy et al. (2005; 2011) have published papers specifically focusing on cost estimating methods for the automotive industry. Roy et al. (2005) have developed a method based on parametric, analogy and detailed estimating techniques to estimate the cost of a new automotive product with a high level of new technologies. In this model, the new technology and current technology parts are segregated and an estimating method for each group is developed. For current technologies, an analogy method is used to use historical data to obtain the cost of a part. For new technologies, the method depends on whether a comparator can be found from other parts of the company or other industries. If a CER exists for the comparator, it can be used by adjusting it according to the new product. If not, the cost has to be estimated using expert judgment. The process flow of the model is shown in Figure 4-4.

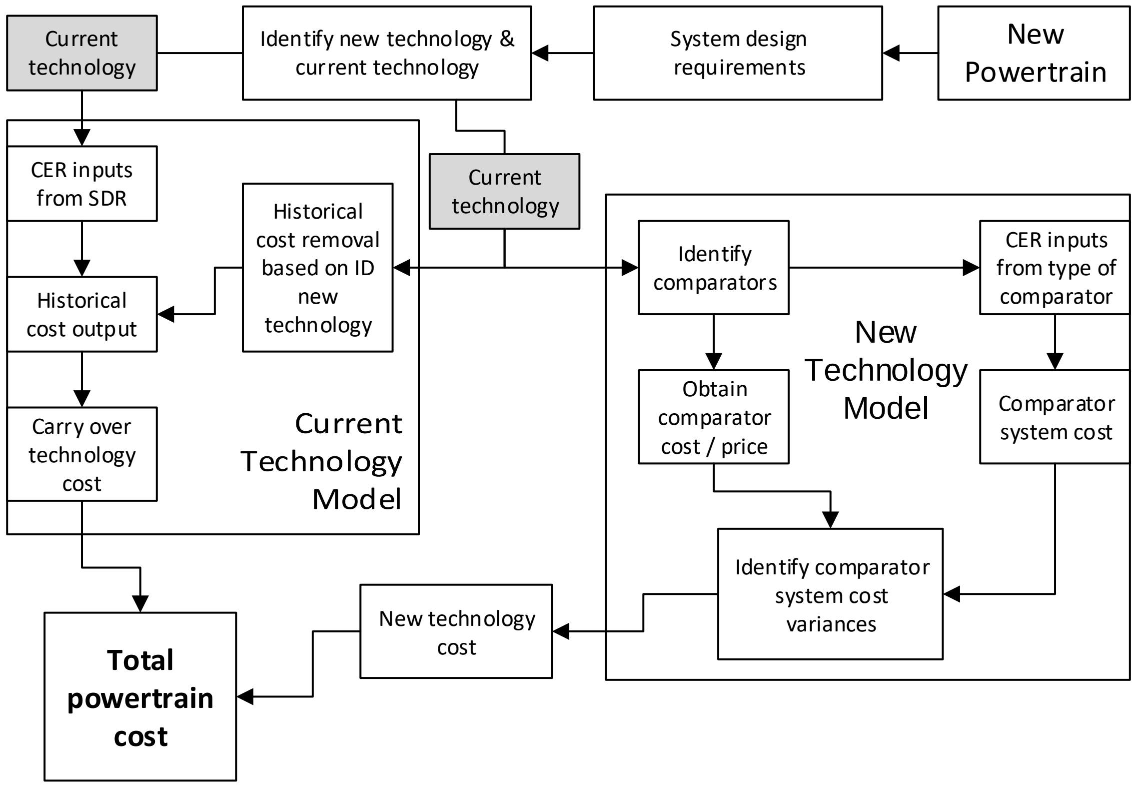

Figure 4-4 "A conceptual process flow for the new technology cost model" (Roy et al., 2005)

Roy et al. (2011) have identified the data needed for cost estimation in the automotive industry and constructed the data in a structured way to be used in a web portal. During the research they have developed a detailed cost estimation process which is developed more into detail in terms of steps and information usage of descriptions (Figure 4-5). Some of the steps of this process need further levels of detail. Cost models need to be specified for producing piece costs and tooling costs. Depending on the manufacturing processes and machines used a specific cost model should be used. Expert judgment has an important role in product costs at this stage. Piece cost and tooling cost can be obtained using one of the above mentioned methods.

The advantage of this process is that all the common costs that need to be considered to be added up to the final cost estimate have been considered in the process. And the simplified process can be followed step by step to deliver a cost estimation.

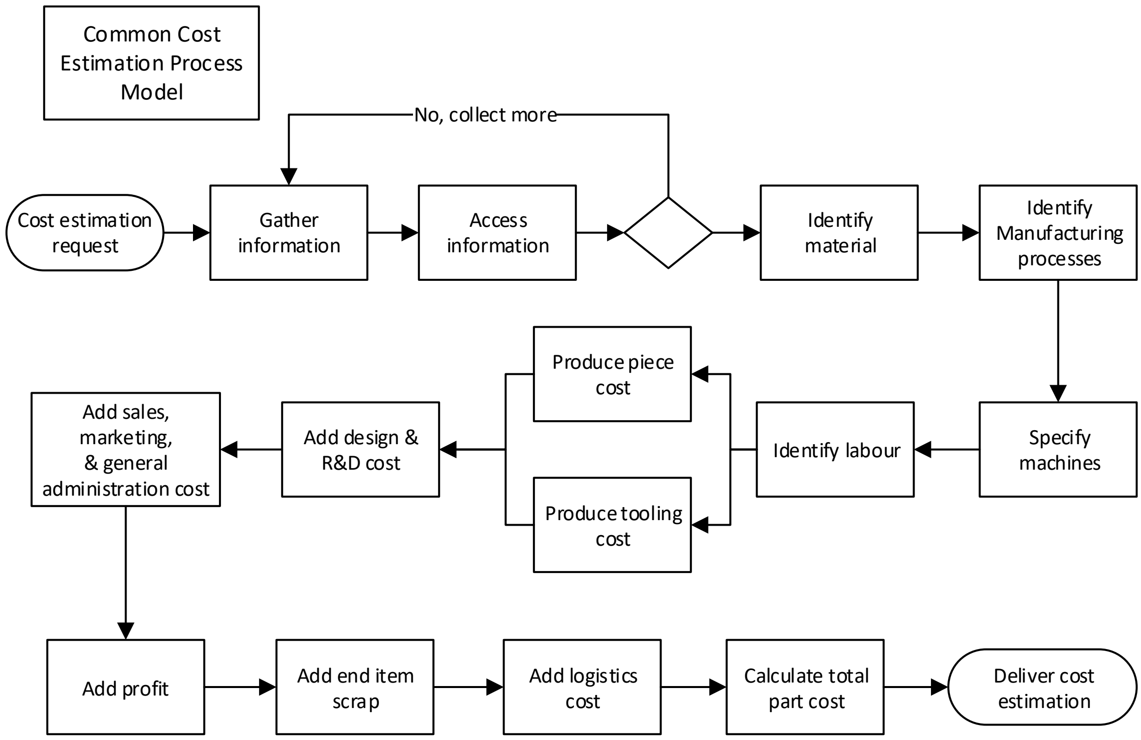

Figure 4-5 Detailed bottom up cost estimating process (Roy et al., 2011)

One of the industries very close to micro CHP industry is the boiler industry. Boilers and micro CHP share many similar components and are used for the same application which is heating and hot water, although micro CHP has an extra product which is electricity. By reviewing the literature no methods were found which have been specifically developed for boilers or similar products.

One of the other industries which have similarity to micro turbine CHPs is Gas turbine (Aerospace) industry. A research has been done on the development of an integrated model for estimation of production cost of helicopter blade assembly. The research by Lin et al. (2012) has focussed on the design process and the model would include an automated process. This model includes a method for manufacturing time estimation of a design, manufacturing system performance evaluation and cost estimation using ABC (Figure 4-6). One of the inputs to the model is CAD data which should be parameterised using the parametric model generation module. The advantage of this process is considering models for time estimation of various processes to make a blade.

The authors have considered a design optimisation module for DFM in the process. Although the process is quite application specific.

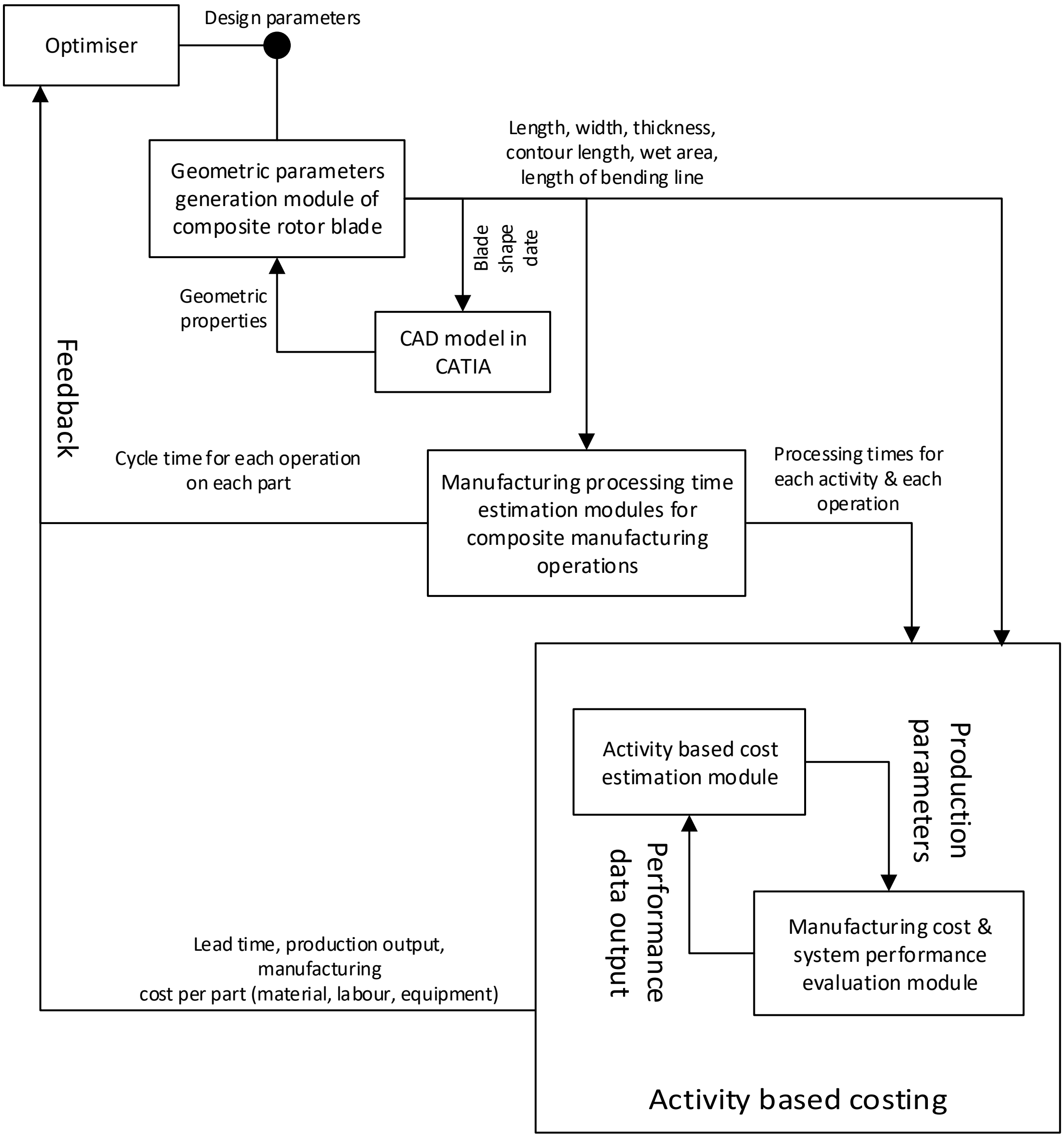

Figure 4-6 Cost estimation process based on product design optimisation (Lin et al., 2012)

4.2.2 Method development

Roy et al. (2011) have presented a detailed bottom-up cost estimation method in a diagram (Figure 4-5). The diagram shows the process step by step.

Because of the advantages of the process developed in research (Roy et al., 2011) specifically simplicity of the process and covering major production costs, this process is selected as the main structure of the cost estimation process.

The cost estimation process starts with gathering information. For cost estimate, information regarding the reason for cost estimation, degree of accuracy and estimate delivery date need to be known. After knowing basic knowledge about the cost estimate, information is required to produce the cost estimate which is needed to be gathered.

For a designed part, CAD engineering drawings contain key information such as dimensions, weight and material. For purchased parts, information can be obtained from the supplier or OEM. If all the information cannot be obtained in this way, the part can be analysed in-house and by using expert knowledge or experience the information can be obtained. Also making approximate drawings of a part can help in analysing an outsourced part.

The detailed cost estimation process depends on the manufacturing process and accordingly the required information depends on the manufacturing process. Estimating the process time for each process follows a specific model. The machinery used for each process are different in type and the amount of involvement of labour in each process is different.

For internal data collection, the cost estimator would be in charge of internal data collection. For external information gathering, the person in most contact with the external source could be involved. Usually sales person is appropriate for this task. In addition, reviewing suppliers or OEM websites and catalogues could be useful. Free online CAD databases could be searched for possible similar or approximate CAD files. The found CAD models should be validated by comparing with the actual part. Online databases can be searched for other necessary information that cannot be obtained through trusted sources.

Organising the collected data is critical, so they could be accessed and analysed easily. Recording data in Excel spreadsheets and using product breakdown structure for organising data is recommended.

The next step in the estimating process would be identifying material. In the case of the studied product, the material has been selected by the designer based on technical requirements and typical manufacturing process. The designer has followed a scientific material selection process based on various requirements and would use finite element method (FEM) simulation for structural and heat transfer analysis for verifying the material selection. The material selection is done based on requirements which mainly are working temperature requirements, structural properties of the material, manufacturing processes involved in fabricating the part, environmental conditions such as humidity and corrosion, physical requirements such as mass, electromagnetic requirements and cost requirements.

Karana et al. (2008) have reviewed the material selection criteria defined by other researches. The list of the criteria is as follows:

Mechanical properties, Physical properties, Chemical properties, Electrical properties, Acoustical properties, Optical properties, Dimensional properties, Business issues, Processing and fabricability, Life of component factors, Cost and availability, Codes, statutory and other, Property profile, Processing profile, Environmental profile, Eco- attributes, Aesthetic attributes, Thermal properties, Environmental resistance, Wear, Corrosion/ oxidation, Service requirements and Maintenance.

As a point of reference Cambridge Engineering Selector (CES) can be used. Material handbooks such as ASM material handbook are also useful references at this stage.

Process selection can be done using CES. Manufacturing process selection mainly is dependent on the type of material and production volume, but other elements such as production tolerances, surface roughness, etc. are considered. Having practical production experience and knowledge about current best practices can be useful in this stage. For detailed manufacturing process selection methods the book by Swift and Booker (2013) can be referred to.

For bought out parts, information can be sought from suppliers or OEMs or otherwise expert judgment can be used.

The next step would be machine selection; this step would be done based on the process selected in previous stages. Different machines for a process can exist, and can have different utilisation rates, depreciation and utilities cost. Machine specification can be done by consulting production experts or machine OEMS or if the knowledge is available, personal judgement. Depending on the production volume and production strategy, the number of machines and equipment should be considered. Machine selection methods have been developed by researchers considering various criteria and using different decision making methods. A sample of these methods is developed by Myint and Tabucanon (1994) based on AHP for machine selection for flexible manufacturing systems. The multiple criteria that they have used for the decision making can be seen in Figure 4-7. The criteria are grouped into 6 groups of Investment cost, Capacity, Flexibility, Utilisation rate, Unit cost and Economic risk.

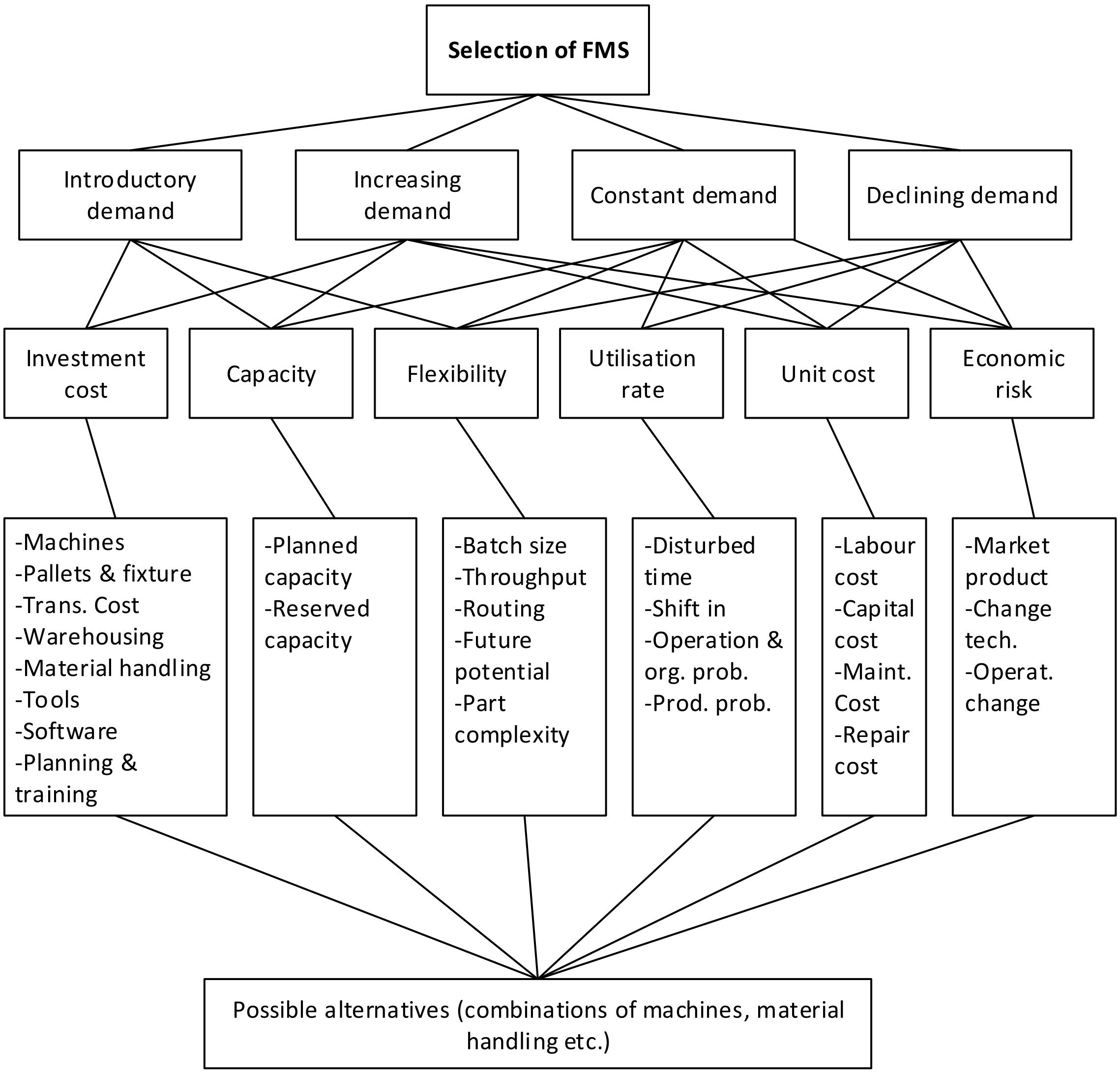

Figure 4-7 - Multi-criteria hierarchical structure for decision making (Myint and Tabucanon, 1994)

Following the estimation process in Figure 4-5, the next step is identifying labour. By specifying type and number of machines, the number and skill level of labours needed for the production can be specified. Number of working hours may also depend on the production volume. Depending on production plans, there might be more than one working shift. In a small company, the labour might be involved in other roles as well.

The next step in the process is producing piece cost and tool cost which are the core of cost of a product. Roy et al. (2011) mentions that the piece cost and tool cost estimate should be separated. Compared to the piece, tools are changeable parts of a machine and last for a certain amount of production and are often paid for in advance so the production can begin. Therefore, it is important to know how many tools are needed for the intended production volume. The piece cost would be the sum of labour, material and machine cost except tooling cost. Overhead costs would be added later in the calculation.

For the piece cost, depending on the manufacturing process, the best cost model should be selected. For the case of the collaborating company, casting and machining are the two main processes used to manufacture parts.

Jung (2002) has developed a model for machining cost estimation.

$$\begin{aligned} Manufacturing\ cost = (R_0 + R_m)\left(\frac{T_{su}}{Q} T_{ot} + T_{no}\right) \\ + material\ cost \\ + factory\ expenses \end{aligned} \quad \textbf{(4-1)}$$

Where, R_0 is operator's rate. R_m is machines rate. T_{su} is set-up rate. T_{ot} is total operation time. T_{no} is non-operation time. Q is batch size.

For obtaining times where the actual operation is not available for time study, correlations developed by other researchers based on empirical data can be used. Jung (2002) has presented various models for calculating the machining time for creating different features by machining. Also Jung, JY. (2001) has presented tables of approximate values for set-up times and material removal rates and surface generation rates.

One of the major manufacturing processes is casting. Madan et al. (2007) have reviewed the models developed for casting and has presented them in a table presented in Table 4-3.

Table 4-3 Cost estimation models for casting reviewed by (Madan et al., 2007)

System	Input	Issues addressed	Methodology	Remarks
Lowe and Walshe (1985)	Eight-digit code representing part geometric features	Labour cost for die making	Retrieval system with the help of a nine-digit code based on part geometry	Calculates the labour cost for die manufacturing
Poli *et al.* (1988)	Six-digit code based on geometric features	Early die cost and cycle time estimation	Computations by applying knowledge in the form of charts and graphs	Finds die cost with respect to a reference part
Dewhurst and Blum (1989)	Part geometric characteristics, alloy properties, machine capabilities	Die-casting cycle time, part cost	By application of empirical relations	Die cost based on total volume of material removal
Bidanda *et al.* (1998)	Manual input of geometric characteristics and other information	Permanent mould cost	System checks the manufacturability in steps as the user inputs information	Knowledge displayed to the user, works with the help of user interactions
Chen and Liu (1999)	User interacts with the system to evaluate the design for cost effectiveness	Preliminary design evaluation for injection moulding	Cost model for design effectiveness, geometric characteristics and cost analysis	Features as units of cost, limited to die cost only
Shing (1999)	Part geometric characteristics , alloy properties, machine capabilities	Part cost	Use of empirical relations	User inputs the number of cavities
Shehab and Abdalla (2002)	Envelope dimension and volume of part are extracted from the geometric model	Die cost	Computations based on empirical relations knowledge	Attempt for automation, other input is manual
Park *et al.* (2002)	Part geometry characteristics	Total cost	Die cost, processing cost and material cost	Applicable to single cavity, machine clamp force as constraint
Wang *et al.* (2003)	Eight-injection part feature factors are input manually	Die cost	Case-based reasoning and artificial neural networks	Part library is updated if a new case is found
McAdams and Bidkar (2003)	Manual input of part characteristics	Die cost	Uses Dixon-Poli method for manufacturability analysis	Simple features such as hole and boss are extracted
Nagahanumaiah and Mukherjee (2005)	Part feature characteristics	Die cost	Part feature mapping with mould die for calculating manufacturing cost	Uses machine hourly rate to find manufacturing cost

Casting cost can be divided into the following costs:

- Tooling cost (Mould die cost, Trimming die cost)
- Die material cost
- Processing cost
- Energy cost

A costing model has been developed by Nagahanumaiah et al. (2005) for die tooling cost.

$$C_{mould} = C_m + \left[C_{bmc} \times \left(1 + \frac{\gamma}{100}\right)\right] n_c + C_s + C_d \quad \textbf{(4-2)}$$

C_{mould} total mould cost,

C_m die material cost,

C_{bmc} basic manufacturing cost,

γ cost modifiers,

n_c number of cavities,

C_s secondary element cost,

C_d tool design and tryout charges

In order to calculate die casting process time, Madan et al. (2007) suggest to calculate the cost for single aperture trimming die cost with the help of part geometric data and the knowledge base. The model is as follows:

Die-casting cycle time and processing cost

Total processing time = Molten metal pouring + metal filling + metal cooling + die opening + part extraction + die lubrication + die closing

$$C_{pc} = \left(\frac{T_{su}}{N} + \frac{T_{cy}}{n_c . y}\right) R_{op} \quad \textbf{(4-3)}$$

C_{pc} die-casting processing cost,

T_{su} set-up time,

T_{cy} machine cycle time,

N batch size,

R_{op} machine operating rate,

n_c number of cavities,

y production yield (< 1).

Trimming cycle time and processing cost

$$C_{tpc} = \left(\frac{T_{tsu}}{N} + \frac{T_{tcy}}{n.y}\right) R_{top} \tag{4-4}$$

C_{tpc} trim processing cost,

T_{tsu} trimming set-up time,

T_{tey} trimming machine cycle time,

R_{top} trimming machine operating rate.

Material cost

The amount of metal fed = the cast material + overflow material + the amount in the feed system

$$V_s = V_c + V_o + V_f \tag{4-5}$$

V_s total shot volume (cm^3)

V_c cast volume (cm^3)

V_o Overflow volume (cm^3)

V_f volume of the feed system (cm^3)

In material cost calculation, it has to be noted that extra material can be reclaimed and used later. Also, material lost during the processing and handling has to be considered.

$$C_{mt} = [V_c C_w \left(1 + \frac{f}{100}\right) + V_s C_f](\frac{\rho}{1000}) \quad \textbf{(4-6)}$$

C_{mt} material cost / component,

ρ material density (g/cm^3),

C_w alloy unit price (£/kg),

f percentage of material loss,

C_f flux charges £/kg of alloy.

Energy cost

Energy is used for melting metal and holding the molten metal in a furnace.

$$Energy\ cost = \frac{Q_{total}}{Q_{fuel}} \times \eta_{fur} \times C_{fuel} \quad \textbf{(4-7)}$$

Q_{total} total heating value required/kg of alloy,

Q_{fuel} heating value of fuel/kg,

C_{fuel} cost of fuel £/kg.

Add overheads and logistic costs

Finally, costs related to design, R&D, sales and marketing and administration costs should be added. In addition, logistic costs are to be considered, mainly to transfer the good to the customer.

One of the important areas in cost estimation is data storage. The data and information gathered should be stored in a defined way, so that they can be accessible easily in future. One of the common ways is to use a product breakdown tree structure for storing data. All parts and components need to be coded for easy access. Usually coding systems would be defined internally, and include characters related to their top system, assembly and sub-assembly and the version.

In any cost estimation, the estimate needs to be corrected for mass production. Learning curve is one of the elements affecting the estimate for mass production. The productivity of labour would increase as they repeat a task or process due to learning curve. For mass production tooling cost and set-up cost would be divided by the batch size or the number of parts the tooling can be used for.

4.2.3 Case Study

Samad Power Ltd. is developing a combined heat and power product with micro turbine engine. The company is trying to use available technologies in the automotive industry for making the gas turbine engine to reduce costs. Also the system includes some parts with new technology. These parts had to be designed and developed. Also some modifications have been done to the available technology parts such as modification to turbocharger parts. For other non-core parts, such as heat exchanger and pumps, off the shelf parts have been used. Some parts of the product's core are shown in Figure 4-8.

For the cost estimation, some characteristics of the company have to be considered. As the product being developed is novel, no similar product can be found. But this novel product includes some parts which are off-the-shelf or some parts that have similarities to parts being used elsewhere. It should be considered that the company is a start-up and no historical cost data is available internally. And also for new technology parts no cost data can be obtained. And due to the nature of the development stage, there would be high levels of uncertainty and some changes to the product or parts would happen in future.

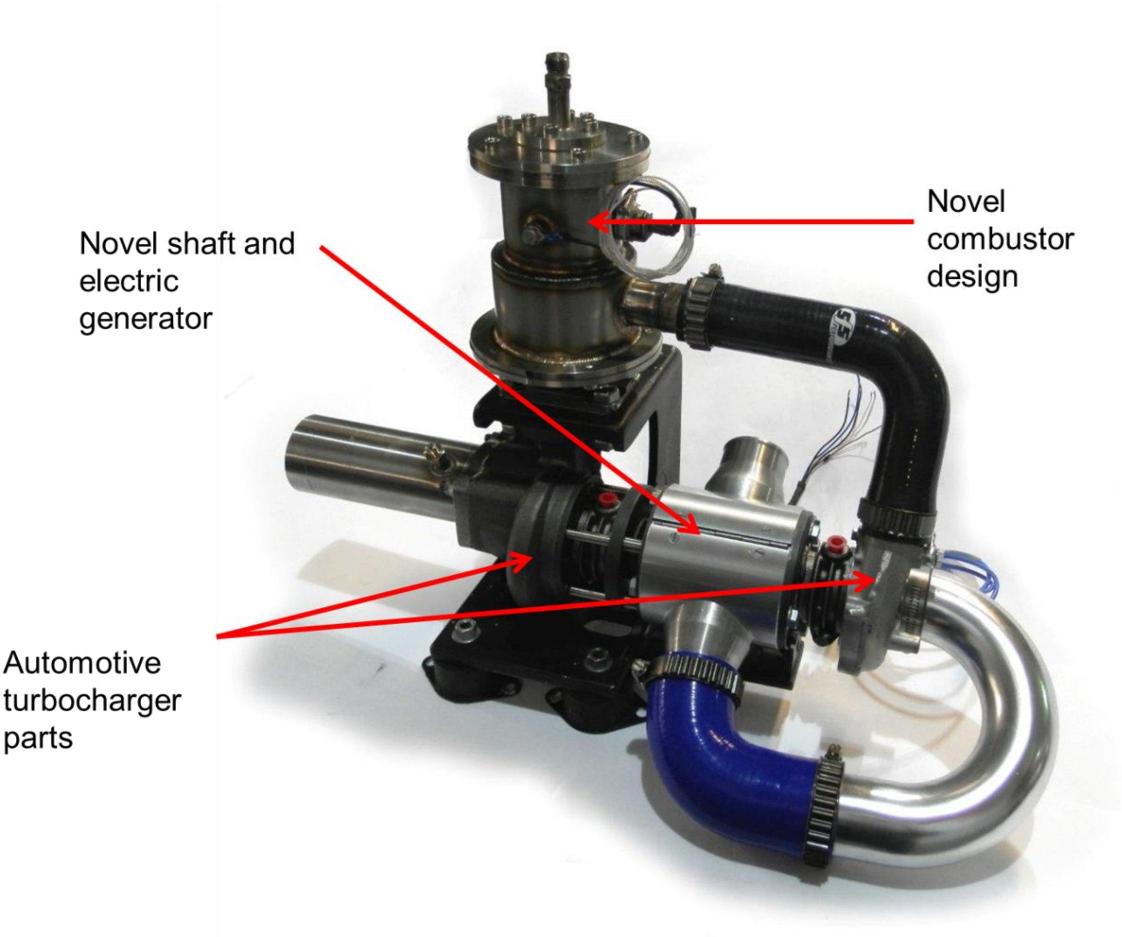

Figure 4-8 Gas turbine engine of the TGB product

The aim of this case study is to follow the developed cost estimation method for two of the main parts of the gas turbine. The data are collected from internal and external sources and Microsoft Excel spreadsheets are used for data analysis. The internal sources for collecting data are the technical team and the managing director, in addition to the free access of the researcher to the actual parts and engineering drawings. Also, the participation of the researcher in design tasks has developed internal knowledge about the parts. The external sources of data are tier one suppliers and partners.

Data are mainly extracted from CAD drawings and physical and visual analysis and measurement of the actual product.

Data are available in the forms of engineering drawings, material information, manufacturing processes, factory data, physical part and part specifications.

Some of the data such as engineering drawings, material information and part specifications are not released by the OEMs for the off-the-shelf parts.

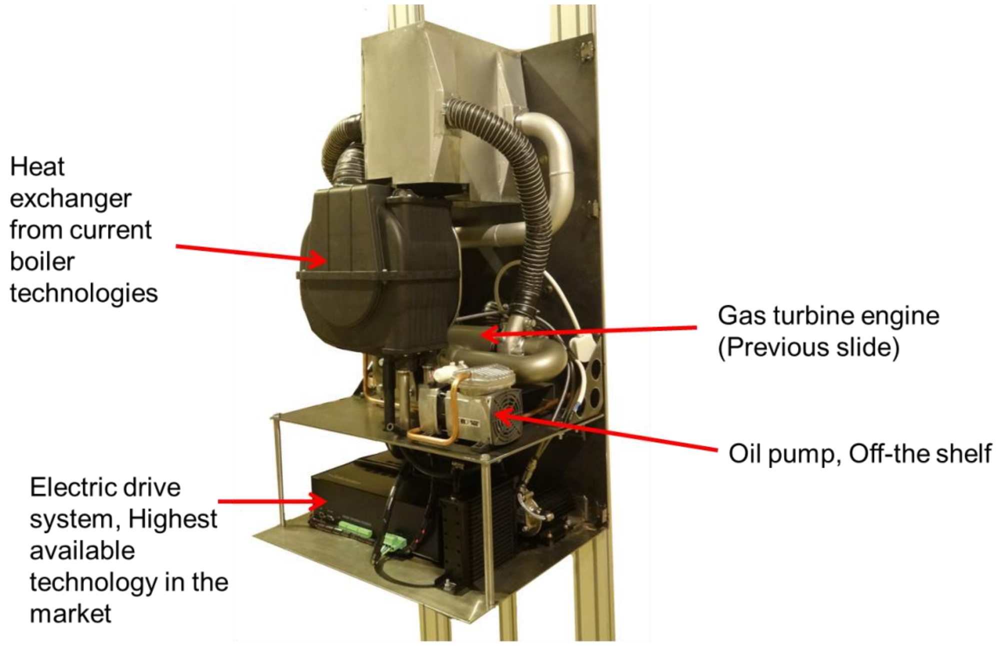

Figure 4-9 Main components of the TGB

For the case study two main parts were chosen; the compressor wheel and the shaft. The reason for this selection is the two different processes that these parts are made with.

4.2.3.1 SHAFT

The shaft is made out of 3 pieces. The material of the shaft is case hardening Steel EN36B (The data sheet can be seen in Appendix E.1).

Figure 4-10 – Three parts of the shaft

The properties of the shafts are as **Error! Reference source not found.**.

Table 4-4 The properties of the shaft parts

Part	Shaft part 1	Shaft part 2	Shaft part 3
Designer	Samad Power ltd	Samad Power ltd	Samad Power ltd
Manufacturer	Owen development	Owen development	Owen development
Material	EN36B	EN36B	EN36B
Primary method	Machining bar stock	Machining bar stock	Machining bar stock
Secondary method	Heat treatment	Heat treatment	Heat treatment
Weight (g)	56	50	110 (inc. Turbine)
Length (mm)	129.70	96.40	96
Max. diameter (mm)	14.60	12.20	15.30

In order to calculate the material size, the total amount of material used for each shaft needs to be calculated. Also, this should be used to obtain the total material needed for the batch size. For the shaft, certain length of round bar of Steel would be used. For round bars the dimensional cost drivers are diameter and length.

The minimum diameter and length of material needed for each shaft and batch size are as follows, this data are extracted from engineering drawings:

Table 4-5 Material cost estimation for the shafts

Part	Material	Stock diameter	Stock length (mm)	Material cost [assumed] (£/m)	Total cost (£)
Shaft part 1	EN36B	5/8 in dia. bar	155	5	0.78
Shaft part 2	EN36B	5/8 in dia. bar	115	5	0.58
Shaft part 3	EN36B	5/8 in dia. Bar	110	5	0.55
Batch size (Q)			83		
Total stock length for 83 units [min.] (mm)			**31540**		

Also the volume of material removed to make a part has been calculated as:

Table 4-6 Volume removed after machining

Part	Material	Stock diameter	Removed volume (mm^3)
Shaft part 1	EN36B	5/8 in dia. bar	17955
Shaft part 2	EN36B	5/8 in dia. bar	16428
Shaft part 3	EN36B	5/8 in dia. Bar	14016

The removed volume has been calculated from the CAD drawings.

List of operations for the parts are presented in Table 4-7. These operations have been obtained from CAD drawings and expert knowledge.

Table 4-7 Features and manufacturing operations to make shaft part 1

Part	**Material**	**Stock diameter**	**Feature**	**Operation**
Shaft part 1	EN36B	5/8 in dia. bar		
			Hole	Drilling
			Thread	Threading
			Step	Turning
			Step	Turning
			Hex	6 face remove
			Step	Turning
			Groove	Turning
			Cylinder	Turning
			Groove	Turning
			Cylinder	Turning
			Step	Turning
			Step	Turning
			Thread	Threading

The material remove rate for EN36B has been estimated using Table 4-8 developed by Jung (2002) and by comparing to similar materials. It is assumed that HSS tools will be used.

Table 4-8 List of material remove rate for different materials (Jung, 2002)

Material	Hardness (BHN)	MRR turning (in^3/min)	MRR face milling (in^3/min)	MRR end milling (in^3/min)	MRR drilling (in^3/min)
Low Carbon Steel	150-200	0.48	0.25 x *n*	0.08 x *n x l*	3.8
Medium Carbon Steel	200-250	0.42	0.23 x *n*	0.05 x *n x l*	3.4
Alloy Steel	150-200	0.50	0.22 x *n*	0.05 x *n x l*	3.6
Stainless Steel	135-185	0.50	0.23 x *n*	0.06 x *n x l*	2.3
Tool Steel	200-250	0.27	0.11 x *n*	0.02 x *n x l*	1.2
1in diameter tool; *n* is the number of teeth per cutter and *l* is the cutter length.					

The hardness of tool steel is 200-250 BHN and the hardness of EN36B is 270-340 BHN.

By using proportional relationship, the material remove rate for EN36B can be calculated as:

Table 4-9 Material removal rate estimated for EN36B

Material	Hardness (BHN)	MRR turning (in^3/min)	MRR face milling (in^3/min)	MRR end milling (in^3/min)	MRR drilling (in^3/min)
Tool Steel	200-250	0.27	0.11 x *n*	0.02 x *n x l*	1.2
EN36B	270-340	0.20	0.08 x *n*	0.015 x *n x l*	0.88
1in diameter tool; *n* is the number of teeth per cutter and *l* is the cutter length.					

So the operation time can be calculated as Table 4-10.

Table 4-10 Operation time calculations for shaft part 1

Part name	Material	Stock diameter	Feature	MRR	Volume removed (mm^3)	Volume removed (in^3)	Operation time per part (min)	Operation time per part (s)
Shaft part 1	EN36B	5/8 in dia. bar						
			Hole	0.88	477	0.029	0.033	1.99
			Thread	0.20	50	0.003	0.015	0.92
			Step	0.20	3007	0.183	0.917	55.04
			Step	0.20	166	0.010	0.051	3.04
			Hex	(6 teeth) 0.48	380	0.023	0.048	2.90
			Step	0.20	286	0.017	0.087	5.24
			Groove	0.20	151	0.009	0.046	2.77
			Cylinder	0.20	260	0.016	0.079	4.76
			Groove	0.20	151	0.009	0.046	2.77
			Cylinder	0.20	130	0.008	0.040	2.38
			Step	0.20	4737	0.289	1.445	86.72
			Step	0.20	5472	0.333	1.670	100.18
			Step	0.20	2660	0.162	0.811	48.69
			Thread	0.20	24	0.001	0.007	0.44

And set-up times and non-operational times can be calculated as Table 4-11:

Table 4-11 Other time calculations for shaft part 1

Part name	**Material**	**Stock diameter**	**Feature**	**Operation time per part (s)**	**Set-up time (s)**	**Set-up time (s)**	**Non-operation time (s) (9% Operation time)**
Shaft part 1	EN36B	5/8 in dia. bar					
			Hole	1.99	1620 (once for each part) + 720	2340	0.18
			Thread	0.92	720	720	0.08
			Step	55.04	720	720	4.95
			Step	3.04			0.27
			Hex	2.90	5500+30	5530	0.26
			Step	5.24	720	720	0.47
			Groove	2.77	720	720	0.25
			Cylinder	4.76	720	720	0.43
			Groove	2.77	720	720	0.25
			Cylinder	2.38	720	720	0.21
			Step	86.72	720	720	7.81
			Step	100.18			9.02
			Step	48.69			4.38
			Thread	0.44	720	720	0.04
Total for one part				317.84		14350	28.61

Total set-up time of a batch is sum of first time machine set-up time plus set-up time for each tool.

The operation costs are estimated as:

- Manual lathe operator rate: average of £11.00/hr
- Lathe machine rate: assumed: £6.00/hr
- Factory cost assumed: £1.00 per part

By using equation (4-1) the cost per shaft part can be calculated as:

Table 4-12 Cost estimated for making of the shafts

Part name	R_o	R_m	T_{ot}	T_{su}	T_{no}	C_m	C_f	Cost per part (£)
Shaft part 1	£11/hr	£6/hr	317.84s	14350s	28.61s	£0.65	£1/part	1.21
Shaft part 2	£11/hr	£6/hr	290.71s	5940s	26.16s	£0.49	£1/part	1.15
Shaft part 3	£11/hr	£6/hr	260.24s	2880s	23.42s	£0.453	£1/part	1.12
						Total cost		£3.48

- Tool steel hardness: 200-250 BHN
- EN36B case hardening Steel: 270-340 BHN

4.2.3.2 Compressor wheel

The compressor wheel is made out of Aluminium Alloy LM16 (The data sheet can be seen in Appendix E.2.).

Figure 4-11 Compressor wheel of TGB02

Table 4-13 Properties of the compressor wheel of TGB02

Part	Compressor wheel
OPM	Garrett
Material	Aluminium alloy LM16
Primary method	Die casting
Secondary method	Machining
Weight	21g

The batch size for the compressor wheel would be 83.

The total material needed for casting is calculated as:

Table 4-14 Total material cost for the compressor wheel

Part name	Material	Final product weight (g)	Total stock weight	Material cost [assumed] (£/kg)	Total cost (£)
Compressor wheel	Al alloy LM16	21	25 g	5	0.125
Total stock weight for 83 units [min.] (kg)		**2075**			

Mould material cost can be calculated as follows:

- Material: Grey Iron
- Weight (assume): 20 kg
- Cost (assume): 1 £/kg
- Material cost: £20

According to Madan et al. (2007) the mould basic manufacturing cost can be calculated using equation (4-8).

$$C_{bmc} = \sum_{i=1}^{k} I_i \left(\frac{L_i}{S}\right) M_f \qquad (4\text{-}8)$$

L_i total cutting length of feature (i = 1 to k),

S corresponding feed (mm/min),

M_f corresponding machine minute rate (hour rate/60),

I_i, k machine complexity factor for feature i, number of features.

For simplicity the basic manufacturing cost of the mould is assumed to be £150.

By using equation (4-2) tooling cost can be calculated as:

$$Tool\ cost = 20 + [150 \times (1 + 0.20)] \times 1 + 0.05 \times 200 + 120$$
$$= £330$$

- Cost modifier: 20%
- Number of cavities: 1
- Secondary element cost: 5% of manufacturing cost
- Tool design cost (6 hours of work/ £20/hr): £120

Die-casting cycle time and processing cost can be calculated as:

$$C_{pc} = \left(\frac{T_{su}}{N} + \frac{T_{cy}}{n_c . y}\right) R_{op} \quad \textbf{(4-9)}$$

C_{pc} die-casting processing cost,

T_{su} set-up time,

T_{cy} machine cycle time,

N batch size,

R_{op} machine operating rate,

n_c number of cavities,

y production yield (<1).

Machine set-up time: 10 s

- Machine cycle time: 60 s
- Batch size: 1
- Machine operating rate: £10/hr (£2.78 X 10-3 /s)
- Number of cavities: 1
- Production yield: 0.8
- C_{pc}= *£0.25*

Trimming process cost can be calculated as:

$$C_{tpc} = \left(\frac{T_{tsu}}{N} + \frac{T_{tcy}}{n.y}\right) R_{top} \quad \textbf{(4-10)}$$

C_{tpc} trim processing cost,

T_{tsu} trimming set-up cost,

T_{tcy} trimming machine cycle time,

R_{top} trimming machine operating rate.

- Trimming set-up time: 2
- Trimming machine cycle time: 2 s
- Machine operating rate: £10/hr (£2.78x10-3/s)
- C_{tpc}=*£ 0.125*

The cost of energy required for the casting process can be calculated as:

$$Energy\ cost = \frac{Q_{total}}{Q_{fuel}} \times \eta_{fur} \times C_{fuel} \quad \textbf{(4-11)}$$

Q_{total} total heating value required/kg of alloy,

Q_{fuel} heating value of fuel/kg,

C_{fuel} cost of fuel £/kg.

- Heat capacity of Ni-resist 5: approx. 500 J/kg.K
- Melting point: approx. 1200ºC or 1473 K
- So an increase from 25ºC to 1200ºC which is 1175ºC is needed.
- Q_{total}=587.5 x 1.30 (30% for loses and keeping heat) = 764 kJ/kg

$$Q_{total} = 587.5 \times 1.30 = 764\ \mathrm{kJ/kg}$$

- Natural Gas heating value: 20,000 btu/lb = 46522 kJ/kg

$$Q_{fuel} = 46522\ \mathrm{kJ/kg}$$

- Natural Gas price: approx. 5p/Kwh = 55p/m^3 = 68.75 p/kg

$$C_{fuel} = 68.75 \text{ p/kg}$$

- Burner efficiency: 80%

$$\eta_{fur} = 1.2$$

- Total Energy cost: 0.9 p x 3.3 = 2.97 p/kg for each product

$$Energy\ cost = \frac{764}{46522} \times 1.2 \times 68.75 = 1.36 \text{ p/kg}$$

Total casting cost can be calculated as:

$$C_{Casting} = Raw\ material\ cost + Mold\ Material\ cost + Tooling\ cost + Die\ cast\ process\ cost + Trimming\ process\ cost + Energy\ cost \quad \textbf{(4-12)}$$

$$\frac{Tooling\ cost}{Batch\ size} = Tooling\ cost\ for\ one\ part \quad \textbf{(4-13)}$$

- $Batch\ size = 83$
- $C_{Casting} = 9.9 + \frac{20}{83} + \frac{390}{83} + 0.25 + 0.125 + 0.0136$
- $C_{Casting} = £15.23$

After the casting is completed, the part needs to be finish machined to final shape. The method used for calculating the machining cost is same as the method used for shaft cost estimation (Equation (4-1)).

The material removal rate needs to be estimated for the aluminium alloy. The machining processes for the wheel are a reaming operation and two finishing turning operations.

Reaming time can be calculated by Jung (2002):

$$t_{fr} = \frac{A_r}{R_r \times cf} \quad \textbf{(4-14)}$$

t_{fr} is the reaming time (min),

A_r is ream area (in^2),

R_r is the surface generation rate for reaming (in^2/min),

C_f is the correction factor for R_r.

Ream area for diameter of 5.08mm and depth of 25mm is 398.98mm^2 and converted to inches is 15.71in^2.

R_r is assumed to be 10 in^2/min

cf is calculated to be 0.2766

The reaming time is calculated to be 5.68 minutes.

$$\begin{aligned} cf &= -0.335 \cdot D_r^2 + 1.3 \cdot D_r + 0.03, \quad if\ D_r < 1\ in \\ &= 0.04 \cdot D_r^2 + 0.36 \cdot D_r + 0.6, \quad otherwise \end{aligned} \quad \textbf{(4-15)}$$

Also, the approach time of reaming can be calculated as:

$$\begin{aligned} t_{or} &= 0.89 + \frac{1.15 \cdot D_r}{R_r}(min.), \quad \text{if } \mathrm{D_r} < 1 \text{ in} \\ &= 0.78 + \frac{2.26 \cdot \mathrm{D_r}}{\mathrm{R_r}}(\text{min.}), \quad \text{otherwise} \end{aligned} \quad \textbf{(4-16)}$$

D_r is the diameter of the reamer (in)

Approach time is calculated as 0.91 minutes.

The operation time for reaming is the summation of approach time and reaming time.

So the total operation time would be 0.91 plus 5.68 which would be 6.59 minutes.

$$t_{fr} = \frac{A_f}{R_t} \tag{4-17}$$

t_{fr} is the finish turning operation time (min)

A_f is the finish cutting area (in^2)

R_r is the surface generation rate of turning for material (in^2/min)

R_r is assumed to be 14 in^2/min

A_{f1} is calculated as 8.85 in^2.

A_{f2} is calculated as 7.60 in^2.

The finish turning operation time for operation 1 is 1.58 min.

The finish turning operation time for operation 2 is 1.84 min.

The approach time of the tool is approximately:

$$t_{at} = 5.4(s), \qquad if D \geq 2\ in$$
$$t_{at} = 3.8 \cdot \sqrt{0}(s), \quad otherwise \tag{4-18}$$

D is the diameter of a round bar.

The approach time for operations 1 and 2 would be 5.4 s.

The total time for the turning for operation 1 would be 1.67 min and for operation 2 would be 1.93 min.

Table 4-15 Times calculated for compressor wheel

Part	Material	Stock Size	Feature	Surface generation rate (in^2/mm)	Cutting area (in^2)	Approach time (min)	Operation time (min)	Set-up time (s)	Set-up time (min)	Non-operation time (s) (9% Operation time)
Compressor wheel	Al alloy LM16	25 g								
			Reaming	10	15.71	0.91	5.68	4300 + 800	85	0.51
			Turning	14	8.85	0.09	1.58	800	13.3	0.14
			Turning	14	7.60	0.09	1.84	800	13.3	0.17
						SUM	9.1		111.6	0.82

The machining cost will be as following:

Table 4-16 Machining cost for compressor wheel

Part	R_o	R_m	T_{ot}	T_{su}	T_{no}	C_m	C_f	Cost per part (£)
Compressor wheel	£11/hr	£6/hr	546s	6700s	49.14s	-	£1/part	19.96

The cost has been calculated using equation (4-1) and by considering batch size of 83.

The total cost of the compressor wheel would be:

$$C_{total} = 15.23 + 19.93 = £35.16$$

The results have been presented to the technical manager and the managing director of the company in separate meetings.

The technical manager had comments regarding some of the numbers. The numbers he had in mind for the cost of making the shaft and the wheel were higher than the estimated number. The numbers he had in mind were based on his experience and knowledge. The difference can be justified by considering the definition of the cost estimate, as what costs would add up to the total cost estimation. In the developed method the pure fabrication cost of a part is considered, whereas in many quotations issued, extra profit margins, extra overhead costs and higher rates for machine depreciation are added. Also operation times vary by the skill of workers and by considering learning curves, operation times are higher at start of a new tasks and the time improves as the task is repeated.

Regarding the method itself, he thinks the method is not as simple as it should be. By explaining his expectation, it can be realised that a parametric tool with simple inputs such as volume or size is what he expects. A tool to be able to make design decisions very quickly.

Cost data for material hardening, also material handling, labelling and packaging should be added to the tool as well.

A meeting was set with the managing director of the company to present the results to him. Part of the meeting was spent on presenting the developed method and case study results to him. His feedback about the overall method was that it looked good and useful and the level of the detail was what he was looking for. He had some comment about some of the detailed numbers in the case study results. For example, he commented on drilling time into Steel and said it would take more than 2 seconds for the operation.

He suggested considering 5% of material weight for material waste during machining.

Also, he suggested that as the main manufacturing process for some of the engine parts would be investment casting, it is good to add a method for investment casting cost estimation as well.

4.2.4 Discussion

During the method development it was realised that expert judgment still has an important role in any cost estimation procedure. With the knowledge and experience, it is difficult to obtain an accurate estimate. It is observed that experience in manufacturing processes and familiarity with engineering design are necessary for any production cost estimate.

At the development stage due to high number of unknowns and uncertainties, the accuracy of estimates would be low and when considering these with a start-up company developing a product which has novel parts, the level of uncertainties would be greater. In the collaborating company, it was observed that it was not known exactly what machinery or tools would be available for manufacturing, so compared to a case where the company already is aware of their manufacturing capabilities, there is higher uncertainty level.

Lack of a recording and documentation system is seen in the company. Also it is observed that many activities of the collaborating company are based on trial and error and learning is happening in most of the activities, which make the data recording more difficult.

It was seen that for the parts acquired from suppliers, obtaining cost data is challenging. The situation is worst when the parts are bought from distributers rather than directly purchasing from OEMs or suppliers. Because the distributers have limited information about a supplied part.

In order to improve the estimation accuracy, methods are needed for estimating individual process costs and operation times. An extensive time study and building a time data can help in getting better estimates in the future.

Detailed cost estimation methods require a large amount of input data which need spending lots of time, and need experience and knowledge.

Lack of similar products or not, indeed having access to similar product's data was the main reason for not using analogy or parametric methods.

At the development stage and with the characteristics of start-ups, there is no experience and idea about labour times and to obtain time data, time study methods need to be used such as MTM and MOST

There are a number of suggestions for future improvements of the developed method. A correction factor should be included in the method for mass productions. Lack of risk analysis and sensitivity analysis method can be seen in the methods, which are needed in future developments. For parts that are used widely in other industries such as heat exchanger, parametric methods could be an option. Especially for the machining operations, a method to estimate operation times is necessary.

4.3 ‘Make or buy’ decision making

In this section the methods and results related to the objective “To develop a process for ‘Make or Buy’ decision” are discussed.

4.3.1 Introduction

The first step in the method development was a detailed literature review. The literature review started with the wide areas of ‘Transaction theory’, ‘Resource-based view’ and ‘Outsourcing’ as the route of the topic of ‘Make or buy’ decision making. As the literature review was progressing, the area was focused according to the objective. The topics followed for this topic are shown in Figure 4-3.

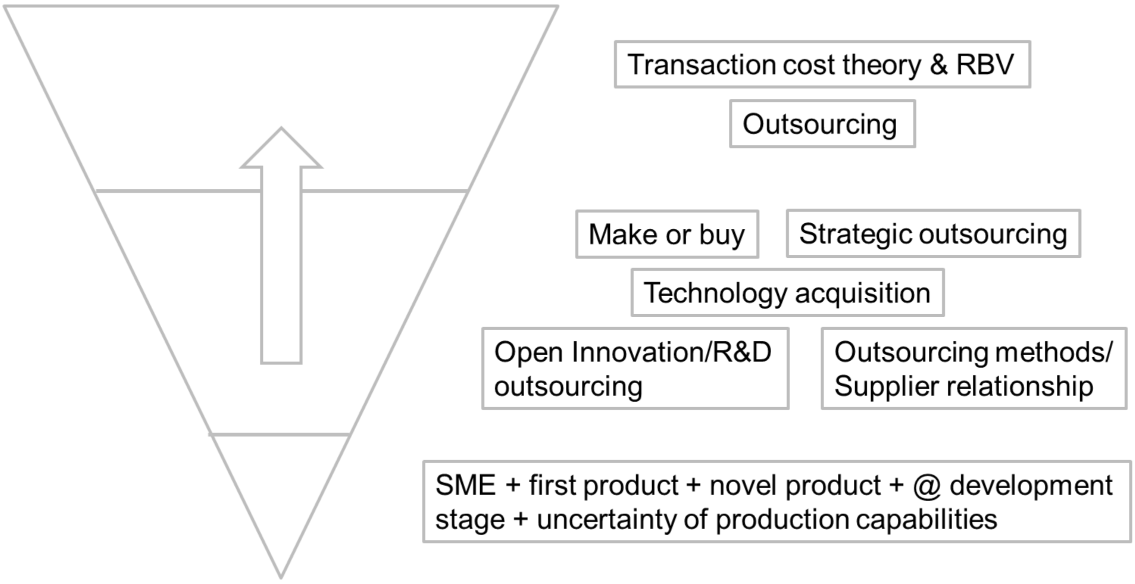

Figure 4-12 Focusing literature review topics fo 'Make or buy'

One of the focuses of the literature review was on research done in the area of ‘Make or buy’ with the focus on SMEs. The keywords used to search for literature about SMEs related research is as follows:

- Make or Buy SME
- Outsourcing decision SME
- "make or buy" small enterprise
- make OR buy micro
- outsourcing decision small enterprise

- supply chain network decision SME

The SME related research found was mostly industry specific with the focus on software/IT industry and services such as accounting. Also, decision making for offshore outsourcing was one of the focus areas.

The list of the papers are presented in Table 4-17.

Table 4-17 - 'Make or buy' SME related researches

Authors	**Subject**	**Studied group**
Daneshagr, F., et al., 2013	Decision factors	SMEs software acquisition in Thailand
Kurokawa, S., 1997	Reasons for outsourcing and decision making factors	R&D small technology firms in US & Japan
Sledgianowski, D., 2008	Outsourcing strategies and decision making of ERP	One SME case study
Chang, SI., et al., 2012	Outsourcing provider selection methods and factors	IT/IS industry
Bayrak, T., 2013	Factors needed for evaluating outsourcing decision	IT systems for SMEs
Kramer, T., et al., 2013	Outsourcing decisions of software	offshore outsourcing for SMEs
Everaert, P., et al., 2007	Sourcing strategy & and degree of outsourcing the function	Accounting functions for SMEs
Abdul-Halim, H., et al., 2012	Literature review about the factors and motivations for outsourcing	SMEs
Li, L., Qian, G., 2007	Reasons or conditions for partnership	SMEs
Abdul-Halim et al., 2012	Motivation for outsourcing	SMEs

Abdul-Halim et al. (2012), concerning the motivation of SMEs for outsourcing, have written that “when they outsource their activities, they are more driven by lack of access to the types of know-how, technologies, capital, economies of scale and other resources that the bigger organizations enjoy.” They go onto saying, “Therefore, it is argued that SMEs tend to engage in outsourcing in order to procure the required expertise.”

The next step was to review research done with the wider focus area of all companies and enterprises.

One of the most cited papers in this area written by (Buchowicz, 1991) has analysed companies in terms of the make-or-buy decision making process with the focus on manufacturing software. Buchowicz (1991) has suggested three stages for the decision making:

1) Strategic fit evaluation

2) Initial categorization

3) Selection

Buchowicz (1991) has developed one of the first process models in the literature and 14 propositions have been given in relation to the decision making as shown in Figure 4-13. Buchowicz (1991) mentions the lack of empirical research in this field. Therefore, in his study he has gone through two phases of data collection. In the first phase he has done structured interviews with managers and technical staff from 20 companies or operation divisions. In the second phase he has taken an unstructured interview and field investigation approach. Such studies give an overall view of what is the common practices in industry and what are opportunities for improvement. However, the date of the studies should be considered in reviewing literature as changes in the flow of industry, practices and mind sets happen by time.

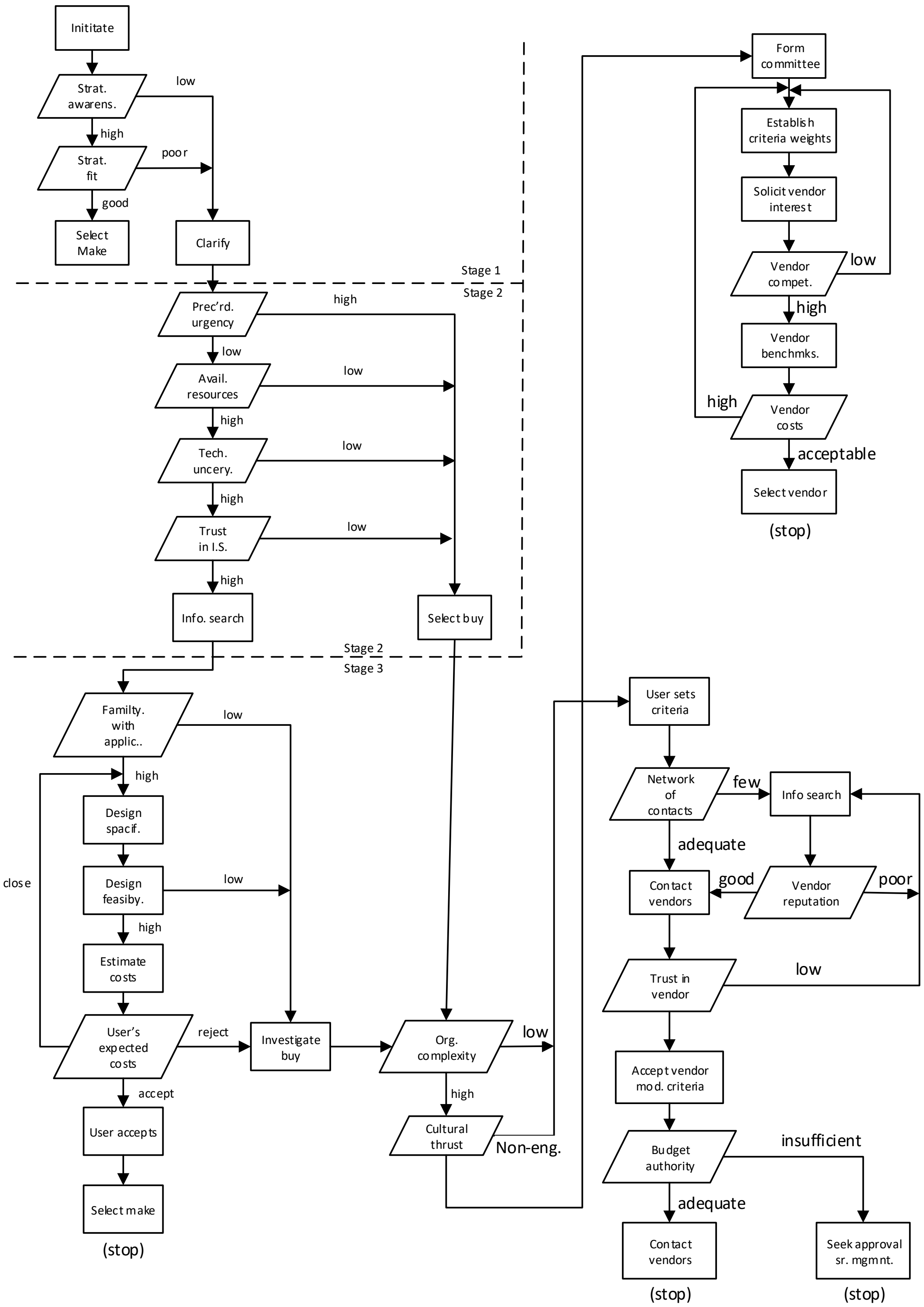

Figure 4-13 A process model developed by (Buchowicz, 1991) for make-vs.-buy decision process

A framework has been developed by Platts et al. (2002) which includes internal factors in the decision making as well as the external factors which would trigger the need for considering this decision making. The framework gives a holistic view of the area of ‘Make or buy’ decision making.

The advantage of this framework is that the authors have brought together different aspects and levels of the ‘Make or buy’ decision making addressed by other authors into one method. The decision making factors have been identified through review of the literature, interviews with industries and exploratory industrial case studies (Platts et al., 2002).

A weighted score method has been used for decision making in the method. Figure 4-14 shows the frame work developed by (Platts et al., 2002). One of the advantages of this method was considering the trigger in the decision making process, especially in the costing area. One of the key points that should be considered, is the need for a facilitator or coordinator for the decision making methods regardless of the method itself. The facilitator or the coordinator needs to have a minimal familiarity with the decision making process.

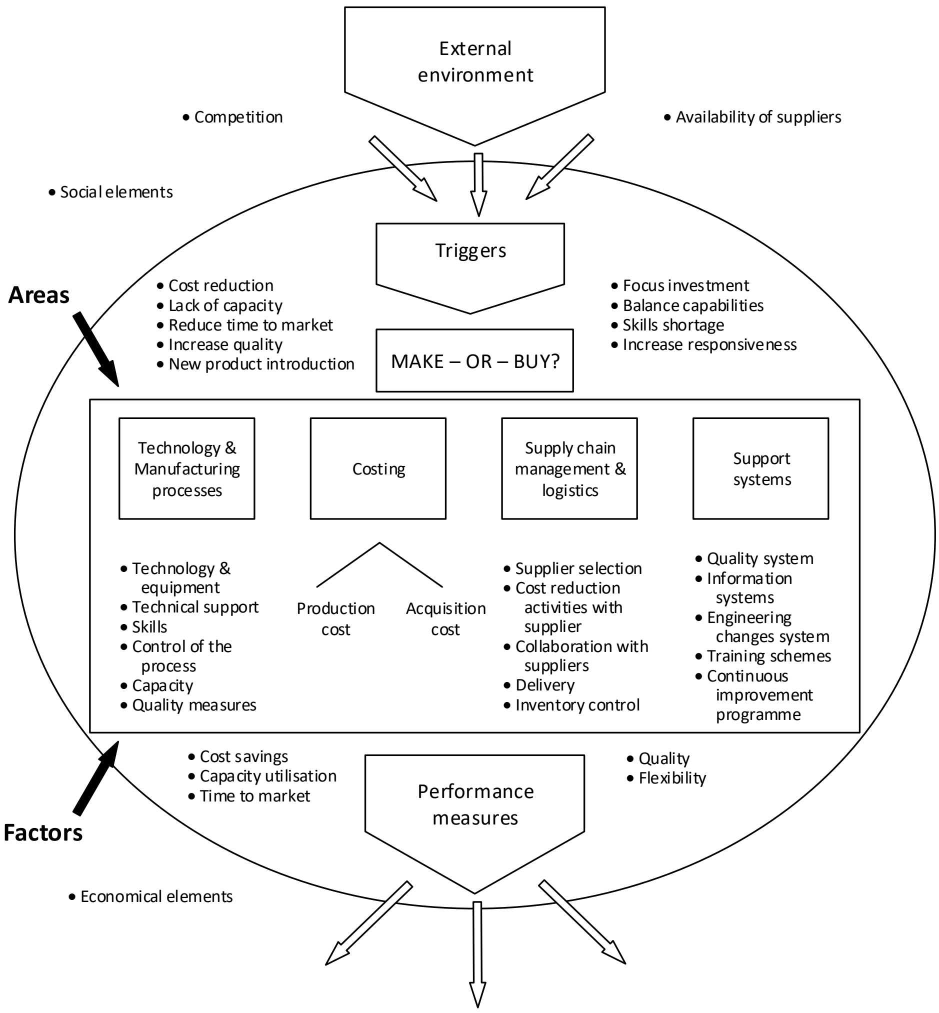

Figure 4-14 Make-or-buy decision making framework developed by (Platts et al., 2002)

Lee et al. (2009) have developed a method for technology acquisition mode selection based on ANP multi-criteria decision making. 5 groups of factors have been included in the method which consists of 21 factors that have been identified from empirical studies. ANP is a generalisation form of AHP which both use a weighting and ranking decision making method. Unlike AHP that the elements are considered independent of each other, in ANP the elements can have dependency (Satty, 1996). Many real world decision problems cannot be structured in a hierarchy, and elements in different levels would have interaction and dependency.

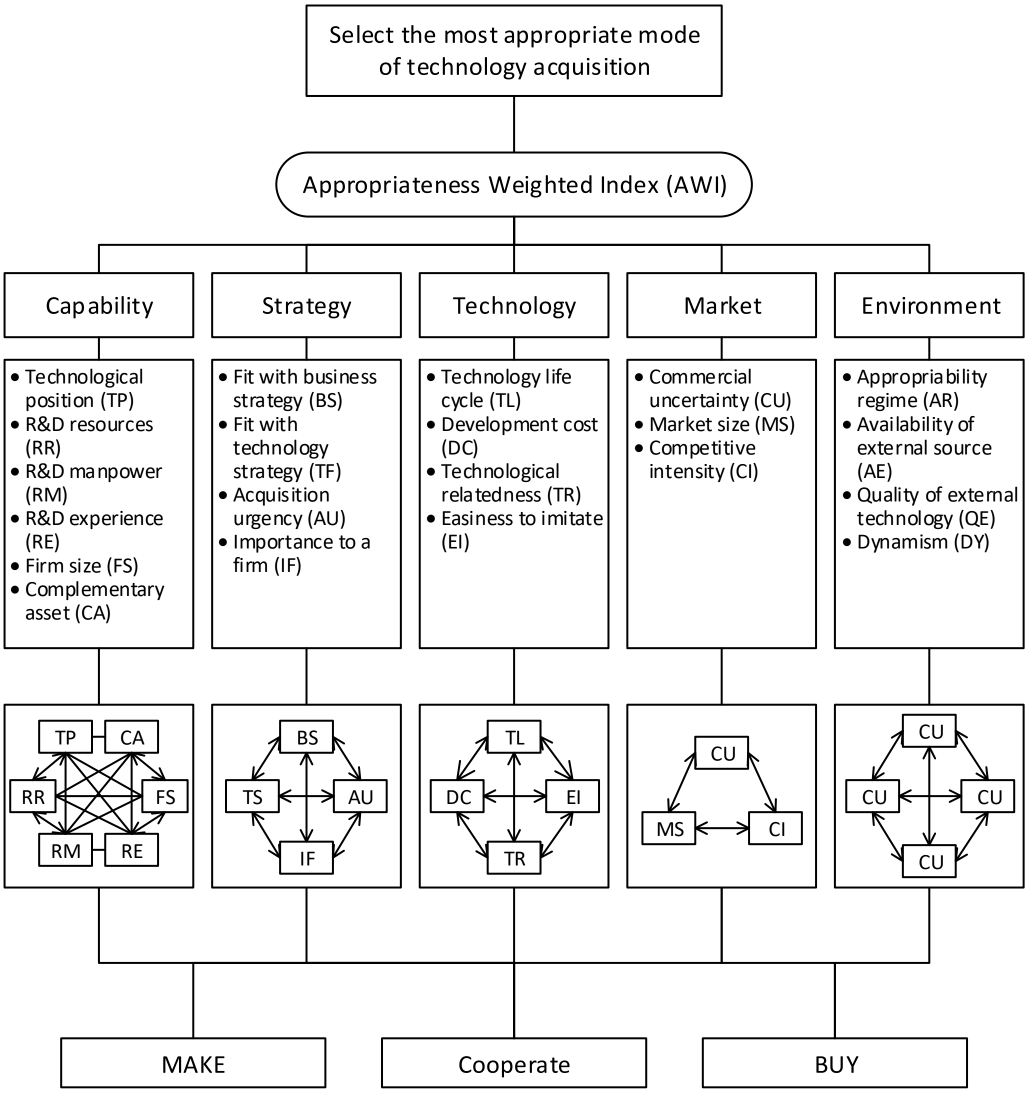

Figure 4-15 Technology acquisition mode selection model (Lee et al., 2009)

A research has been done by Tayles and Drury (2001) which has similarities in terms of research methodology to the current research. Tayles and Drury (2001) have analysed a large company's AS IS model and have developed a strategic sourcing (Make-or-buy) model based on the AS IS model. The research methodology of the research has similarities to this thesis in terms of focus on one company and action type of research where the researchers act as observer. They mention that the make-or-buy decision affects profitability, investment decisions, working capital, borrowing and competitive position. One of the observations of the paper which could be an advantage for SMEs is the behavioural improvement among the participating managers in the decision making process. The model has shown that it improves dialogue amongst the managers and it would help, not only ‘Make or buy’ decision making, but other decision making tasks by improving mutual discussion. In addition, because of the required inputs for the decision making model, the awareness and importance to these inputs such as cost data would increase which would result in better decision makings in all aspects (Tayles and Drury, 2001).

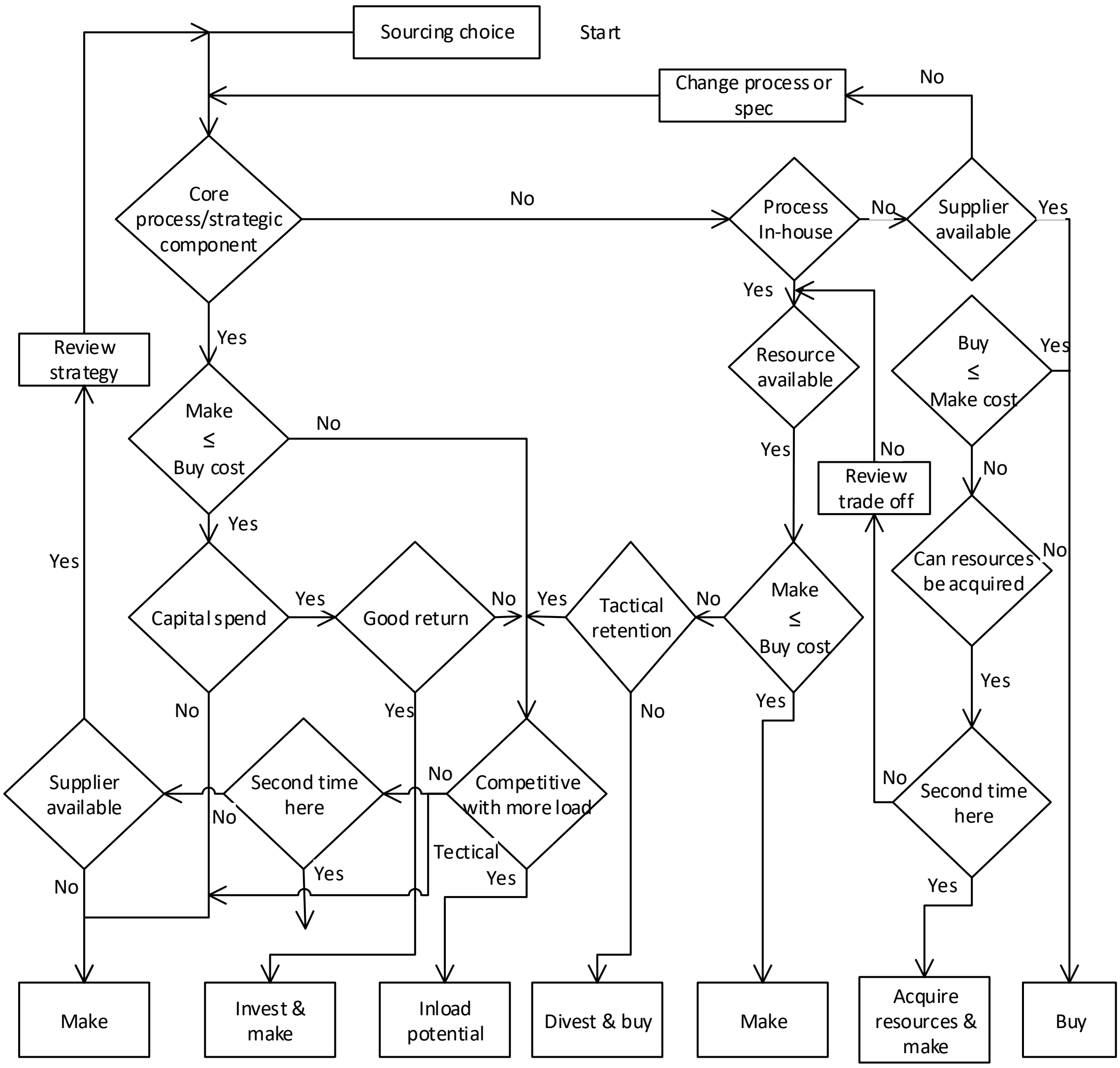

Figure 4-16 Decision making process developed by (Tayles and Drury, 2001)

Liao et al. (2010) have developed a conceptual framework for prototype outsourcing. The advantage of this framework is simplicity and the fact that it covers the three stages of making the outsourcing decision, choosing the supplier and managing outsourcing. The framework is at conceptual stage and needs more detailed development.

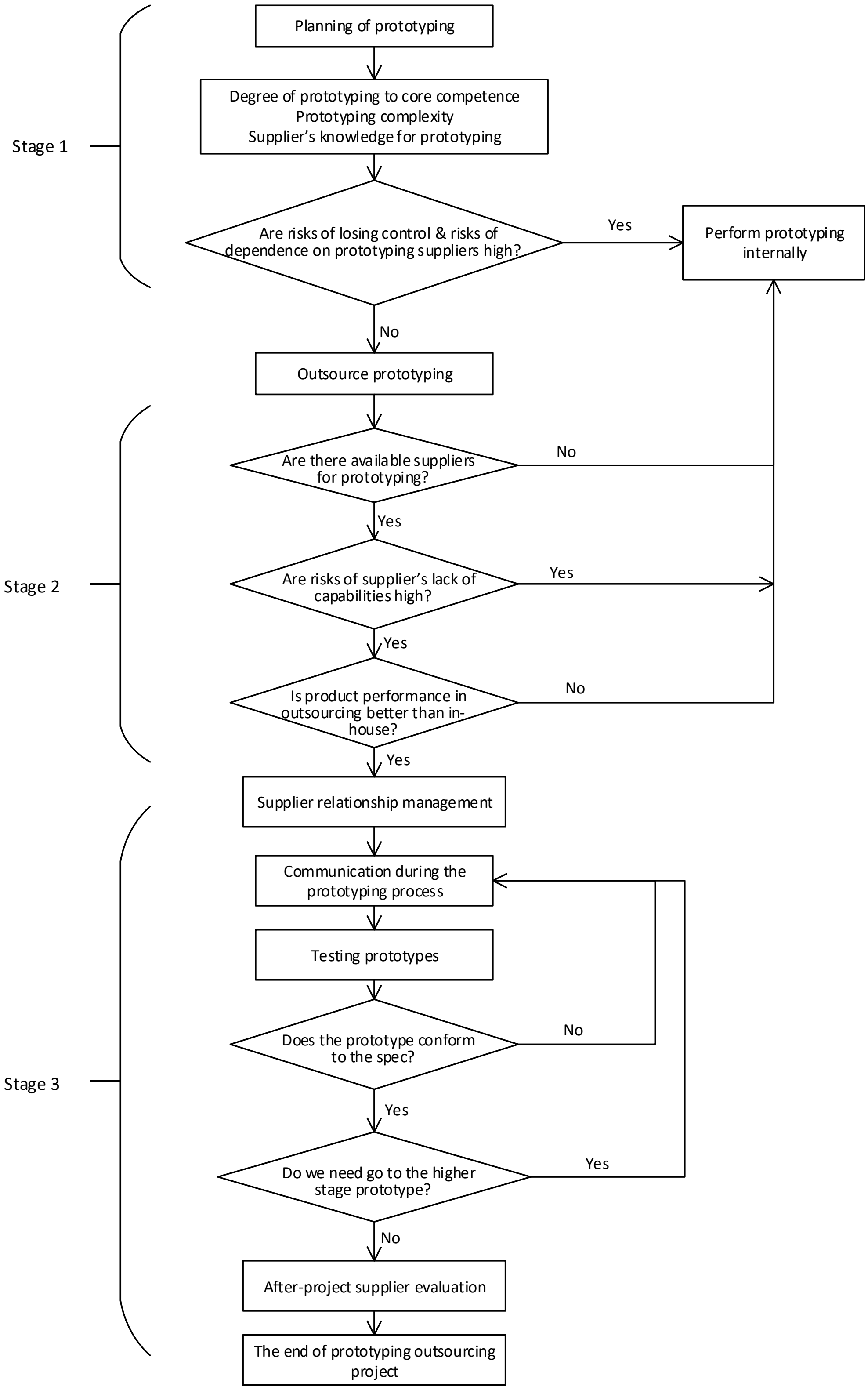

Figure 4-17 A framework for prototyping outsourcing proposed by (Liao et al., 2010)

A number of other papers have been identified which are case specific or are limited to analysing current practices in some industries.

- Daim and Kocaoglu (2008) have studied the technology acquisition routes and strategies is electronic manufacturing companies in Turkey and US
- Cantarello et al. (2011) have studied Italian design-oriented firms on the method they use for NPD and the uncertainties they face on that.
- Moses (2011) has analysed the ownership of cross-functional make or buy decision process in three large companies.
- Wang et al. (2013) have developed a Fuzzy multiple-goal programming for make or buy decision making based on cost-effectiveness in hi-tech manufacturing
- Parry et al. (2006) have discussed the benefits of outsourcing engineering commodity procurement and have done a case study on an American large firm.

One of the important areas under the umbrella of ‘Make or Buy’ is technology acquisition method. Chiesa (2001) states three ways that technology acquisition happens:

- Internal development
- Cooperating with other firms of institutions
- Buying the technology

Also, Williamson (1985) mentions three governance forms that firms can manage their transactions: market (licensing, cross-licensing), hierarchy (mergers, vertical integration and acquisitions) and hybrid forms (strategic alliances).

Commercial Off-the-Shelf (COTS) is another area under the ‘Make or buy’ umbrella. By reviewing the related literature, it was realised that COTS is more used for computer software sector and electronic hardware and the papers found were case specific to these sectors.

The knowledge gap can be summarised as follows:

- Most SME related literature is more analysis of current practices in different sectors or countries than suggesting or developing methods

- In SME literature there is a huge concentration on IT/IS outsourcing factors and methods.
- Most research has focused on important decision factors in different areas
- Most research is either theoretical related to factors or survey of industry
- One of the other areas of focus is the decision for offshore outsourcing.
- The focus is mostly on currently available products or services rather than under development products which have lots of uncertainty. Also as the case study company is at development stage of their first product, they are uncertain of their future production capabilities and resources.
- Lack of link between factors and final decision is seen in the literature
- Large companies have much more complex consequences when making decisions and have more organisational complexity, rather than SMEs which have a simpler organisation and are more flexible.

4.3.2 Method development

The work on the topic of the ‘Make or buy’ started from the point which this requirement was seen in the studied company. Although the importance of ‘Make or buy’ decision making and the weakness of SMEs in this field is discussed in the literature review chapter, however the requirement was first mentioned by the managing director in a meeting related to factory set-up cost estimation. In a meeting on 07th December 2011 the managing director expressed their need on knowing the price to buy parts of the TGB and how to make the parts. Also he mentioned the need to know rough process for the assembly of their product. The requirement was further developed into making decisions on what parts to make and what parts to buy.

The development started by identifying the current practices in the company in making ‘Make or buy’ selection for different parts. The mapping was done mainly through close observation and analysis of the company practices and activities. Although where required a few meetings were held to explore the detail of the activities and validate the findings.

In order to identify the AS IS practice of 'Make or buy' in the company, the activities around the development of the TGB was mapped which includes 'Make or buy' as well. The mapping was done using IDEF0 function modelling methodology (Section 4.1.3). The result of IDEF0 mapping is presented in the Appendix A.1.

In addition to the mapping, a detailed explanation of the practices is presented in the results section (Section 4.3.3).

The development was continued by the identification of the best practices through literature review (Section 2.8). The best practices were used to improve the current practices.

The developed process is used for a case study on the TGB and the results are validated.

4.3.3 Results

As mentioned earlier 'Make or buy' is a strategic decision which can affect an organisation's activities in the long run. For small companies which are more vulnerable than large companies and have limited resources, making a correct decision is critical and vital.

The method is developed for a case that outsourcing has been selected as an option, but the major challenge is which components to make and which ones to buy.

For the collaborating company two stages can be defined with their own characteristics. First stage is development stage (current stage) which the company is dealing with a new technology (developing a novel product) which is the first product of the company. Because of this there are uncertainties about how the final product would look like.

The next stage would be production stage which carries the uncertainty regarding the future production capabilities. Production capabilities include the production resources such as financial and human resources and physical production capabilities such as machinery and equipment.

It should be considered that any decision made at the development stage must consider the effect and impact on the production stage and if a production strategy is selected by the company, it should be considered in any decision making.

Because of being in the development stage, for any ‘Make or buy’ decision making, both design activities and production activities should be considered. Therefore, technology acquisition or open innovation can be options in the decision making.

Due to lack of financial resources for any SME, partnerships and joint developments can be considered in the development stage with the suppliers.

A framework is suggested to include all the areas that need to be covered in the decision making process:

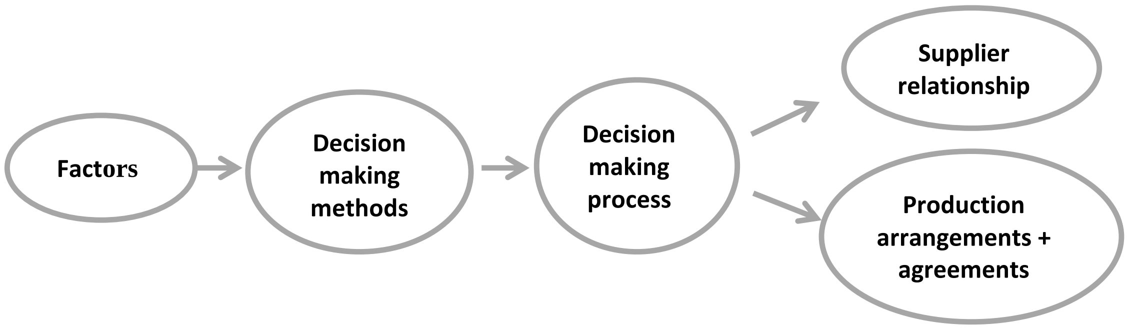

Figure 4-18 'Make or buy' framework

During the study the current practices of the studied company are identified and modelled. The AS IS model will be analysed and compared to the best practice.

The AS IS model was derived from the IDEF0 diagram and 2 hours of interviewing of the technical manager of the company. The current ‘Make or buy’ decision making process can be seen in Figure 4-19.

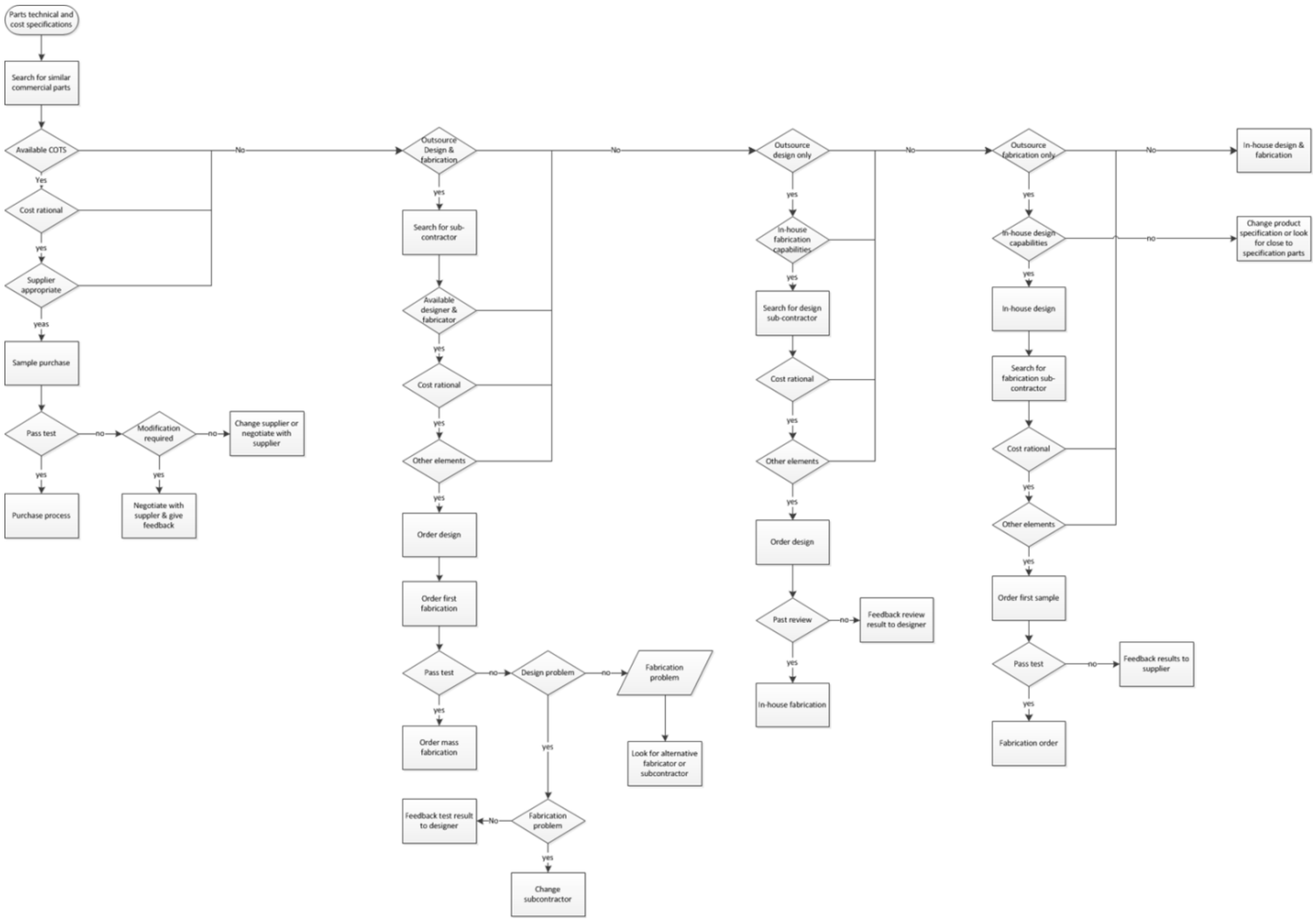

Figure 4-19 'Make or buy' AS IS model of the company

In the observed company it is seen that the decisions were made by the managers of the company which are also shareholders of the company. In making decisions, as they are shareholders as well, financial consequences of the decision are highly considered. But lack of Cost engineering knowledge is tangible in the company's decision making and skilled staff in this area are needed.

For the process of "Make or buy" the company follows a "common sense" process and in developing this process, their engineering background has helped. As mentioned earlier the company lacks Cost Engineering experts, but the CEO has gone through an MBA course. Figure 4-20 illustrates an example of the "Make or buy" process in the studied organisation. This process was carried-out for a shaft and finally it was decided that the shaft be designed in-house and the fabrication outsourced.

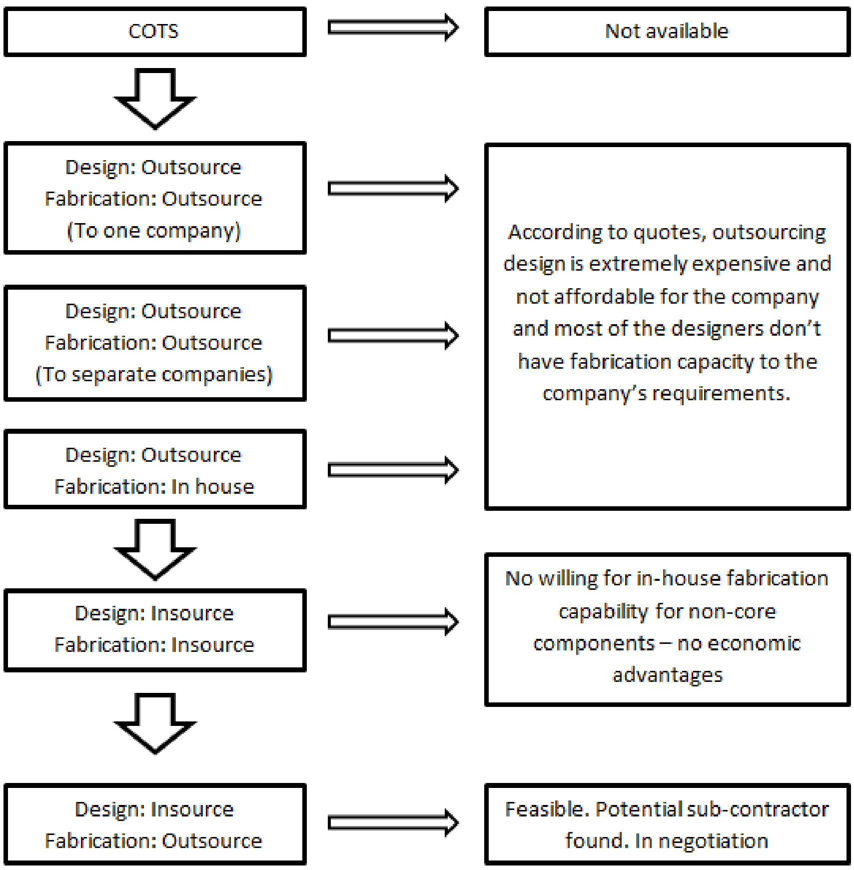

Figure 4-20 Sample of the 'Make or buy' process in the company

The strategy of the company, so that it is able to have a chance in the competitive market and introduce a low price product to the market, was to use already existing products in the market. By combining them in a novel, logical and technical working order, a novel low cost product will be built.

In the process of decision making the priority option would be Commercial Off-The-Shelf (COTS). By having defined product specifications, similar parts and products which would satisfy the required specifications and have proven technology would be searched for.

Searching would be done by looking for vendors through the internet and contacting them through phone and email and also enquiring from experienced people in industry.

In the case of finding an appropriate product, a sample product would be ordered and different levels of testing would be performed to ensure the quality and suitability of the part.

One of the decision elements is the cost. As mentioned earlier, one of the main characteristics of the TGB would be low cost, and to ensure the low final cost of the product, low cost components have to be used in the system. Therefore, the purchase price of the found products should be appropriate in relation to final product cost. After technical approvals volume purchase prices would be negotiated.

Also, during the process of purchase negotiations, the vendor's supply capabilities and support capabilities would be considered too. The supplier should have the capability to supply products according to the company's production volume and manufacturing strategy. One of the other requirements from the supplier is the possibility of minor design changes to the components according to the company needs. This requirement could be overlooked for critical components where the importance of the other elements is higher.

Some available parts may be a component of an already existing product. The selection of COTS for this type of part depends on the desire of the OEM to sell the part separate of the main product, otherwise other options have to be sought.

For some products the price of the assembled product is less than the separate components of the same product.

If an appropriate part is not found, the next stage in the decision making process would be to consider designing the product. There would be several options in terms of insourcing or outsourcing this process. Table 4-18 illustrates 4 possible options for designing a new part to satisfy company's requirements in addition to the COTS option. These four options are created by having two options of insourcing and outsourcing for both design and fabrication of parts.

Table 4-18 Available decisions for 'Make or buy' in the company

COTS +

		Design	
		Outsource	Insource
Fabrication	Outsource	X	X
	Insource	X	X

By experience of requesting for quotation for outsourcing design and fabrication it is found that this option is not feasible and the company cannot afford costs of this option and selecting other options would be more cost beneficial. One of the reasons of ignoring this option is the unwillingness of the designers to hand over detailed design of the parts, very high cost of design from scratch and later modification constraints. Also until now no company was found to have production capabilities close to the studied company's volume requirements.

The company is not willing to invest in in-house manufacturing capabilities and as most mechanical parts are non-core parts, so the option of in-house manufacturing is not considered.

The option of outsourcing design and fabrication can have two sub-sections. As well as entrusting the design and manufacturing to one organisation, in order to gain economic advantages, the tasks can be given to separate organisations. Even there is the possibility of outsourcing the assembly to subcontractors.

It is understood that some parts of the TGB might have the potential to be considered as core competency such as the combustor. But the main competitive advantage in terms of design could be the way of assembly of the system and the control system which includes the control algorithm. It would be preferable to design and fabricate these parts in house. But due to in house production constraints and cost implications, external fabrication would have priority.

There are some obstacles for outsourcing for which one of the major obstacles is the confidentiality of core competence. In order to outsource any of the processes, a solution for this obstacle should be considered. In the case of the collaborating company the use of Non-disclosure agreements has been the common act. Also, joint partnerships with suppliers in a way that both sides would have financial incentives and non-financial interest in the project is another action used by the company.

In addition to the qualitative part of ‘Make or buy’ decision making, there are quantitative factors that need to be considered.

For production decision making, the cost of production and cost of acquisition are the two main costs that need to be compared for the decision making (Platts et al., 2002). Cost of production includes the cost of acquiring machinery and equipment or the machine rates, depending on the availability of the machines in the factory, overheads, labour costs, and material handling costs. Cost of acquisition includes the administration costs, purchase costs, and inspection costs.

Platts et al. (2002) has listed the typical costs that need to be considered to build each cost (Table 4-19).

Table 4-19 List of typical cost build-up items (Platts et al., 2002)

Supplier cost	In-house cost
Material cost	Material
Labour cost	Labour
Supplier overhead cost	Overhead
Transportation	Stock handling
Purchase orders	Training
Telephone calls	Availability of labour
Technical support	Management of parts
Investigating sources (visit to supplier)	Space
Unrecovered in-house overhead	

In addition to decisions for the production stage, there are choices for the development stage. There are mainly three ways that technology acquisition can happen (Chiesa, 2001):

- Internal development
- Cooperating with other firms of institutions
- Buying the technology

Daim and Kocaoglu (2008) by doing a literature review have listed the routes for technology acquisition in firms:

- Sponsoring university research
- Industry–university research consortia
- Supporting employees' graduate education
- Community colleges
- External R&D centres
- Consultants
- In-house technology development
- Licensing agreements
- Vendors/suppliers
- Technical meetings
- Technical journals
- Participation in trade shows
- Purchasing of existing technology

Open innovation is another route for technology acquisition. Chesbrough (2003) has described the idea of open innovation. In this idea a firm instead of having a research centre for innovation, would take advantage of innovation done by other firms especially small firms and buy their idea.

Also, Daim and Kocaoglu (2008) have listed the expected impacts of technology acquisition through mentioned routes:

- Productivity was increased
- Product quality was improved
- Product development cycle was shortened
- Number of new products was increased
- Labour–management relations were improved
- Accuracy of the information flows was increased
- Production costs were reduced
- Responsiveness to production schedule changes was increased
- Maintenance costs were reduced
- Service performance was improved
- Domestic sales were increased
- International sales were increased

In selecting an appropriate technology acquisition mode the following (Table 4-20) factors need to be considered (Lee et al., 2009):

Criteria	Sub-criteria
Capability	Technological position
	R&D resources
	R&D manpower
	R&D experience
	Firm size
	Complementary asset
Strategy	Fit with business strategy
	Fit with technology strategy
	Acquisition urgency
	Importance to a firm
Technology	Technology life cycle
	Development cost
	Technological relatedness
	Easiness to imitate
Market	Commercial uncertainty
	Market size
	Competitive intensity
Environment	Appropriability regime
	Availability of external source
	Quality of external technology
	Dynamism

Table 4-20 Technology acquisition modes selection factors (Lee et al., 2009)

van Echtelt et al. (2008) described the benefits of supplier involvement in new product development phase. They indicated that in the short term, it can reduce product development time and cost with improved quality, and in the long term the collaboration will enhance the partnership and can result in more effective coordination, and thereby the ability of focal company to differentiate products. Secondly, supplier involvement during the design phase can provide access to suppliers' new technologies, which may be of strategic importance for future product development activities. For example, the focal company can align the technologies with key suppliers. Finally, the transfer of specific solutions and knowledge during the collaboration to the other projects will benefit the focal company.

The areas that the supplier can be involved in during the design stage are listed in Table 4-21 (Chiu and Okudan, 2010).

Table 4-21 Supplier involvements during design stages (Chiu and Okudan, 2010)

Design stage	Supplier involvement
Problem definition	- Establish specifications - Avoid ambiguity & information distortion - Identify early changes
Concept design	- Key product & process technologies - Product architecture - Contribute key ideas/concepts/critical components - Establish interfaces between product subsystem(s)
Preliminary & detailed design	- Selection of Proprietary parts & components - Tolerance design - Prototype testing & demonstration - Design for manufacturability - Material selection & Bill of materials (BOM)
Production design	- Tooling design - Design for manufacturability - Quality control & assurance - Raw materials

In order to make a decision with all the factors available, Multi-Criteria decision making (MCDM) methods are suggested in several papers (Lee et al., 2009). One of the simplest MCDM methods is weighted score (weighted sum) model. In this method, questionnaires should be given to staff from different departments to score the decision making factors considering their product (Platts et al., 2002).

Besides all the benefits that outsourcing could have for an organisation, there are risks that need to be considered. Anderson and Anderson (2000) in a paper with the focus on outsourcing traps have studied possible risks of outsourcing. One of the traps mentioned in the paper is the risk of technology diffusion. The supplier might leak the confidential information to competitors or they might use the information to make the end product themselves (Figure 4-21).

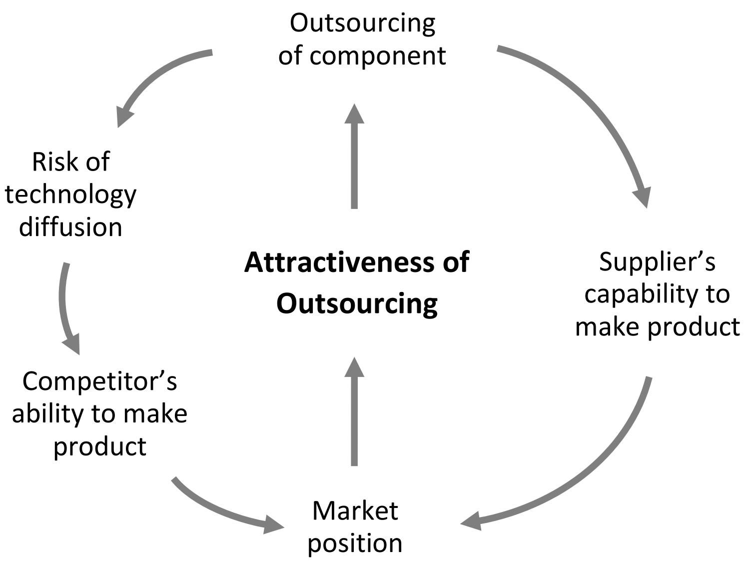

Figure 4-21 First trap, Technology diffusion (Anderson and Anderson, 2000)

There is another risk which is related to over dependence to the supplier. When the supplier realises the vital dependency to themselves they might increase the purchase costs. (Figure 4-22)

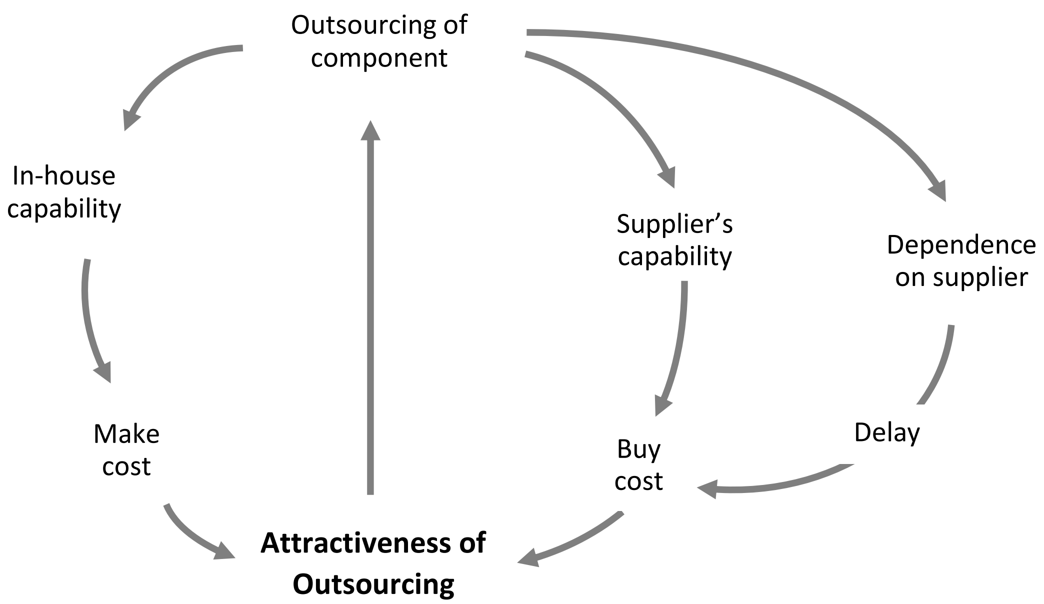

Figure 4-22 Second trap, dependence on supplier (Anderson and Anderson, 2000)

A further risk is that initially the costs may decrease, but due to losing knowledge roots with the supplied part, the knowledge to integrate the parts efficiently with the system would decline which would in return increase costs of integration (Figure 4-23).

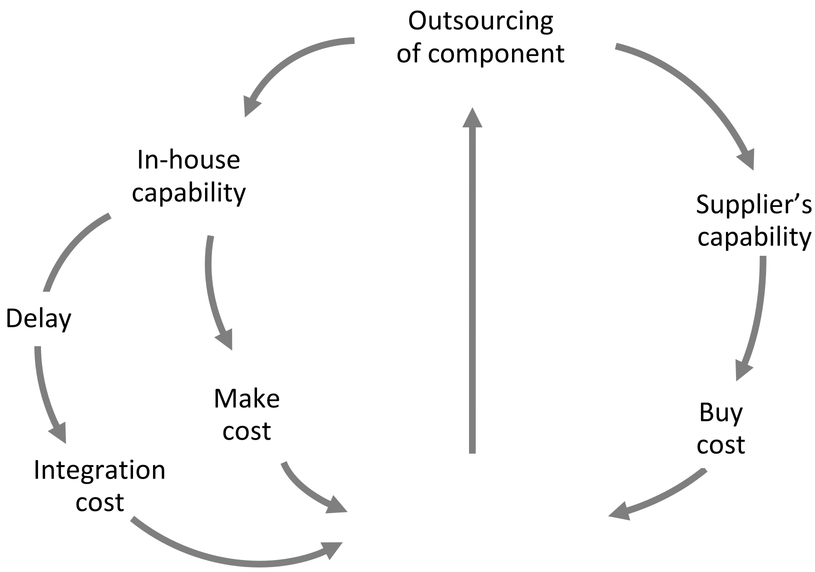

Figure 4-23 Third trap, integration cost (Anderson and Anderson, 2000)

After mentioning the risks, Anderson and Anderson (2000) have suggested methods to avoid the outsourcing traps which are listed in Table 4-22.

Table 4-22 Suggestion to avoid outsourcing traps (Anderson and Anderson, 2000)

Avoiding outsourcing traps
1. **Take the long view.** Most outsourcing traps only reveal themselves in financial results after several years. By then, it may be too late to correct a mistake.
2. **Do not outsource your "core capabilities".** If a technology or service underpins your product's competitive advantage, then you probably should not outsource it.
3. **Consider partial outsourcing of other capabilities.** This approach may allow you to keep sufficient knowledge of your product's component parts and services to keep integration costs low and prevent you from becoming too dependent on a supplier.
4. **If insourcing or partial outsourcing of a critical capability does not make financial sense, then consider using two or more suppliers.** This strategy will keep the supplier's pricing competitive. However, it will also increase the opportunity for technology diffusion.
5. **Develop strategic alliances with suppliers.** Give them economic incentives to keep costs low and to prevent technology diffusion.

4.3.4 Make or Buy Case study

It should be mentioned initially that the decision making is done in the development stage, but the focus is on production stage. These two stages should not be confused in the decision making process.

The collaborating company has decided that in order to be able to compete with big players in the market and have a product with lower cost than the competitor products to have the priority with Commercial off-the-shelf (COTS) parts. The company has more knowledge in mechanical engineering than electronic engineering, so the in-house development capabilities in very limited for electronic parts compared to mechanical parts.

The part selected for the case study is the Shaft of the TGB system.

The first step in the analysis is to see if the part is a core or strategic component. Quinn and Hilmer (1994) in an article about strategic outsourcing define core and non-core activities as "From a strategic outsourcing viewpoint, however, core competencies are the activities that offer long-term competitive advantage and thus must be rigidly controlled and protected. Peripheral activities are those not critical to the company's competitive edge." The definition can be broadened to parts and components of a system as well.

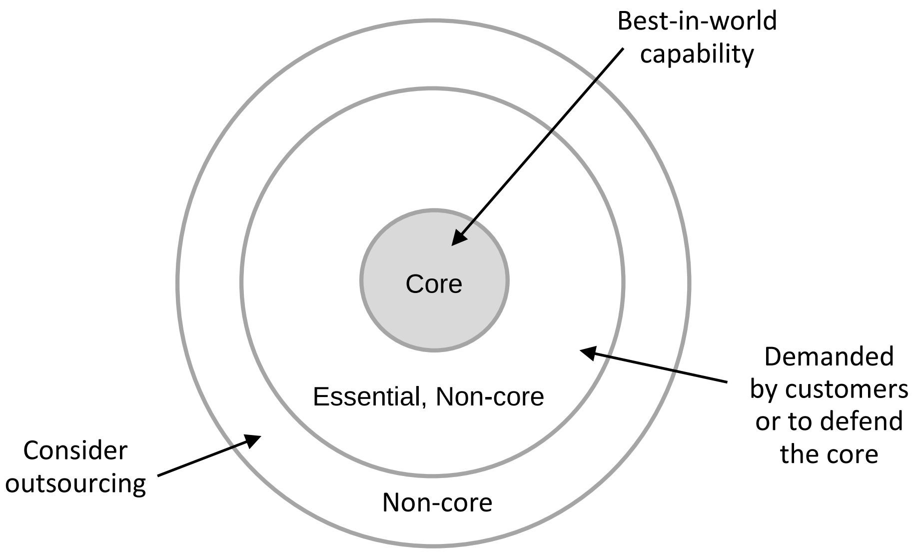

Figure 4-24 Core and non-core components definition (Quinn and Hilmer, 1994)

The product under study is a turbo machinery (rotary) system and the shaft is the core (physical core) of the system, which most components are assembled onto the shaft. Although considered in the system, it won't give a major competitive advantage. Because the technology used is not a high tech and novel technology. The material and manufacturing processes are not novel or high tech.

The first question is that is the product off-the-shelf an option? The product is a turbo machinery (rotary) system and the shaft is the core (physical core) of the system, which most components are assembled onto the shaft. The shaft design (dimensions) is dependent on the design of other core components of the system and the shaft material is dependent on the structural requirements of the system and magnetic requirements (recommended by the electric generator manufacturer) of the electrical generator.

The shaft is highly customised because of its dimension dependency on other components of the product and other components' manufacturer recommendations, so it is very unlikely to find a similar product off-the shaft with the specified specifications. It is not possible to modify other components to fit an off-the-shelf shaft, as other components include core components and off-the-shelf components. This requires most components of the system be modified. So, this option is ruled out.

As discussed earlier, one of the important factors for the company is cost, and the low production cost of the system would be the competitive advantage. The next step in the decision making would be to compare the cost of in-house design and production and outsourcings.

In house shaft design cost:

- 3 days of work
- Designer Rate: Approx. $\frac{£35000}{12} = £2916.67\ per\ month$
- $\frac{£3333.33}{22} = £132.58\ per\ day$
- Overhead rate: (Assume 70% of designer rate) $£110 \times 0.70 = £92.81$
- Software cost rate: Approximately *$1500 (£900) per annum = £3.60 per day (252 working days)*
- *Total = 3 x (132.58 + 92.81 + 3.60) = £686.97*

Shaft fabrication cost can be calculated using Equation (4-1).

Table 4-23 Calculated shaft fabrication cost

Part name	R_o	R_m	T_{ot}	T_{su}	T_{no}	C_m	C_f	**Cost per part (£)**
TGB-SFT-V5-P1	£11/hr	£6/hr	317.84s	14350s	28.61s	£0.65	£1/part	1.79
TGB-SFT-V5-P2	£11/hr	£6/hr	290.71s	5940s	26.16s	£0.49	£1/part	1.61
TGB-SFT-V5-P3	£11/hr	£6/hr	260.24s	2880s	23.42s	£0.453	£1/part	1.56
Total cost (per part)	**£4.96**							
Total cost (1000)	**£4960**							

- Calculate before: £4.96 per part (for batch size 1000)
- For 1000 parts: £4960
- Assumption: If machine and specialised labour available
- Material handling
- Stock holding
- Management of parts
- Space

If the machine and specialised labour were not available:

- Machine technician: Approx. £30,000 per annual
- Equipment required:
- Lathe: approx.£10,000
- Milling machine: approx. £5000
- Miscellaneous: £1000
- Overheads
- Training

Outsourcing:

- Outsourcing design cost:
    - Communication with the designer: 2 Hours
    - Employee rate: $\frac{£132.58}{7.5} = £17.68$

- Overhead rate (70% of employee rate): £12.38
- Communication and office work:

$$2 \times (£17.68 + 12.38) = £60.12$$

- Designer rate: £80/hour
- Designer work: 2 day
- Designer rate: $2 \times 7.5 \times £80 = £1200$
- $£1200 + £60.12 = £1260.12$

- Outsourcing fabrication cost:
  - Fabrication rate: £50/hour
  - Fabrication time for 1000:
  - $946.98\text{s} * \frac{1000}{3600} + 23170\text{s} * \frac{1}{3600} = 269.49\text{h}$
  - Material cost for 1000: £1593
  - Fabrication cost: $£50 \times 269.49 + £1593 = £15067.5$

- Other outsourcing costs:
  - Purchase order cost
  - Communication costs
  - Technical support costs:
  - Visiting supplier (investigation) costs
  - Unrecovered in house overhead costs:
    - Preparing design requirements

- Cost compare:
  - Design costs:

$$Inhouse\ cost < Oursource\ cost$$

  - Fabrication costs:

$$Inhouse\ cost < Oursource\ cost$$

By looking at the cost comparison it can been seen that if only cost would be considered, doing both design and fabrication in-house would be more cost efficient, but only with the condition that the capability and knowledge would be available in-house.

If the fabrication machinery and tools would not be available, the cost comparison would have a different form, and the cost of acquiring the machinery and tools should be added to the in-house cost. If those machinery would be only used for the production of the shaft and no other part, the cost of the machinery has to be distributed over the production size. This means that the in-house cost would be much higher than the current calculated cost and it would be higher than outsourcing cost. In that case outsourcing fabrication would be more cost effective than in-house fabrication.

The experience of working at the collaborating company showed that if you choose in-house manufacturing, the workers would have less motivation to finish their assigned job on-time. One of the identified reasons is that they are being paid monthly and not based on project. On the other hand, for the case of outsourced fabrication, the payment is based on completed jobs and in-order for them to be able to get more jobs in a fixed time frame, they have to finish their jobs as soon as possible and without affecting the quality.

An important risk of outsourcing a part is loss of information. The main way that the company has tried to mitigate this risk is before disclosing any information to the other party, they have to sign a Non-disclosure agreements (NDA) which is a legal binding contract. Also using incentives such as negotiation with the supplier for involvement in the production stage is another method to reduce the risk of loss of information.

4.3.5 Discussion

A process for ‘Make or buy’ decision making has been developed based on the requirements of start-up SMEs and specifically the collaborating company and the research is done through action research, while the researcher was an observer and participant in the researched company.

During the study the lack of Cost engineering knowledge was seen in the company’s actions and decision makings. The company had no access to Cost

Engineering best practices and in the “Make or buy” decision making experience and common sense were the key players. While comparing to best practices, the negligence of some key elements can be seen in the company’s decision making. It is seen that cost is the main element considered in the decision making process. It is important to transfer the best knowledge to the company in an effective way and make them aware of the importance of “Make or buy” decision in the future of their business. Using a Multi-disciplinary decision making method can help them to involve other factors other than cost in the decision making.

4.4 Assembly line design

In this chapter, the method developed for assembly line design would be discussed. The chapter would start with an introduction to assembly line design including a report of the literature review of this area. The development method is discussed in the next section. The result of the method development is presented in the results section and the validation case study is explained next. This chapter would end up with the discussion section.

4.4.1 Introduction

The method development started with reviewing the literature related to Assembly line design. The literature review started with wide area of plant design and concurrent engineering. The review was focused until the focus area of methods for Single product assembly system design (SPASD) with the objective of minimising cost; Methods which are specifically developed for SMEs developing a single product which is their first product; A product which is novel and is currently at the development stage.

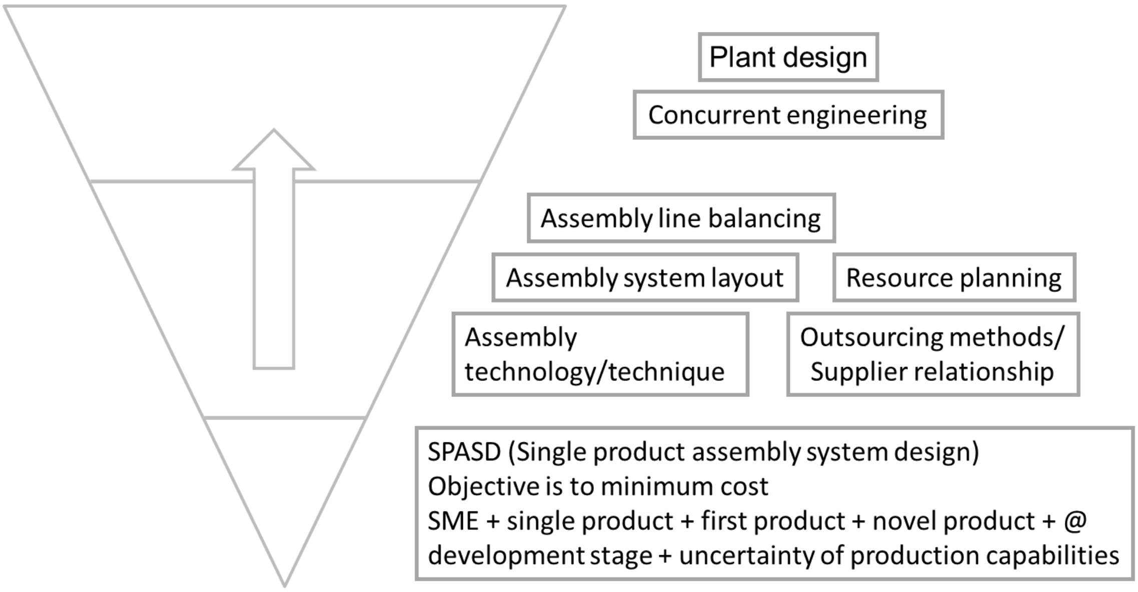

Figure 4-25 Areas covered in literature review for the area of assembly line design

For searching for literature related to SMEs the following keywords were used. The numbers in brackets show the number of initial results found through searching the keyword on Scopus.

- Assembly line design SME (2 results)
- Assembly line design Small enterprise (12 results)
- Assembly line small company (116 results)
- Assembly line SME (8 results)

Out of the found results there were two articles that were directly related to assembly line for SMEs.

In a paper written by Yaman, R. (2008) the design and balancing of a simple assembly line for a small company has been presented. The focus of this study is on designing an assembly line for the production of a tricycle in a bicycle factory manufacturing different types and sizes of bicycles.

In another paper Wang, Q., et al. (2007) have investigated into a system of linear walking-worker (WW) in a SME. They have compared linear WW to linear fixed-worker (FW) and have analysed the impact of changes in workstation and workers number on the system performance.

By realising that limited research has been done with the focus on SMEs, for developing the assembly line design method, research for general industry have been reviewed. Many papers have outlined definitions and basics for assembly line design which have been presented in the following.

Rekiek et al. (2006) define Assembly line design as the design of products, processes and plant layout before the construction of the line itself.

- Design of product involves design review based on <u>DFA</u> rules and <u>precedence constraints</u> between tasks.
- Proposing <u>Operating mode</u> (manual, automatic and robotic) and <u>assembly techniques</u> (Screwing, force fit, etc.) module for each task.
- Line layout is <u>to assign tasks</u> to stations and decide on <u>position of stations</u> and <u>resources</u> of the plant floor.

Also Rekiek et al. (2006) mention that Line layout is composed of:

- *Logical layout:* distributing tasks among station.
  - Assembly line balancing
  - Resource planning
- *Physical layout*: disposition of stations, resources, conveyors, buffers, etc. on the shop floor.

Yamada et al. (2006) has analysed three assembly line designs of conventional assembly line system (ALS), cell production system (ACS) and flexible cell system (FCS) has compared them against production demands (low, medium and high). The result has been presented in a selection table shown in Table 4-24.

Table 4-24 Appropriate assembly line designs based on production demand

Demand quantity (lot size), *Q*	**Net reward *EN***	**Lead time *LT***	**Return on wait *ROW***	**Total**
Small	FCS ACS with smaller *K*	ALS	ACS with smaller *K,* FCS with larger *K*	ACS
Medium	FCS	ACS with smaller *K* ALS	ACS with smaller *K*, FCS with larger *K*	FCS
Large	FCS	ALS	ACS ALS	ALS
Viable	FCS	ACS FCS	FCS	FCS

An overall methodology has been presented by Rekiek et al. (2006) which includes six steps:

- Set the desired workcentres, and for each of them assign tasks into workcentres, dealing with precedence graphs, set the desired number of stations, and set the desired cycle time.
- Set the desired links between workcentres.
- Balance the whole plant (set of workcentres).
- Position workcentres and stations.

- Evaluate the efficiency of the corresponding plant layout using a simulation package. Check the congestion of the plant, analyse the flow, the material handling, and storage area requirements, etc.
- If no satisfying solution is found, exchange the tasks (without violating precedence constraints) and change the links between workcentres.

Some researchers have more focused on the basics of assembly line designs. Categorising assembly line design problems and identifying factors involved in assembly line design are included in the topics found in literature review.

Erel and Sarin (1998) in a survey of assembly line balancing procedures have classified the balancing problems and the solution procedures as shown in Figure 4-26.

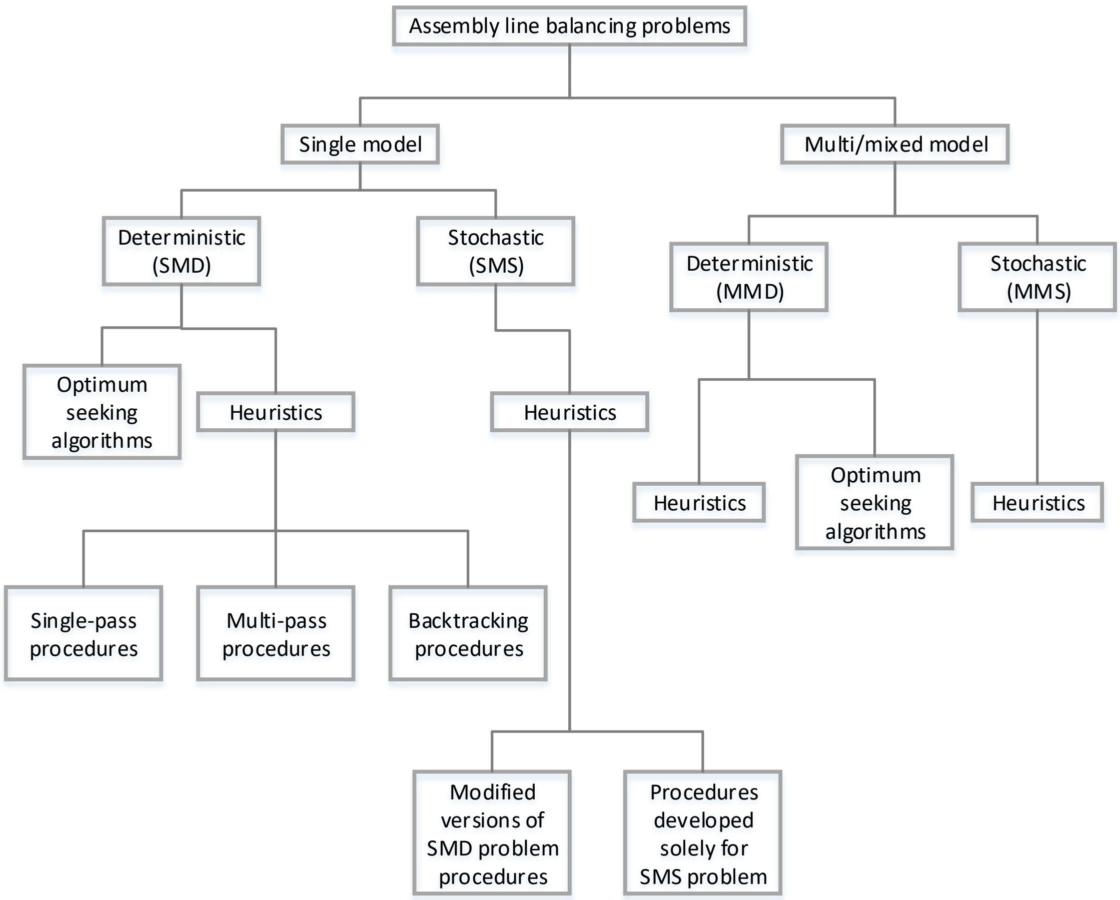

Figure 4-26 Classification of assembly line balancing problems (Erel and Sarin, 1998)

Zha et al. (1998) have identified factors involved in integrated design and assembly planning. The factors are shown in Figure 4-27.

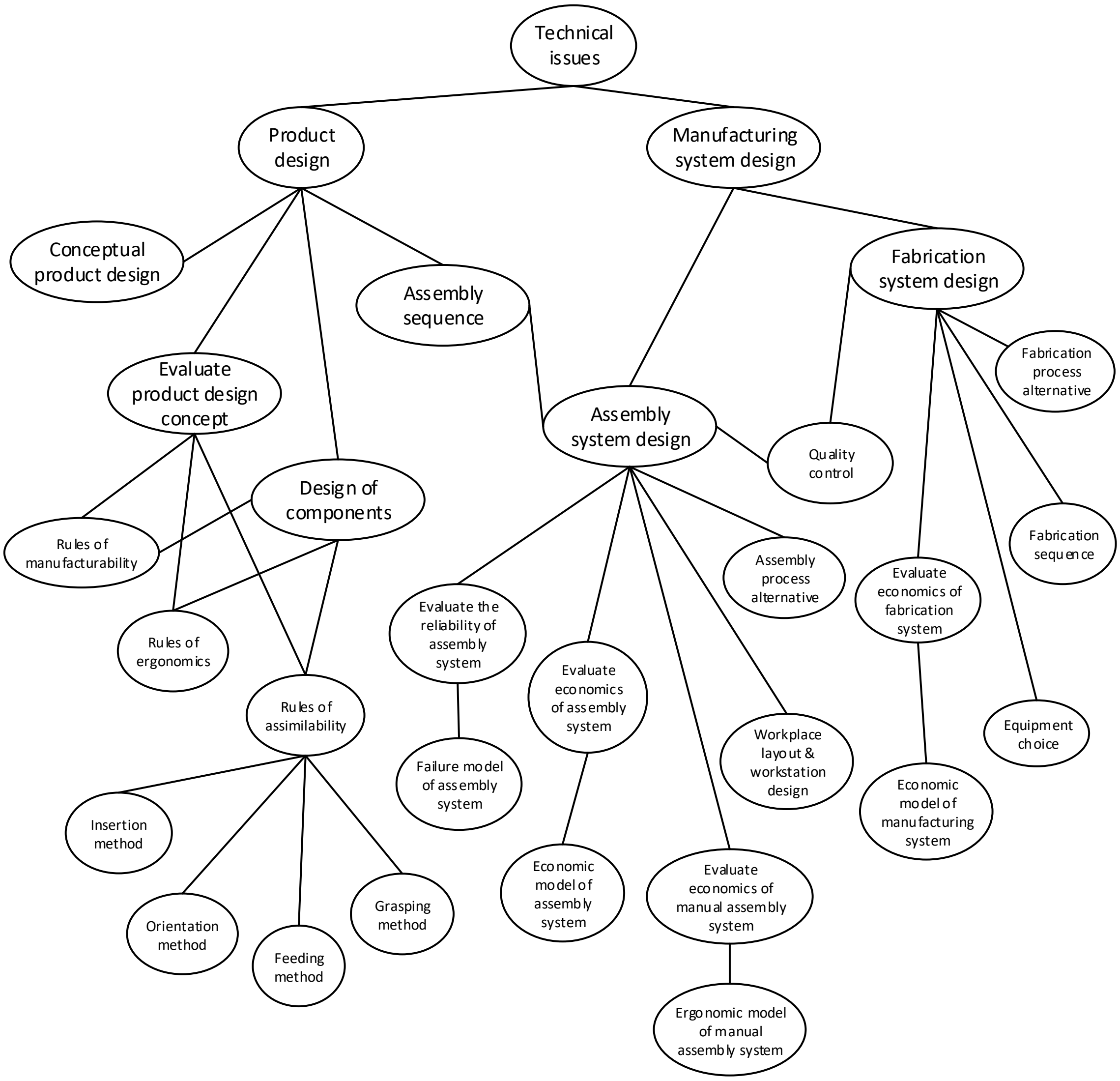

Figure 4-27 Factors involved in integrated design and assembly planning (Zha et al., 1998)

They also have proposed a process for integrated design and assembly planning (Figure 4-28).

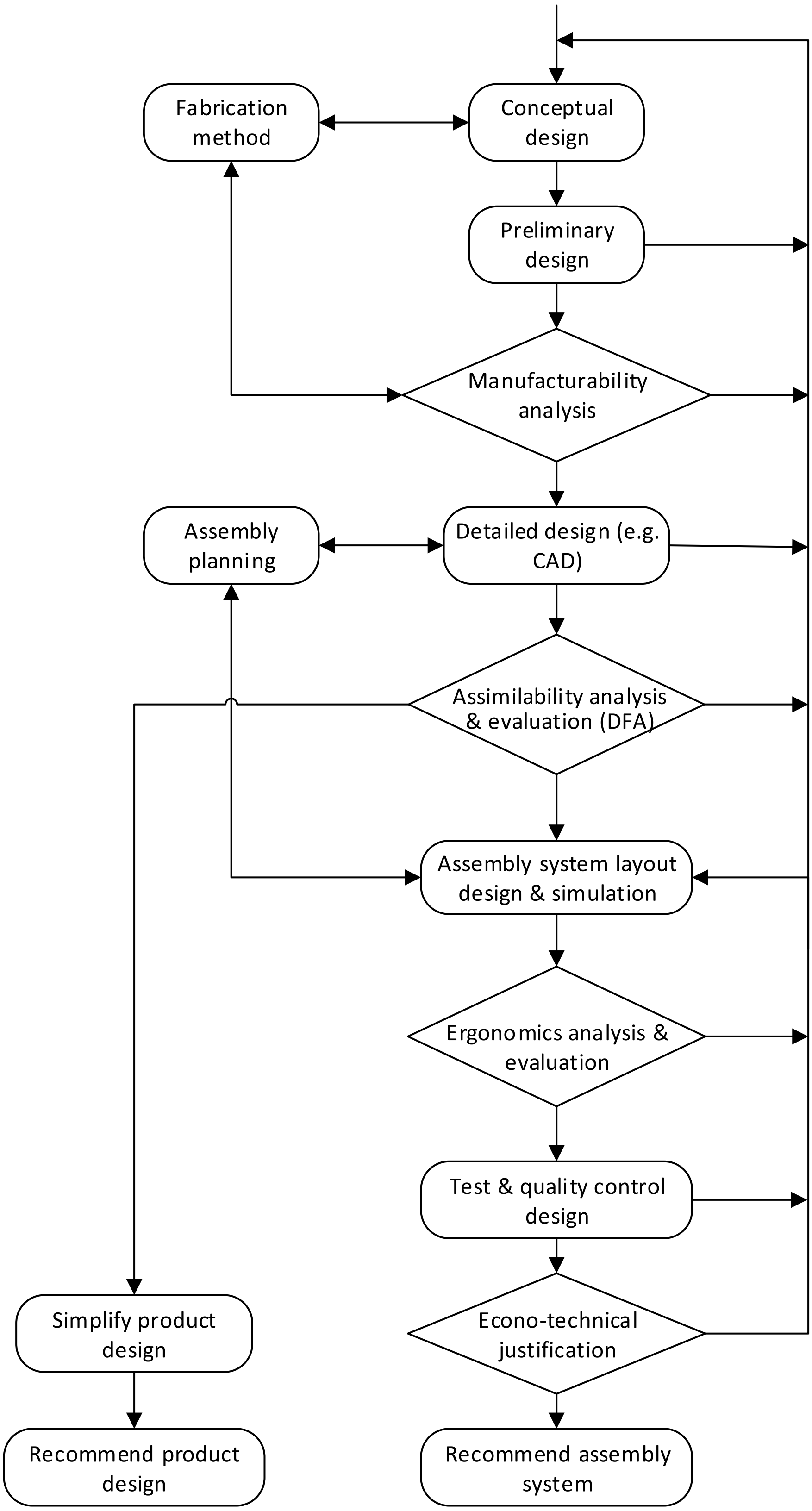

Figure 4-28 Process for integrated design and assembly planning (Zha et al., 1998)

One of the other areas of research related to assembly line design is layout comparison for different cases. These cases could be specific production lines or specific target for an assembly line.

One of the examples of this type of research has been done by (Sengupta and Jacobs, 2004). They have analysed three types of layouts in a TV production plant. They have compared an unpaced serial assembly line, Serial, single task (SST) cell assembly system and Parallel, single task (PST) cellular system. They have simplified the systems, by considering 4 tasks, 4 workstations and 4 workers. The assembly lines are demonstrated in Figure 4-29.

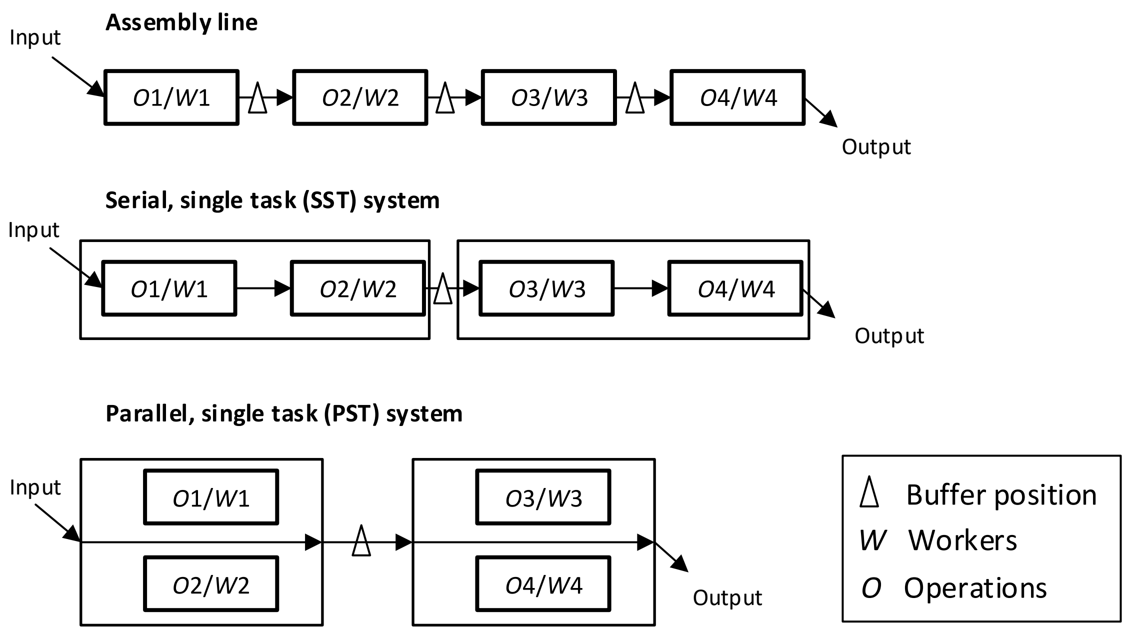

Figure 4-29 3 different types of assembly line layout analysed by (Sengupta and Jacobs, 2004).

The result of the analysis is presented in table where the most appropriate systems are shown against different product/process environments.

Table 4-25 Matching systems with different product/process environments (Sengupta and Jacobs, 2004).

Product/Process environment	Most appropriate system
Low variance, low setup times	Assembly line & assembly cells are equivalent
High variance, high setup times	Assembly cells significantly superior to assembly line. Among the cellular systems, PST system is generally the best system
Inefficiencies in team working, Low variance, low setup times	Assembly line better than assembly cells at relatively low levels of inefficiency
Inefficiencies in team working, High variance, High setup times	Assembly line better than assembly cells at extremely high levels of inefficiency
Labour specialisation benefits, Low variance, low setup times	Assembly line better than assembly cells when cell task times are only 10-20% higher than assembly line task times
Labour specialisation benefits, High variance, high setup times	Assembly line better than assembly cells when cell task times are 40-50% higher than assembly line task times

Another comparison type research has been done by Gong et al. (2011). In this paper assembly lines and assembly cells manufacturing system with real-time distributed arrival time for just-in-time oriented production environment have been compared. The comparison is simulation based performance comparison.

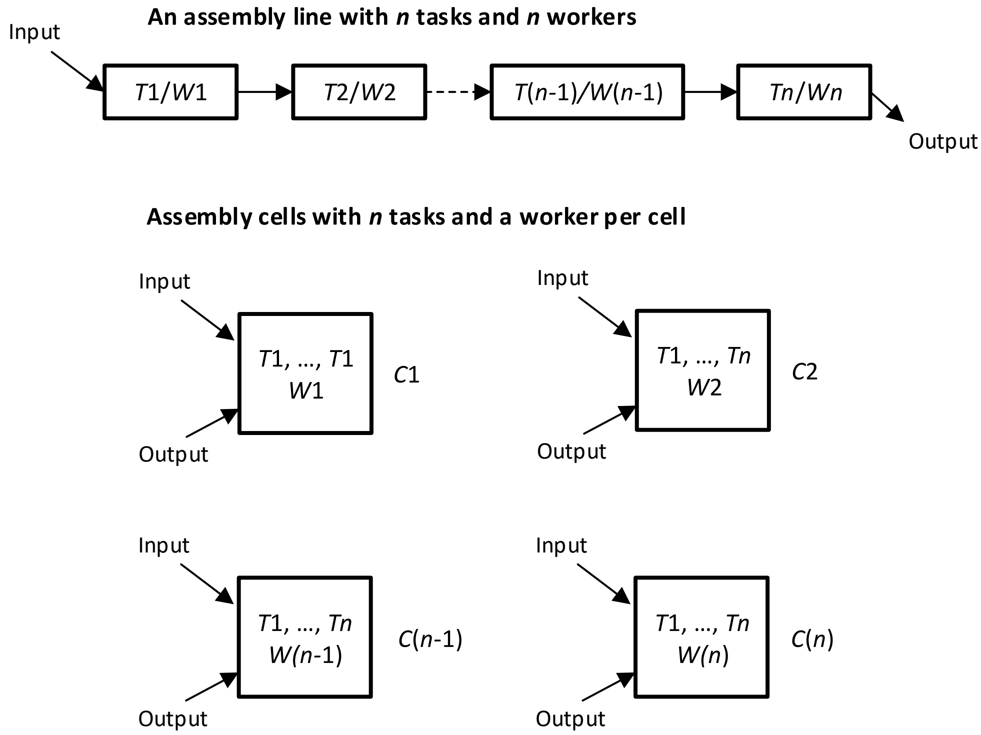

Figure 4-30 Comparison of assembly line system with assembly cell system (Gong et al., 2011)

The result of the comparison shows that for the specific research case, assembly cells can have better performance than assembly lines. The result of simulation of 300 products shows that assembly cells counteract the detriment caused by tardiness and earliness by approximately 90%.

In another paper by Wallace (2008), the changes in assembly systems in Volvo is analysed based on the reasons for selecting the systems. The researcher has observed and interviewed Volvo in Sweden. Volvo changed the system from flow-line to a short-line (cell) system and again changed to flow-line system. This analysis showed that management of flow-lines is better than cell system, as everything is more visible, programmable and manageable. It is easier in flow-lines to see and identify sources of problems. It was showed that unlike academic analysis, the production of the flow-line was more than cell system, which according to the author is due to better management conditions of flow line compared to cell system.

Assembly system (layout) selection is one of the other areas of focus in research related to assembly lines.

In one of the earliest researches done in this area, Wild (1975) has developed a three step system selection procedure. The steps are feasibility study, appraisal based on quantifiable factors and appraisal based on non-quantifiable factors.

In the paper, for the feasibility study a table was given for some factors. For quantifiable factors, relative cost or inefficiencies are considered and for the final stage, a table of non-quantifiable considerations is given.

Khan and Day (2001) have developed a method for assembly system design. This method is one of the few methods that includes various aspects of assembly line design and takes into account all types of assembly lines, e.g. manual or automated, single, multi and mixed lines with deterministic or stochastic operation times. It includes, assembly system selection, deciding on suitable cycle times and line balancing and parallel line and workstations consideration.

Khan and Day (2001) have proposed a process for assembly line design called the knowledge based design methodology. The process is shown in diagram in Figure 4-31.

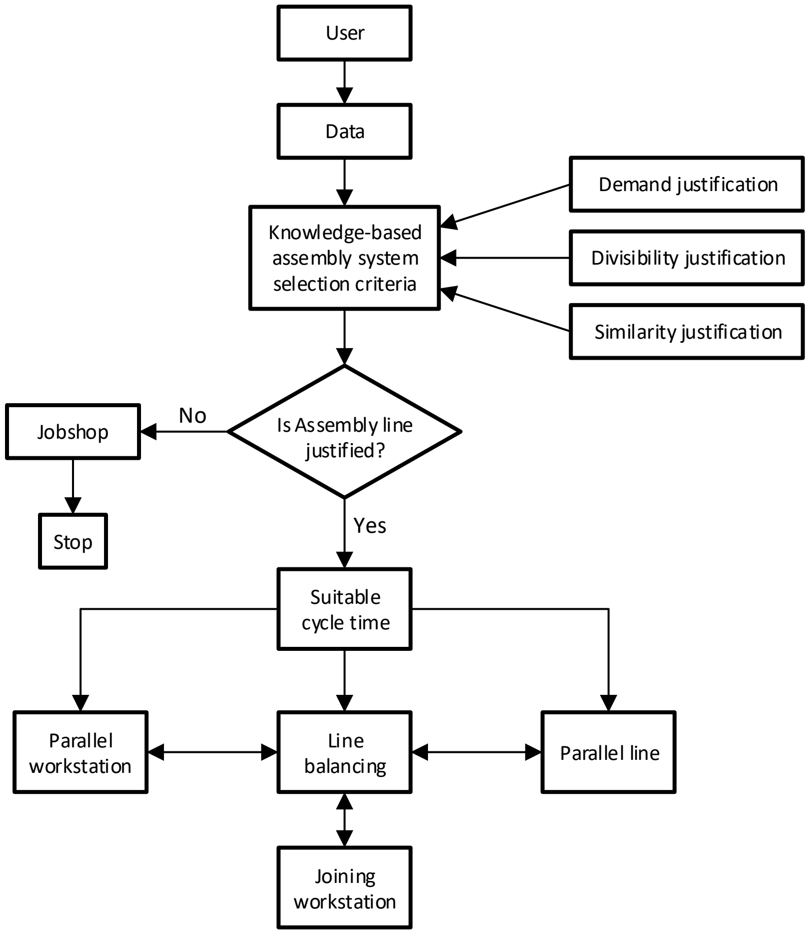

Figure 4-31 'Knowledge based design methodology' a process for assembly line design (Khan and Day, 2001)

Another research done in this area is by Swift et al. (2004). They have developed a strategy for assembly system selection based on technological and economical considerations, including component and assembly design, component variability and production conditions. In this method a list of selection drivers is given. A 7-step process is proposed for the selection strategy as shown in Table 4-26.

Table 4-26 7 steps of assembly system selection by (Swift et al., 2004)

1. Carry out a DFA analysis on the product and redesign accordingly against the product design specification
2. Identify critical component characteristics and dimensional tolerances and set appropriate process capability targets
3. Obtain an estimate of annual production volume and variant spectrum
4. Determine the likely system type from the assembly system selection chart
5. Consider each PRIMA for the system(s) under consideration and review: a. The process and its variations b. Economic considerations c. Typical applications d. Design aspects e. Quality issues
6. Obtain assembly cost estimate(s)
7. Review selected assembly system against business requirements

As a part of this process a chart is given to determine the likely system type (Figure 4-32)

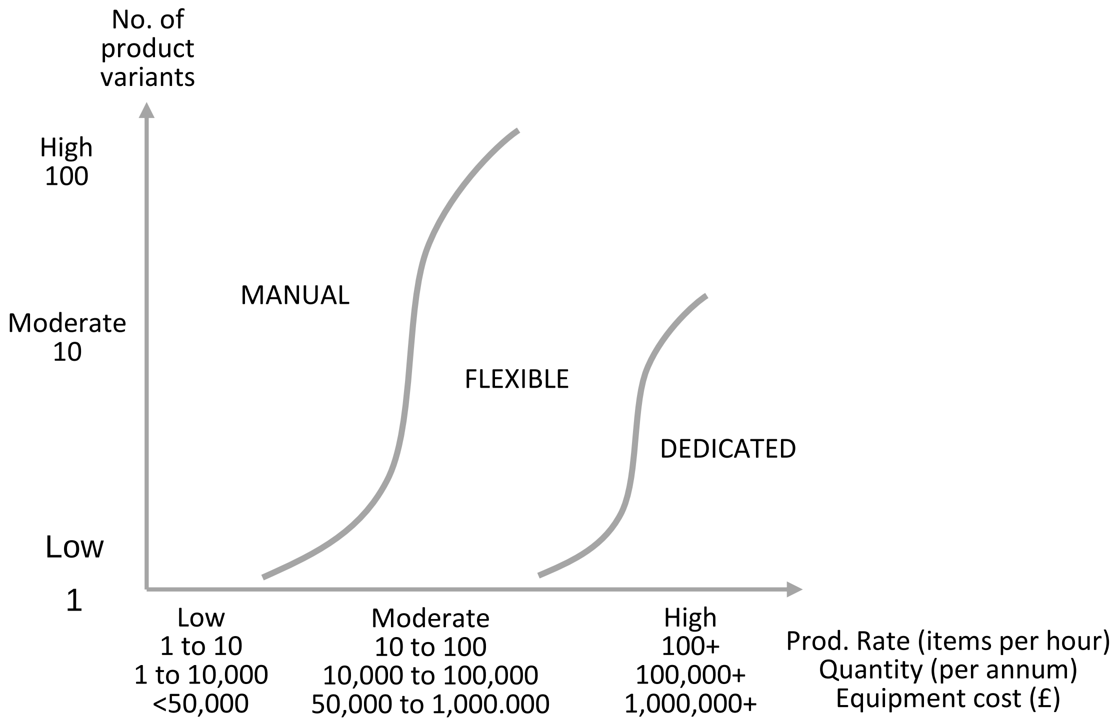

Figure 4-32 Assembly system selection based on production volume and number of product variants (Swift et al., 2004)

A tool has been developed by Shtub and Dar-El (1989) based on AHP and LCC techniques. In this method the benefits and LCC of candidate assembly systems will be evaluated. The candidate assembly systems are chosen by a ranking system based on AHP.

The criteria for the evaluation of the assembly systems have been presented in Figure 4-33. The criteria have been categorised in three groups of criteria related to operating system, planning and control system and conveyance system. The criteria are mainly related to sensitivity and reliability, flexibility of the system, responses to different changes and quality of product.

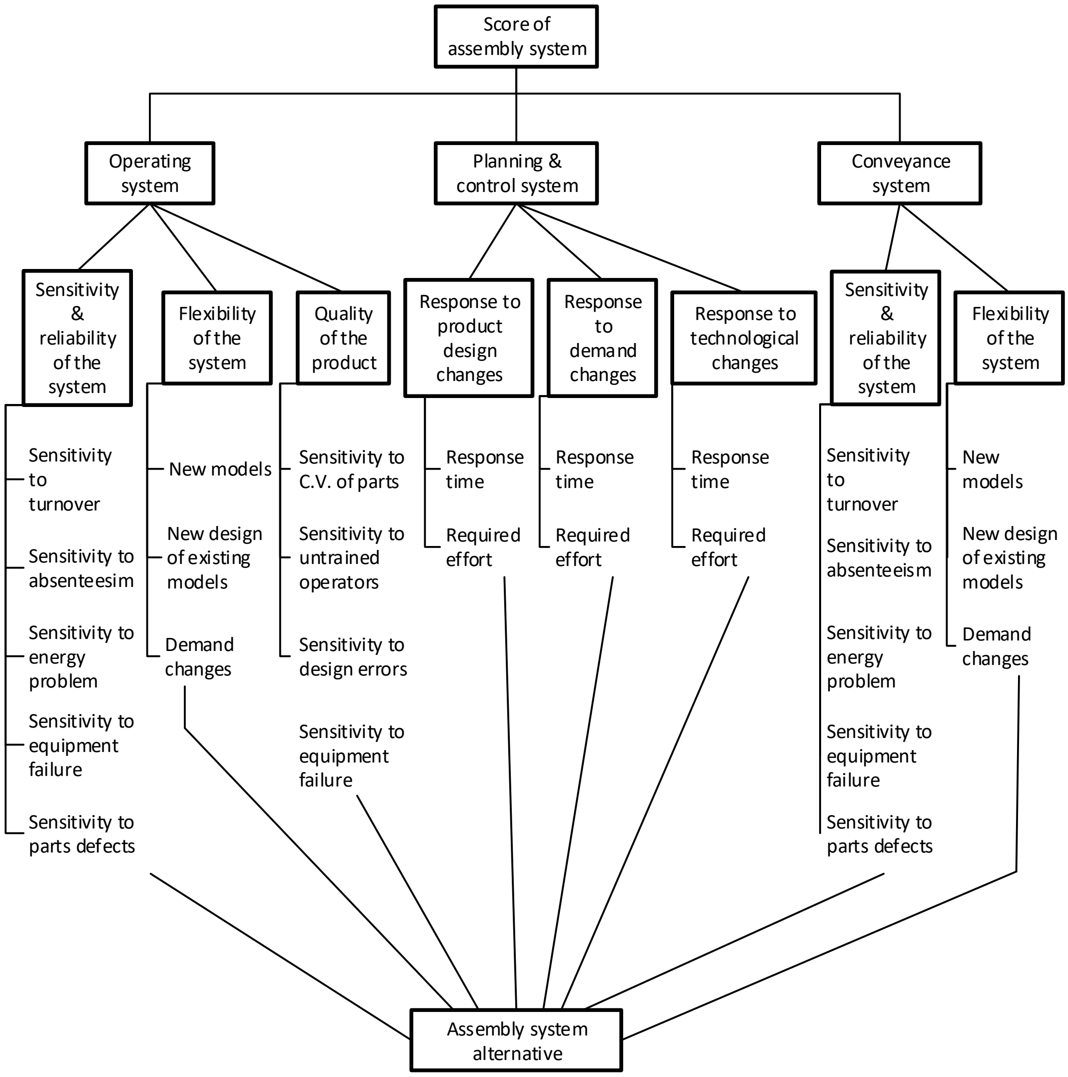

Figure 4-33 Criteria for evaluation of assembly systems (Shtub and Dar-El, 1989)

Shtub and Dar-El (1989) have presented the cost break down structure of an assembly line in a chart shown in Figure 4-34. In this figure costs involved for designing, operation and retirement of an assembly have been presented. Costs related to commissioning the assembly line need to be added to the list.

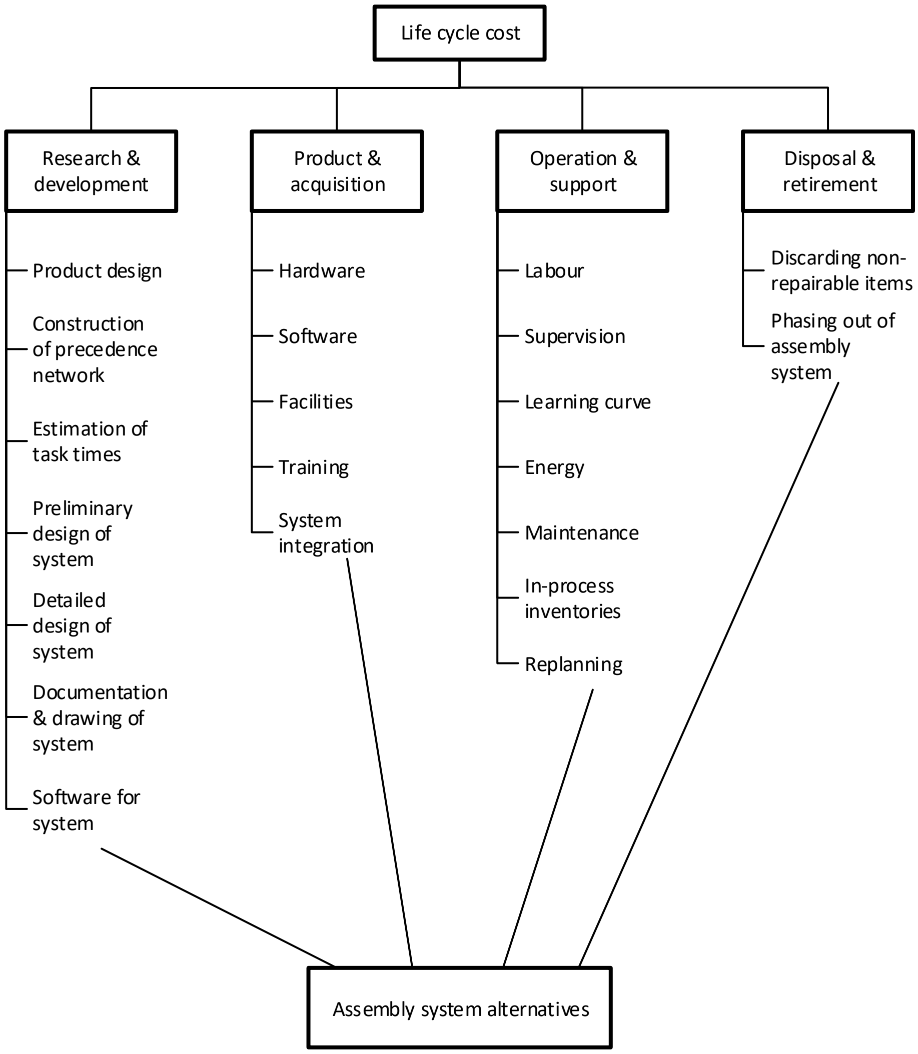

Figure 4-34 Cost break down structure of an assembly line

Daganzo and Blumenfeld (1994) have developed an analytical model to evaluate serial and parallel designs for an assembly system. The model is to identify when each is cost-effective. The result shows that the final trade-off is between labour and equipment costs.

The research gap can be summarised as:

- A large amount of work done in the area of assembly line design is about the optimisation of a current assembly line where the product is already being produced; in our research assembly line design is being discussed for a future product.

- Most of the research found have focused on assembly line balancing for different assembly layouts, systems and modes. According to Abdullah et al. (2003) the area with lowest research on is assembly system/process selection.
- There are very few works on an integrated method for both logical layout and physical layout design.
- At the development stage, where still decisions are being made, there is no idea about the factory and no size limit is defined.

4.4.2 Method development

One of the requirements of the collaborating company was to have a tool for estimating set-up cost of their future production plant. One of the main cost drivers of a factory purchase or rental cost is area size of a factory and in order to calculate the area size needed for a factory, the area size needed for each section of the factory has to be estimated separately. As the main area of a factory is the production and assembly area, the area size has to be calculated with acceptable amount of accuracy. Different layers of assembly line design that need to be covered to determine the plant area are shown in Figure 4-35.

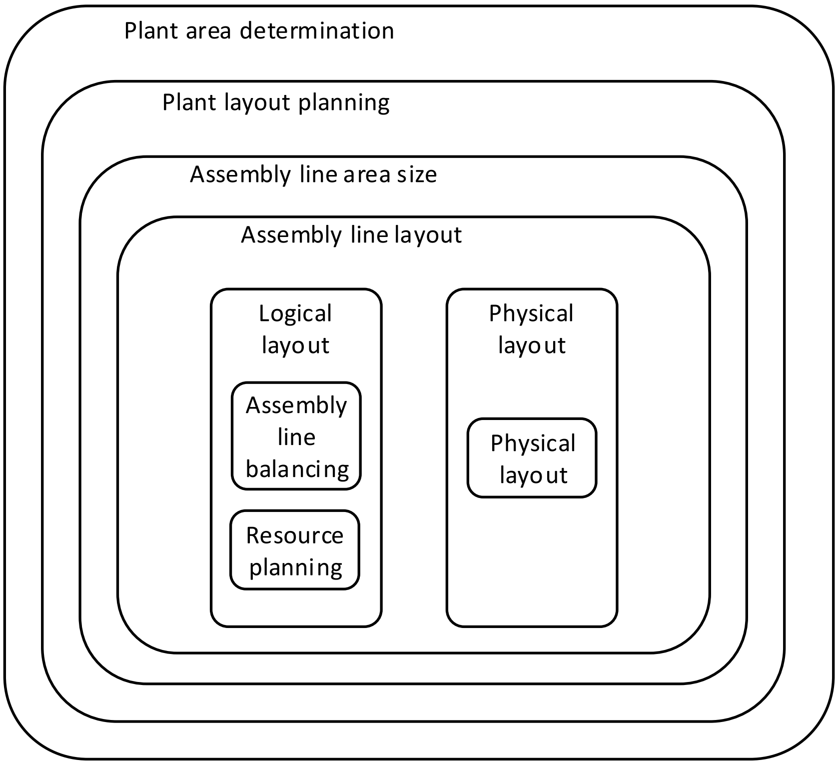

Figure 4-35 Different layers of assembly line design to determine the plant area

Also, in order to know the tools and equipment and number of staff needed for production, the assembly line needs to be designed at this stage.

The development started by identifying production requirements and production plans of the collaborating company. The main requirements of the company were to have a line with low production cost and high degree of flexibility. The focus of the development was on a manual assembly line with one product with only one configuration in the line.

As the company needed quick assistance, several assembly line layouts were chosen from the literature and also some were suggested by the management of the company. The layouts were evaluated and by using expert opinion a specific layout was selected to be able to meet company's requirements. By studying the product and using technical member's opinions, the assembly process was designed and the size of the assembly line was defined. Other areas such as painting and packaging and storage areas were added to the design of the assembly area.

In order to develop the method into more detail, further literature review was done to identify literature best practices.

As during the development stage, the main task is decision making, methods which could help in the decision making process or methods would help to compare different assembly systems and layouts are more useful.

4.4.3 Results

Based on literature best practices a general process for assembly line design is developed.

The steps of the process are as following:

- Define product assemblies & subassemblies
- Draw precedence diagram
- Select: Assembly line or Assembly cell
- If assembly cell, how many cells
- If assembly line: Serial or Parallel lines or Parallel workstations
- Define number of workstations
- Area size for each workstation
- Area size for conveyor, feed-in systems, walking area, etc.
- A percentage for clearances

The process has been illustrated in Figure 4-36.

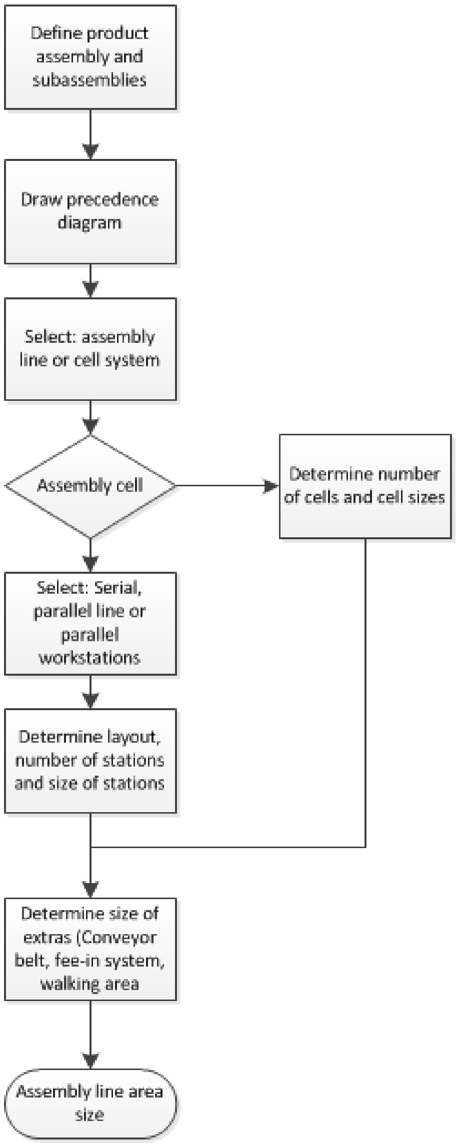

Figure 4-36 Process for assembly line design

4.4.4 Case study

There were two stages for the case study done during the project for the area of assembly line design; one case study was done earlier in the project to help the collaborating company for preliminary decision makings at that point and a detailed case study was done later as the main case study for the purpose of validating the developed method.

4.4.4.1 Case study 1

In a meeting with collaborating company the CEO proposed a design for the factory and the assembly line. He suggested that the factory could have a Cell design with an assembly line with a fixed position layout design. In his design the factory would be consisted of assembly cells, a quality check cell and a warehouse. At each assembly cell there would be two technicians working, one electrical and one mechanical technician, which both would work together on assembling one product. He has predicted that each couple of technicians could complete two units per day. At the start of a working day, the technicians would collect the required parts for assembling the units for a day and would place the parts on shelves around the assembling work station. As a unit is completed, it would be carried to the quality check cell which the unit would be checked and run to assure its quality and safety. And following a successful quality check the unit would be packaged in the same place and would be sent for dispatching.

In Figure 4-37 a schematic of the proposed factory and assembly cell layout is presented.

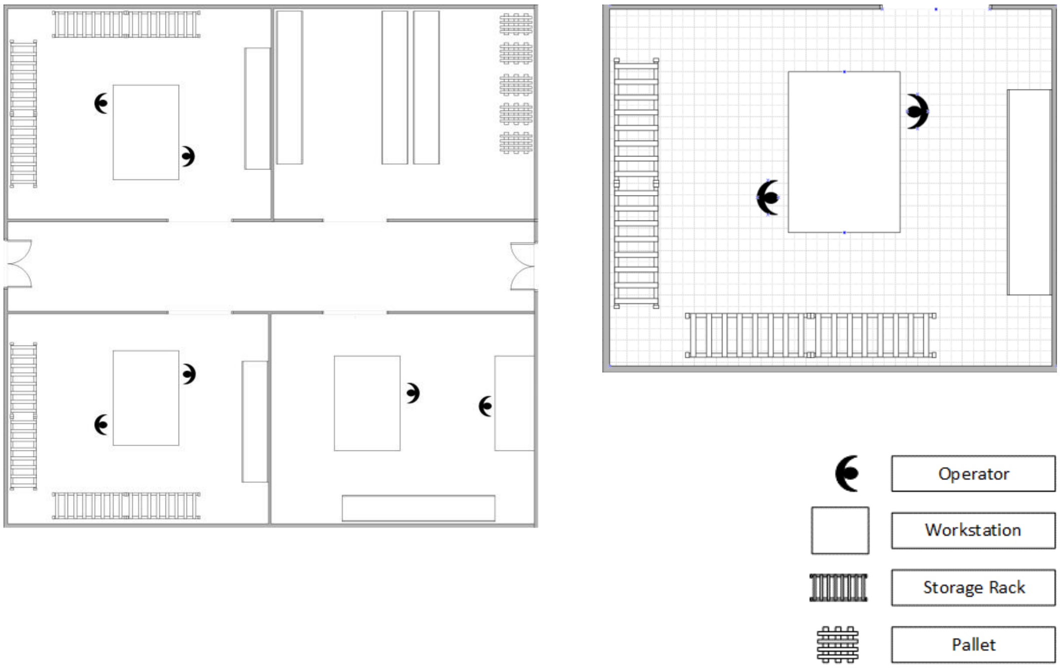

Figure 4-37 Proposed plant and assembly line layout

Moreover, the CEO has suggested to have a research and development (R&D) centre next to the factory. The R&D section would be consisted of a workshop, an office area and resting area. The schematic of the plant design can be seen in Figure 4-38.

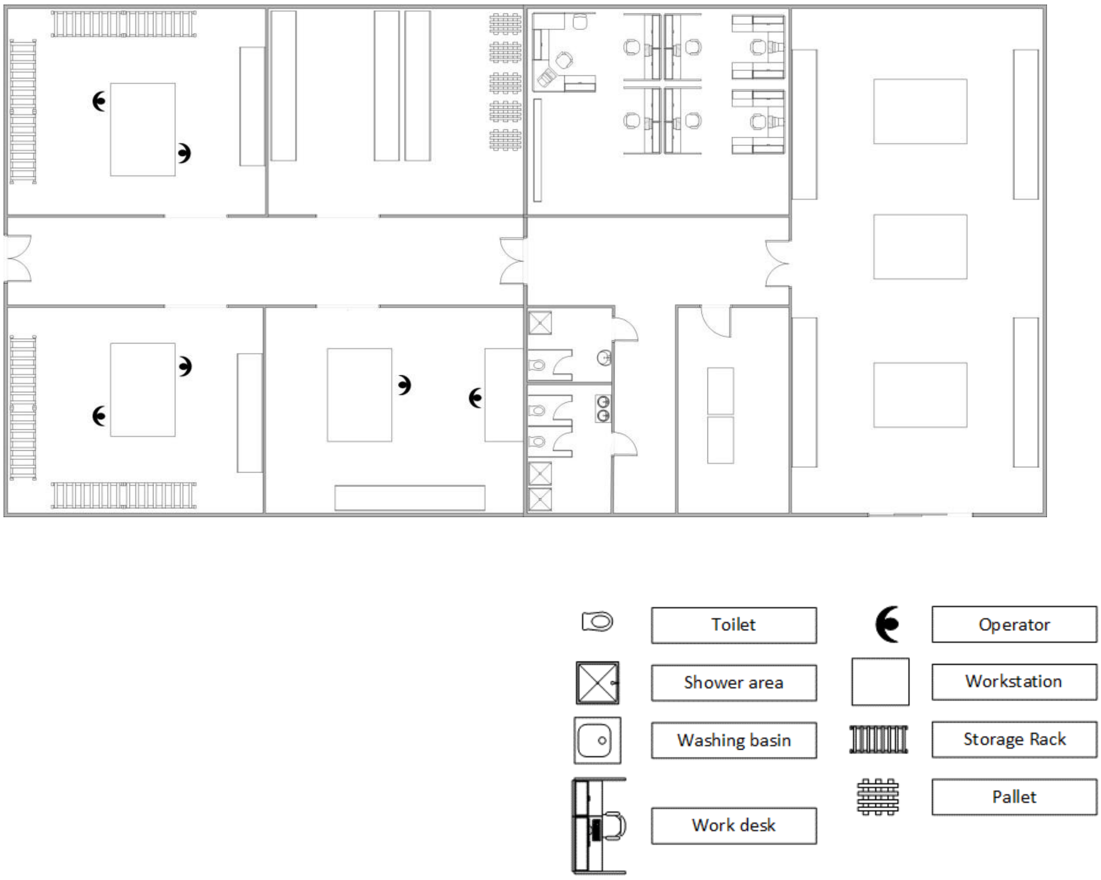

Figure 4-38 Plant schematic including R&D area

The layout design was presented to Expert 1 and he commented on the design. Expert 1 thought that the current design would certainly have a large amount of walking time in the cells and around the factory. There would be walking from assembly cells to the warehouse, walking inside the assembly cell and around the workstation and walking from the assembly cell to the quality check area and this movement would add no value to the product. Furthermore because of the limited area of the cells and the need for moving around the workstation, the assembly cell would become congested. The walking routes during assembly tasks are shown in Figure 4-39.

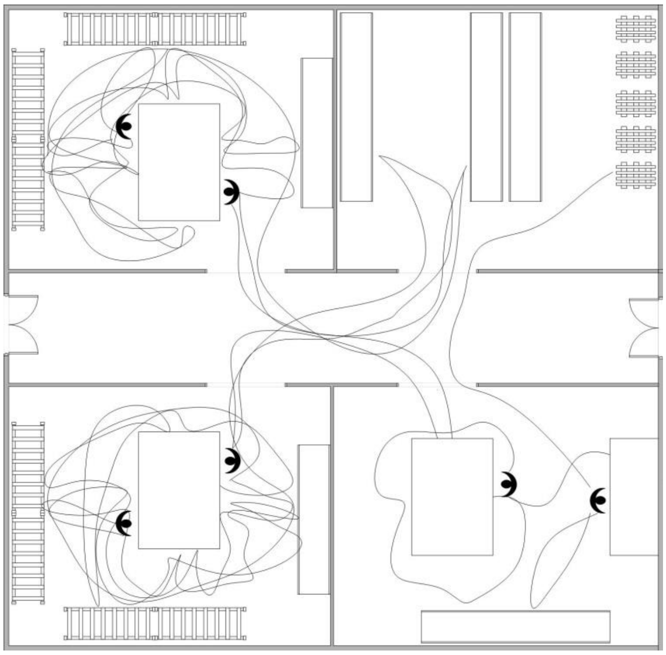

Figure 4-39 Plant workflow

Expert 1 mentioned that cell layout is suitable for low volume and high variety of products and as our client would have one product and in 5 year time would reach high volumes the cell layout would be inappropriate. The current layout would be fine for 2 outputs per day, but it would have around 5 times more walking around than assembly time and would be inefficient. As the plant output per year would increase to 100,000 units per year in 5 year time, this design wouldn't be suitable.

One of the other disadvantages of this design is the bottlenecks at the quality check (QC) area. In order to decrease the congestion at the QC cell, the rate of QC should be more than the actual required rate. Also the time balancing should be accurate and any problems or delays in the assembly cells would cause waiting at the QC.

In the cell design, unless there are noise or pollution or safety restraints, there is no need to have walls or partitions between cells. Walls would cost and add no value. Moreover, removing he walls would add more passage space through cell layouts.

Having two skilled technicians is not necessary. One semi-skilled technician can assemble both mechanical and electrical parts. The skilled technicians would be over-skilled for this job, and they would get bored and possibly leave the job. Car assembly lines use semi-skilled workers with daily or one or two week trainings.

In terms of health and safety issues, each cell should have two exits, one main exit and one fire exit, and there should be enough ventilation and lighting.

One of the main disadvantages of this layout is its limitation for Volume increase. Because of the design of the cells and space limitation, it’s not possible to increase the number of technicians per cell or increase cell areas. Therefore, the only way to increase the volume of production is to add more cells to the factory. Adding more cells requires more space which would cost much.

Expert 1 suggested the use of either a straight line layout or variations of it such as U-shaped layout or staggered layout, depending on the available area.

To have effective material supply to the assembly lines, direct feed to the lines can be used. In this case the suppliers would transfer the parts are directly to the feeding lines across the assembly line. The feed lines can either be gravity fed or electrically fed. If it’s not possible to have all the material directly delivered to the line, material holding area can be considered.

It is possible to arrange with the suppliers to hold the supply at their own holding area and they would be responsible for materials being hold. In motor industry the supplier is only paid when the product comes out of the production line. Storing material would have costs. Also stacking up and using equipment such forklifts would add no value and will have extra cost.

In the U-shaped layout, by adding more technicians the production rate will increase. It is possible to assign a complete assembly job to each person or place each technician at one or a number of workstations and assign specific tasks to them.

The total factory layout can also be a straight line layout or a U-shaped layout where material would enter from the entrance and would leave the factory from the loading bay.

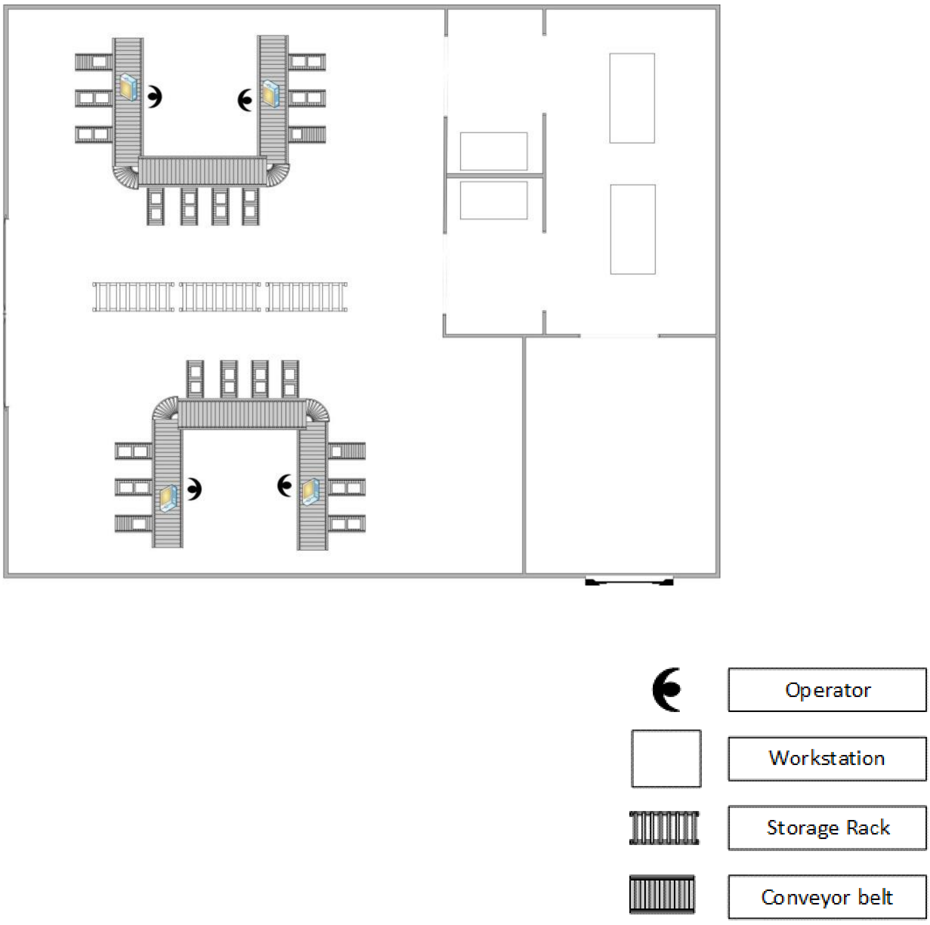

Figure 4-40 Suggested U-shaped assembly line and plant layout

As it can be seen in Figure 4-40, the plant can be consisted of two U-shaped assembly lines. The material would flow in from the main entrance and the parts would directly go into the feed lines. And when a product assembling is finished the product would move to one of the two QC areas. After the QC process is done successfully the product would move to the packaging area and following packaging they are transferred to the dispatch area where the products are loaded into the specific vehicles.

4.4.4.2 Case study 2

The production requirements of the company are as follows:

- Production of 1000 units for the first year and increase up to 100000 units in 5 years

- An assembly line with the lowest capital requirement

In the first step, the time needed to produce each unit is calculated based on 1000 units and 100000 units per year.

- 1000 units for first year
    - 252 working days, 8 hour shift
    - $\frac{1000}{252} = 4 \text{ per day}$
    - $\frac{8}{4} = 2\ hours\ for\ each\ product$
- 100000 units per year
    - 252 working days, 8 hour shift
    - $\frac{100000}{252} = 400\ per\ day = 50 \text{ per hour}$
    - $\frac{8}{400} = 0.02\ (1.2\ min) \text{ hours for each product}$

For 100000 units per year, if there be 3 shifts per day:

- 3x 8 hour shift pattern
- 5 working days per week, covers 120 hours a week
- 100000 per year
- $\frac{100000}{252} = 400 \text{ per day}$
- $\frac{24}{400} = 0.06\ (3.6 \text{ min}) \text{ hours for each product}$

For the detail calculations the following assumption would be used:

- No breaks
- No paid lunch
- A task cannot be split between two stations
- Precedence relationship must be considered in assigning tasks to stations
- All tasks must be assigned to stations, no task can be ignored
- Task process times are fixed and are independent of work station
- Due to higher process time of testing and packaging, these two tasks are considered separately and a separate cell or station is considered for them.

In the next step the product assemblies and subassemblies should be determined. A simplified product breakdown structure is shown in Figure 4-41.

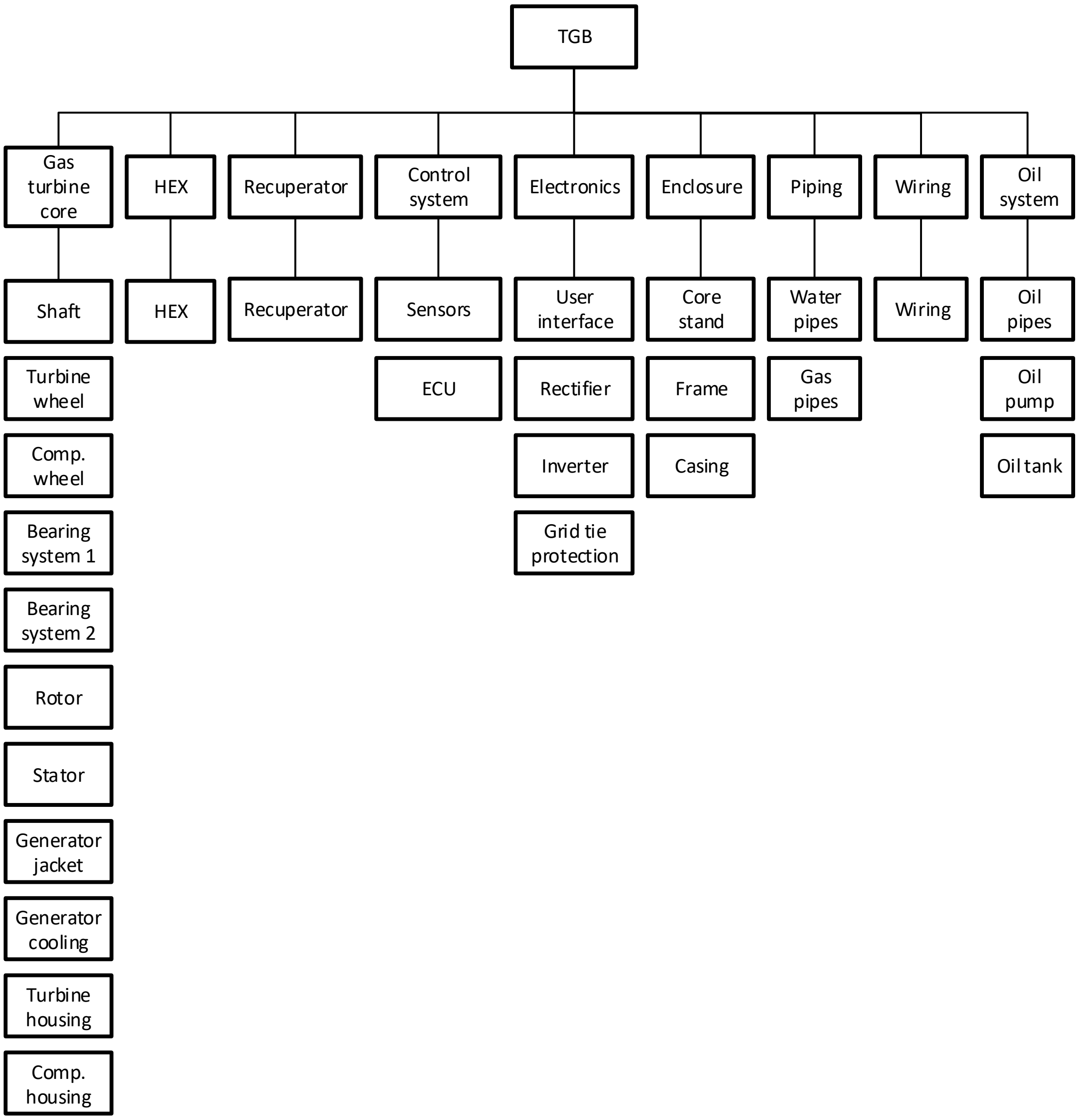

Figure 4-41 TGB02 simplified product breakdown structure

In order to make the use of the diagram easier a simple number coding system would be used. In this system all top level subsystems would be given a unique number or letter. Also, the parts would be given a unique number or letter. The combination of the two codes would define a part in the system. This system is only being used for this analysis and in reality a detailed coding system is being used in the company. Part codes can be defined based on numbers in the tree structure in Figure 4-42.

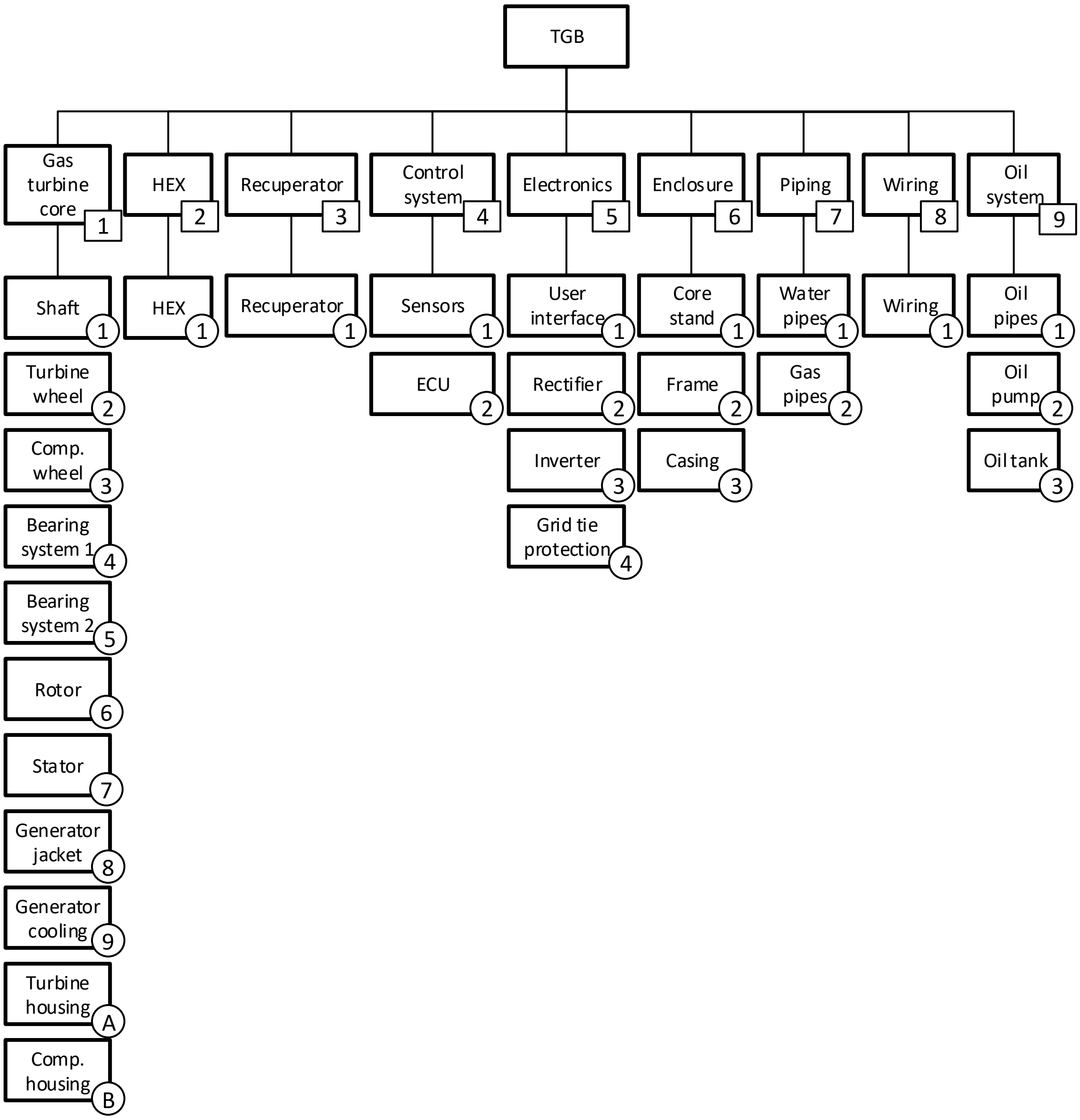

Figure 4-42 Coded product breakdown structure

For the next step a list of assembly tasks should be defined. In addition to the part code, a task code should be defined for each assembly task. The task codes and parts codes are shown in Table 4-27.

Table 4-27 List of assembly task and codes

Task code	Part code	Task
10	10	Assembling Gas turbine core
21	21	Assembling HEX
31	31	Assembling Recuperator
41	41	Assembling sensor
42	42	Assembling ECU
51	51	Assembling User interface
52	52	Assembling rectifier
53	53	Assembling inverter
54	54	Assembling grid tie protection
61	61	Assembling core stand
62	62	Assembling frame
63	63	Assembling casing
71	71	Assembling water pipes
72	72	Assembling gas pipes
81	81	Assembling wiring
91	91	Assembling oil pipes
92	92	Assembling oil pump
93	93	Assembling oil tank

The next major step is defining the precedence graph. The graph is drawn based on the relation of tasks to each other and their precedence in relation to each other. The precedence graph for TGB02 is shown in Figure 4-43.

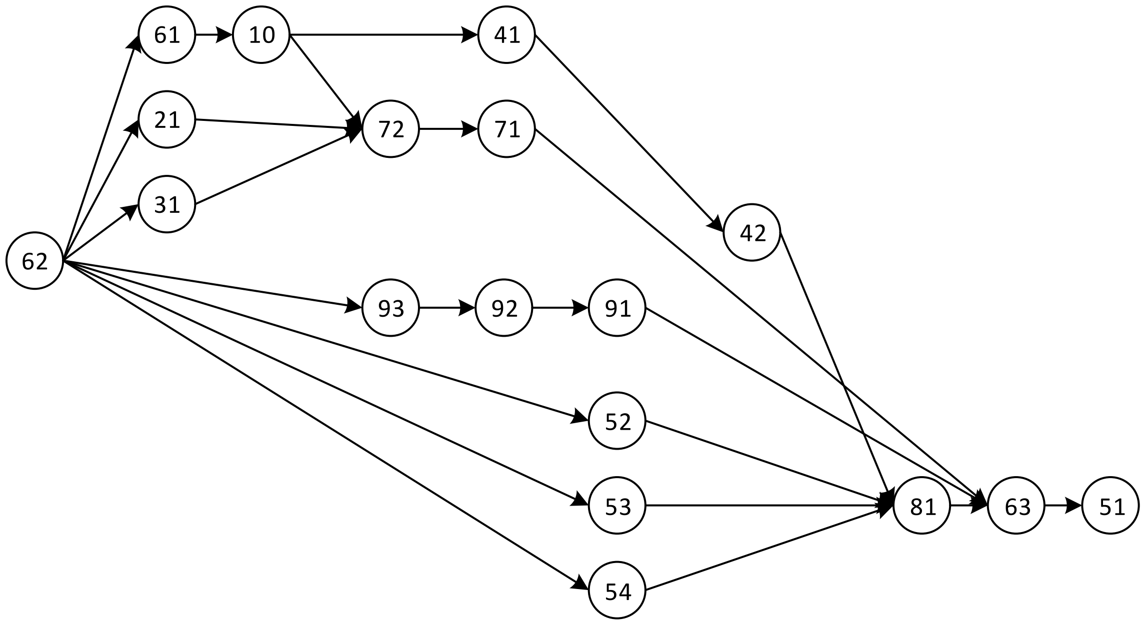

Figure 4-43 TGB02 assembly task precedence graph

Determining the task times is the next step in the assembly line design. The task times can be determined either by time study of the tasks or expert knowledge and experience. For this case study an estimation of task times is used based on experience and expert knowledge.

Firstly, the detailed tasks for each major task is determined. As an example, the major task of assembling a heat exchange consists of the tasks of aligning the heat exchanger and tightening 4 bolts and nuts into their holes.

Table 4-28 Table of detailed tasks of TGB02 assembly

Task code	Part code	Task	Sub-tasks
10	10	Assembling Gas turbine core to stand	Align – tighten 4 normal size bolts & nuts
21	21	Assembling HEX	Align – tighten 4 normal size bolts & nuts
31	31	Assembling Recuperator	Align – tighten 4 normal size bolts & nuts
41	41	Assembling sensors	(2x sensors) align 1 – tighten small size nut – align 2 – tighten small size nut
42	42	Assembling ECU	Align small - 4 small size screws – connect wires
51	51	Assembling User interface	Align small - Connect wires – 4 small size screws
52	52	Assembling rectifier	Align – 4 small size screws – connect wires
53	53	Assembling inverter	Align – 4 small size screws – connect wires
54	54	Assembling grid tie protection	Align – 4 small size screws – connect wires
61	61	Assembling core stand	Align – 4 normal size bolts & nuts
62	62	Assembling frame	Place on workplace (conveyor) - Align – fix to workplace
63	63	Assembling casing	Align – 7 normal size screws
71	71	Assembling water pipes	(5 pieces of pipe with 8 fittings) 5 alignments + 5 large nuts
72	72	Assembling gas pipes	(4 piece pipe with 5 fittings) 4 alignments + 5 medium size nuts
81	81	Assembling wiring	A good amount of wiring
91	91	Assembling oil pipes	(7 pieces of pipe & 10 fittings) 7 alignments + 10 medium size nuts
92	92	Assembling oil pump	Align – tighten 4 small screws
93	93	Assembling oil tank	Align – tighten 4 medium size screws

The task time for each sub-task in listed in Table 4-29:

Table 4-29 Average time for each sub-task

	Task	Average
1	Align large	4s
2	Align medium	3s
3	Align small	2s
4	Large nuts & bolts (place + tighten)	10s
5	Medium nuts & bolts	8s
6	Small nuts & bolts	6s
7	Screws	4s
8	Large nut	6s
9	Medium nut	5s
10	Small nut	4s
11	Fixing & securing	6s
12	Wire connection	5s

Based on the estimated average time for each sub-task, the task time for the main tasks are calculated as Table 4-30.

Table 4-30 Task time for the main assembly tasks

Task code	Task	Sub-tasks	Time (s)
10	Assembling Gas turbine core to stand	Align large – tighten 4 normal size bolts & nuts	36
21	Assembling HEX	Align large – tighten 4 normal size bolts & nuts	36
31	Assembling Recuperator	Align large – tighten 4 normal size bolts & nuts	36
41	Assembling sensor	(2x sensors) align small 1 – tighten small size nut – align 2 – tighten small size nut	12
42	Assembling ECU	Align small - 4 small size screws – connect wires	23
51	Assembling User interface	Align small - Connect wires – 4 small size screws	23
52	Assembling rectifier	Align medium – 4 small size screws – connect wires	24
53	Assembling inverter	Align medium – 4 small size screws – connect wires	24
54	Assembling grid tie protection	Align medium – 4 small size screws – connect wires	24
61	Assembling core stand	Align medium – 4 normal size bolts & nuts	35
62	Assembling frame	Place on workplace (conveyor) - Align large – fix to workplace	10
63	Assembling casing	Align large – 7 normal size screws	32
71	Assembling water pipes	(5 pieces of pipe with 8 fittings) 5 medium alignments + 5 large nuts	45
72	Assembling gas pipes	(4 piece pipe with 5 fittings) 4 medium alignments + 5 medium size nuts	37
81	Assembling wiring	A good amount of wiring	~60s
91	Assembling oil pipes	(7 pieces of pipe & 10 fittings) 7 medium alignments + 10 medium size nuts	71
92	Assembling oil pump	Align medium – tighten 4 small screws	19
93	Assembling oil tank	Align medium – tighten 4 medium size screws	19

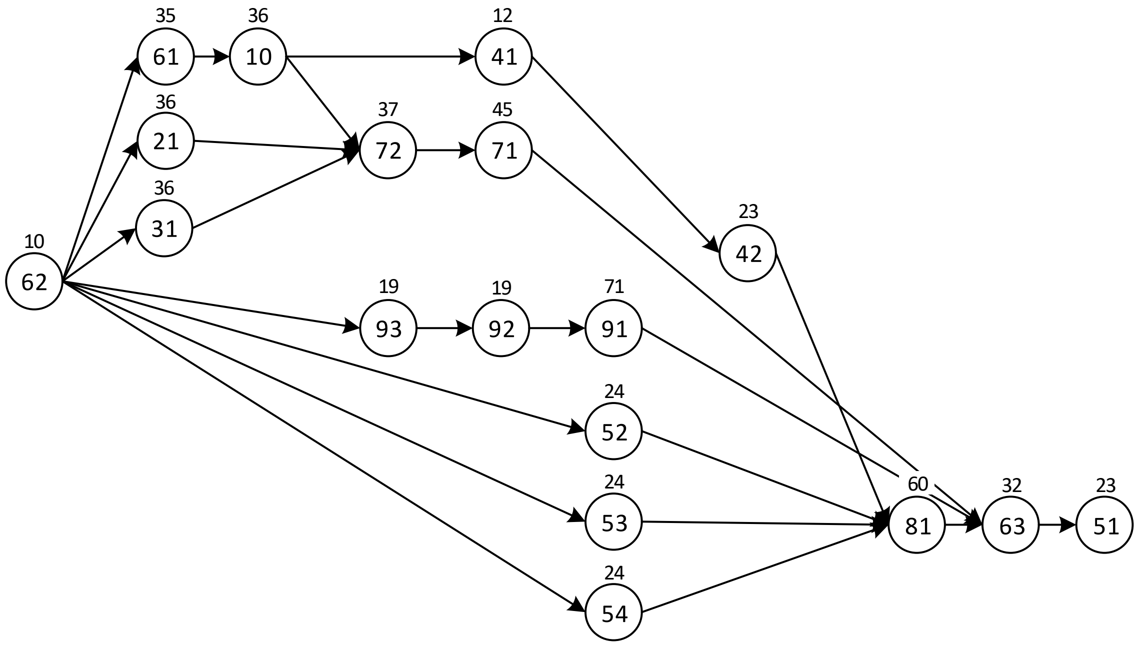

Figure 4-44 Task times in the precedence diagam

In addition to the tasks times, there are other times that have to be added to the assembly time. For a cell system, Initial set-up time, supply racks filling up time, walking time, testing time, packaging time and transfer to warehouse time are the times that can be added.

For an assembly line, initial set-up time, work piece line transfer time, testing time, packaging time and transfer to warehouse time are the time that needed to be added to the task times.

The assembly time calculations for the assembly cell case are as follows:

- Time other than assembly task time: *Initial set-up time + Fill supply racks + walking times + Testing time + packaging time + Transfer to warehouse*
- If $\text{Number of cells} = 1$
- and $Assembly\ time = 566\ \text{s}$
- and $\text{Other times} = 300 + 300 + (50\%\ 0\text{f}\ 566) + 600 + 120 + 60 = 2263$
- Then $\text{Total time} = 2263 + 566 = 2829\ \text{s}$
- and One 8 hour shift
- $8\ hours = 28800\ s$
- $\frac{28800}{2829} = 10\ \text{units per day per cell}$

According to the calculated assembly time and in the time frame of one shift, 10 units can be produced per day.

In the next step, the number of cells needed for the production of 1000 units per year and 100,000 units per day are calculated:

- If production demand of 4 per day
- $2829 \times 4 = 11316$
- So $1/2$ day shift of 1 assembly cell is enough
- If production demand of 400 per day
- $2829 \times 400 = 1131600$
- 1 cell max. production per day $= 10$ units
- For 400 units = min. cell requirement is 40 cells

In the next step, the assembly system capability for an unbalanced linked line assembly system is calculated:

- *line work content = 566 + 120 + 60 = 746* s
- *Number of stations = 5*
- *Tasks divided by similarity of tasks*
  - *Tasks related to core on station 1*
  - *Tasks related to heat exchanger and Recuperator on station 2*
  - *Tasks related to oil system on station 3*
  - *Tasks relate to electronic components on station 4*
  - *Tasks relate to packaging and testing on station 5*

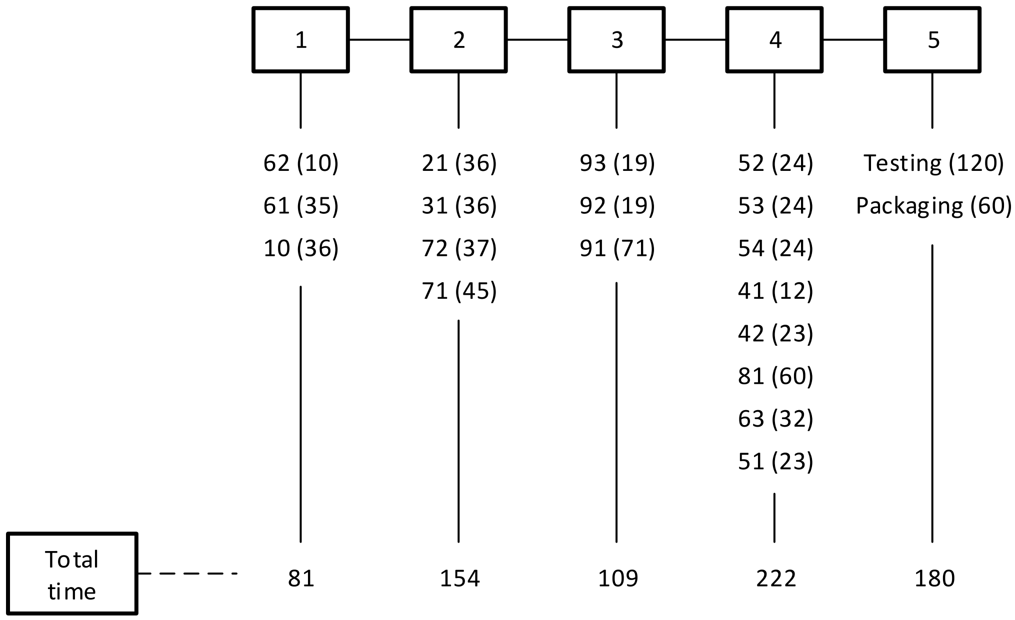

Figure 4-45 Task assignment to workstations

The calculation continues with the calculation of the number of assembly lines needed to meet 1000 units per year and 100,000 units per year production capacity.

- *Cycle time= 222* s
- Batch initial setup time + supply rack initial filling = *300 + 300 = 600* s
- If production of 4 per day = *600 + 1 x 746 + 3 x 222 = 2012s = 33* min
- If production of 400 per day = *600 + 1x 746 + 399 x 222 = 89924s = 1498.7 min = 25* hours
- In order to be able meet daily demand of one working shift $= \frac{25}{8} = 3.125$≈*4* parallel lines are needed.
- If two shifts, 2 parallel lines are needed

The next set of calculations are for a balanced assembly line.

- We assume 5 number of stations
- Use SALBP-2
- Objective minimise the sum of idle time.
- *Average time of sum of task time over 5 stations = 141.5* s
- *Difference to mean time: Station 1= -60.5*

  Station 2 = 12.5

  Station 3 = -32.5

  Station 4 = 80.5

  Station 5 = 38.5
- $If\ one\ line$:
- *Available production minutes per shift = 8x60=480*
- $Takt\ time\ (for\ 1000\ units) = \frac{Available\ production\ minutes}{Production\ units\ per\ day} = \frac{480}{4} = 120\ \text{min}$
- $Takt\ time\ (for\ 100{,}000\ units) = \frac{Available\ production\ minutes}{Production\ units\ per\ day} = \frac{480}{400} = 1.2\ \text{min}$
- $Minimum\ number\ of\ stations\ (for\ 1000\ units)$: $\frac{566}{120} = 4.72 \approx 5$
- $Minimum\ number\ of\ stations\ (for\ 100{,}000\ units)$: $\frac{566}{1.2} = 471.7 \approx 472$

For the production of 4 units per day 5 stations are enough. But for the production of 400 units, 100 lines with 5 stations are needed or the number of stations should be increased. If instead of 1 shift, we have 3 shifts per day, the number of required lines would be divided by 3 which would be [$\frac{100}{3} = 33.33$].

So, the calculations can be done from another perspective. Instead of calculating the required number of stations, the number of stations would be considered fixed and the assembly time required would be calculated.

For this method the cycle time is either average of task times or the highest station time if it is larger than the average time.

Table 4-31 Task times

Task	Time (s)
10	36
21	36
31	36
41	12
42	23
51	23
52	24
53	24
54	24
61	35
62	10
63	32
71	45
72	37
81	60
91	71
92	19
93	19
Sum	566
Average	141.5

Table 4-32 Station times and idle times of initial line configuration

Station 1		**Station 2**		**Station 3**		**Station 4**	
Task	Time (s)	Task	Time (s)	Task	Time (s)	Task	Time (s)
62	10	10	36	52	24	91	71
31	36	72	37	53	24	81	60
21	36	71	45	54	24	63	32
61	35	93	19	92	19	51	23
52	24			41	12		
				42	23		
Station time	141		137		126		186
Cycle	141.5		141.5		141.5		141.5
Idle time	0.5		4.5		15.5		-44.5

As there is a high idle time for station 4, either there is a need for a 5th station (other than packaging station) or the cycle time should be adjusted to the time of the maximum station time.

The first step is to adjust the cycle times. This is done by moving tasks between stations with considering task precedence.

Table 4-33 Station times and idle times of the adjusted line

Station 1		**Station 2**		**Station 3**		**Station 4**	
Task	Time (s)	Task	Time (s)	Task	Time (s)	Task	Time (s)
62	10	10	36	52	24	91	71
31	36	72	37	53	24	81	60
21	36	71	45	54	24	63	32
61	35	93	19	92	19	51	23
52	24			41	12		
				42	23		
Station time	141		137		126		186
Cycle time	186		186		186		186
Idle time	45		49		60		0

Another way is to instead of moving the tasks between the stations and to adjust the cycle time, to add another station to the line.

Table 4-34 Station time and idle time of the line with added station

Station 1		Station 2		Station 3		Station 4		Station 5	
Task	Time	Task	Time	Task	Time	Task	Time	Task	Time
62	10	10	36	52	24	91	71	63	32
31	36	72	37	53	24	81	60	51	23
21	36	71	45	54	24				
61	35	93	19	92	19				
52	24			41	12				
				42	23				
Station time	141		137		126		131		55
Cycle time	141.5		141.5		141.5		141.5		141.5
Idle time	0.5		4.5		15.5		10.5		86.5

The station time and idle time for the line with added 5th station are calculated as Table 4-34.

The third method to adjust the cycle time is to balance the line. A heuristic method is selected for balancing the line.

The process used for balancing is explained briefly as follows:

- Reassign tasks to stations with the aim to decrease idle time.
- In order to have min. idle time, negative idle time would be accepted
- So it can be seen that there is a bottleneck at station 2
- So, in order to eliminate negative cycle time and bottlenecks, so cycle time has to be adjusted to the highest station time

Table 4-35 Balanced line cycle times and idle times

Station 1		**Station 2**		**Station 3**		**Station 4**	
Task	Time	Task	Time	Task	Time	Task	Time
62	10	41	12	52	24	54	24
61	35	31	36	42	23	81	60
10	36	72	37	53	24	63	32
21	36	71	45	91	71	51	23
93	19	92	19				
Station time	136		149		142		139
Cycle time	141.5		141.5		141.5		141.5
Idle time	5.5		-7.5		-1		2.5
New Cycle time	149		149		149		149
Idle time	13		0		7		10

In order to be able to compare the performance and effectiveness of the lines, the line efficiencies could be compared.

$$Efficiency = \frac{total\ productive\ time\ on\ the\ assembly\ line\ per\ cycle}{total\ available\ time\ on\ the\ assembly\ line\ per\ cycle} \quad \textbf{(4-19)}$$

Line efficiency (line with adjusted cycle time):

$$Efficiency = \frac{590}{744} = 79.3\%$$

Line efficiency (line with added station):

$$Efficiency = \frac{590}{707.5} = 83.39\%$$

Line efficiency (Balanced line):

$$Efficiency = \frac{566}{596} = 94.96\%$$

By comparing the 3 different assembly lines, the line with the highest efficiency is the balanced line with heuristic method. The following is the calculation of line capability for 1000 units per year (4 units per day) and 100,000 units per year (400 units per day):

- *Cycle time= 149* s
- *Batch initial setup time + supply rack initial filling = 300 + 300 = 600* s
- *If production of 4 per day = 600 + 1 x 746 + 3 x 149 = 1793* s *= 22.43* min
- *If production of 400 per day = 600 + 1x 746 + 399 x 149 = 60797* s *= 1013.28* min *= 16.89* hours
    - *In order to be able meet daily demand of one working shift =* $\frac{16.89}{8} = 2.11$*≈3 parallel lines are needed.*
    - *If 3 work shifts, 1 line is needed*

Now the results for the cell assembly system, unbalanced assembly line and balanced assembly line are compared.

- Cell system
    - 4 units take 3.14 hours to be assembled
    - 400 units take 314.33 hours to be assembled
    - 1 cell capacity per shift can produce 10 units
    - For 400 units per shift 40 cells are needed
        - Or if 3 shift per day 14 cells are needed
- Unbalanced assembly line system
    - 4 units take 0.55 hours to be assembled
    - 400 units take 25 hours to be assembled
    - 1 line capacity per shift can produce 123 units
    - For 400 units per shift 4 lines are needed
        - Cannot meet demand with 1 line and 3 shifts

- Balanced assembly line system
  - 4 units take 0.37 hours to be assembled
  - 400 units take 19.93 hours to be assembled
  - 1 line capacity per shift can produce 184 units
  - For 400 per shift 3 lines are needed
    - Or if 3 shift per day 1 line is needed

4.4.5 Discussion

It has to be mentioned that at the development stage there isn't a final product ready, and some information about the possible future production plans are needed for preliminary decision making. A method to help to compare between different possibilities would be very useful at this stage.

Due to uncertainties at the development stage, performing an accurate time study is impossible. So an estimation method is used for determining task times.

By analysing the case study results it can be resulted that for low production volume, cell system is more appropriate, as it takes less space and less work force than assembly lines. But as the production volume increases, the assembly line systems seem more appropriate as it needs much less space and much less work force than cell system.

In general, assembly line has more flexibility in changes from 1000 production volume to 100000 per year.

By comparing unbalanced and balanced assembly lines, it can be seen that balanced lines have higher efficiency than unbalanced line.

In order to increase the accuracy of the analysis, number of workers and cost of production has to be added to the analysis. Also in terms of cost, the capital cost of each system, e.g. equipment cost, area size, etc. has to be considered in the comparison as well.

For future work, comparing different layouts of assembly lines such as straight lines and U-shape lines is suggested.

Using simulation software can further help with the analysis by visualising different options and the possibility of further adjustments to the assembly system in order to increase efficiency.

4.5 Factory cost estimation

In this section, the content related to the topic of 'Development of an estimating tool for factory set-up cost' is presented. The chapter starts with an introduction to the area of factory set-up cost estimation including a brief report of the literature review. The chapter continues with the method section which consists of explaining the method for developing the tool. In the result section, the result of tool development is presented and the results of the case study are presented next. The chapter ends up with the discussion section.

4.5.1 Introduction

The development of the tool started with reviewing the literature in related areas starting the wide area of factory set-up cost estimation and focus the search on more specific areas such as factory design and layout or factory facilities and space allocation until all areas related to the topic of the chapter were covered.

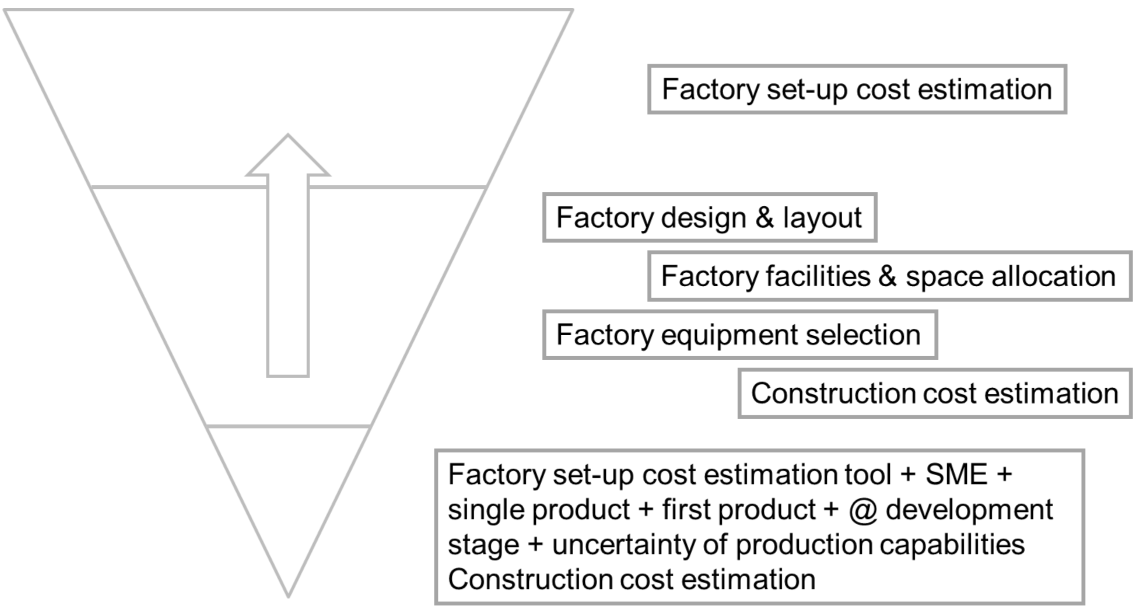

Figure 4-46 Areas covered in literature review for the area of factory cost estimation

There were two series of literature review done for this topic. The purpose for the first series was familiarising with this area and identifying the research gap and the purpose for the second series was identifying best practices and tool development. The first series of literature review results are presented in chapter 2.9.

Scopus was used as the primary main source of literature search and Google scholar was the secondary source of search. A list of keywords was used for the search and the number of related literature is shown in Table 4-36.

Table 4-36 Search results for ' Factory set-up cost estimation' literature search

Keyword	Number of search results	Number of useful papers
Factory cost estimation	170	0
Factory set-up cost estimation	4	0
Factory area estimation	130	0
Factory area calculation	132	0
Factory area size calculation	11	0
Factory area size estimation	13	0
Factory floor size	123	0
Production plant cost estimation	500	0

It can be seen that out of the total of 1083 search results, no paper was found that was related to 'Factory set-up cost estimation'. One of the reasons of not finding any methods in the literature could be that this area is industry specific and there are methods developed and being used in the industry, but these methods have not been reflected in academic papers.

The next step in the search was looking for any tool that was specifically developed for SMEs. Similar result to the above search was found and no tools or methods were found which were specifically developed for SMEs.

The same results were found for the search of specific methods for large companies.

The lack of a tool for estimating the costs of setting-up a factory is clearly seen in the academic literature, although there might be specific tools or methods that are being used in the industry. Majority of the research found is related to existing factories and the focus of many papers is on energy costs of a factory or running costs of a production plant. The focus of the papers has been mainly on specific cost elements and not overall general high level methods.

A tool that would give a cost estimation of a factory at the development stage of the product development was not found during the literature review. The cost estimate at that stage is mainly needed for preliminary decision making or planning.

4.5.2 Method development

One of the concerns of SMEs at the product development stage is funding the project for other life cycle stages. The Pre-production stage which includes product certification and preparing for the production stage, requires large amount of funding. Funding needs to be secured for acquiring a plant for production and obtaining all the required machinery and equipment. In order to be able to plan for that stage and absorb funding, estimation of the factory set-up costs including the plant rental or purchase cost and equipment costs need to be obtained.

The developed tool includes a systematic cost estimation process; it is spread-sheet based and consists of several sections. The development started by gathering requirements from the studied company and by studying general requirements of manufacturing companies at SME level. These were done by having 4 hours of interviews with the manager of the company and literature review.

In the next step the important cost elements affecting the cost of establishment of a factory were researched and identified from the literature. Figure 4-47 presents these cost elements.

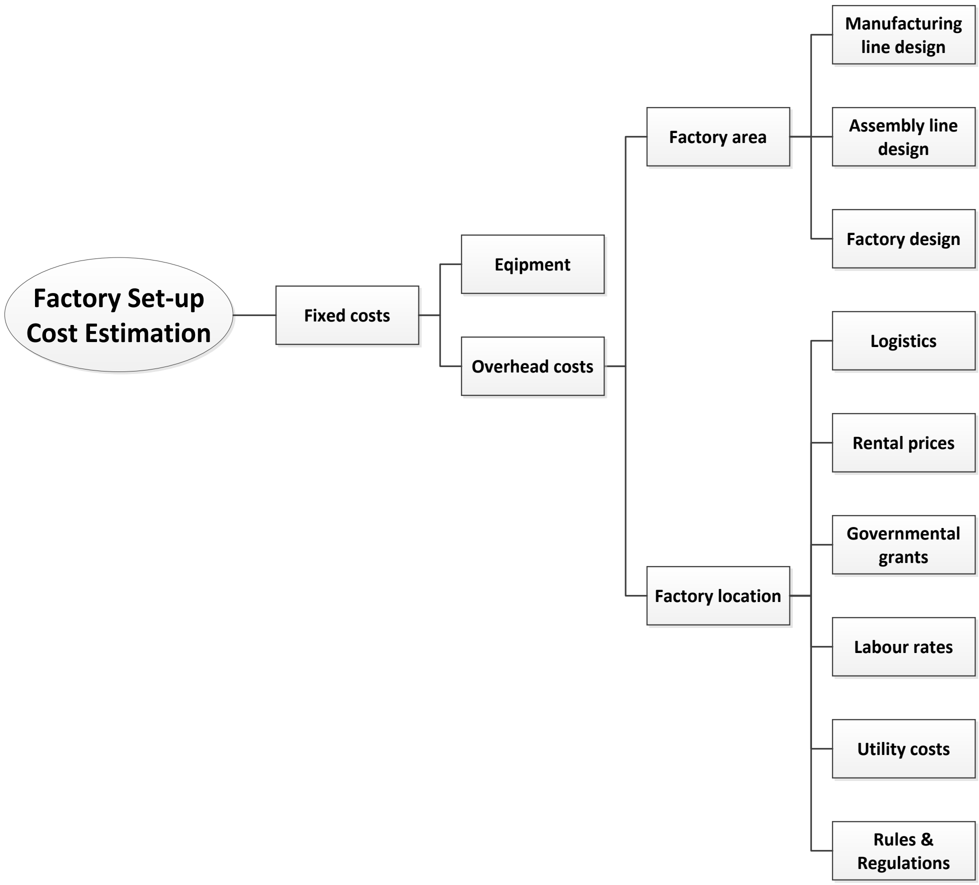

Figure 4-47 Factory set-up cost estimation elements

By literature review, the tools and methods developed in the literature were evaluated and used to develop the tool. The result of the literature review is presented in chapter 2.9 and section 4.5.2.

The initial requirements and company plans are as following. These data were recorded on 25th of October 2011. It should be mentioned that the presented data have been changed since then.

The planned production strategy is Just-in time strategy and the components would come from different suppliers and agreements with suppliers would be made to have supplies within 24 hours.

They have planned to have an assembly only plant and the pilot launch was planned for March 2013 and would have up to 1000 units produced for the first year. For the second year the production would increase to 2000 units and by the 5th year it would be 100000 units. The company requirement was to have an assembly plant with lowest capital requirement. The plant should be designed for 1000 units' production but have the flexibility to be increased to 100000 units per year.

The company requirement was to have no more than 10 people for production activities which most of them would be the current employees of the company. It was planned to rent the plant and the company might have the option of having a disassembly line for services and disposal or recycling.

In a next meeting held in December 2011 with the managing director of the company another requirement was mentioned which was about the plant location. The preferred location would be a location in Bedfordshire, but other options in wales or Eastern Europe should be considered as well. It was mentioned that simplicity and low cost are key requirements for the plant design.

By collecting the data from the company, an overall view of the plans and requirements of the company was made. The development was continued by collecting data about main cost drivers of factory set-up cost and possible available tools or methods for estimating the factory set-up cost.

For the factory location selection, decision making factors and methods were collected through literature review.

The preliminary tool was presented to an expert from Cranfield University for verification and also was discussed with supervisors and the final version of the tool was presented to the managing director and the technical manager of the collaborating company for the purpose of validation.

The tool was used to estimate the set-up cost of the future production plant of the collaborating company and the results were used for negotiations with investors and also production planning of the company.

4.5.3 Results

Factory rental cost is one of the biggest contributors of the overhead costs. In order to find out about the rental cost, two important factors should be obtained. Factory area size and factory location are two important factors which highly affect the plant rental costs. Land prices defer from one place to another. Rental cost is a function of area size. Knowing the minimum area required can help forecasting rental or buying prices of a plant (Pratt, 2011).

The capital cost of a plant is the investment required to design, purchase, build, install and start up its equipment, ancillary facilities and infrastructure (Petley and Edwards, 1995).

Meyers and Stephens (2005) have mentioned 15 steps for developing total space requirements. These steps include determining what will be produced, production volume, make or buy decision, process planning, assembly line balancing and determining Takt time. They have mentioned that for factory area size estimation a total space requirements worksheet should be prepared for each department. The departments required in a production plant according to Meyers and Stephens (2005) are the manufacturing space, production service space, employee services space, office space and outside area space. Other spaces needed to be considered are under the floor (Basement) area, overhead or clear space areas (8 feet above the floor to the ceiling), truss level and the roof.

Hiregoudar and Reddy (2007) have listed the areas and facilities needed in production plant. Figure 4-48 shows these areas and facilities.

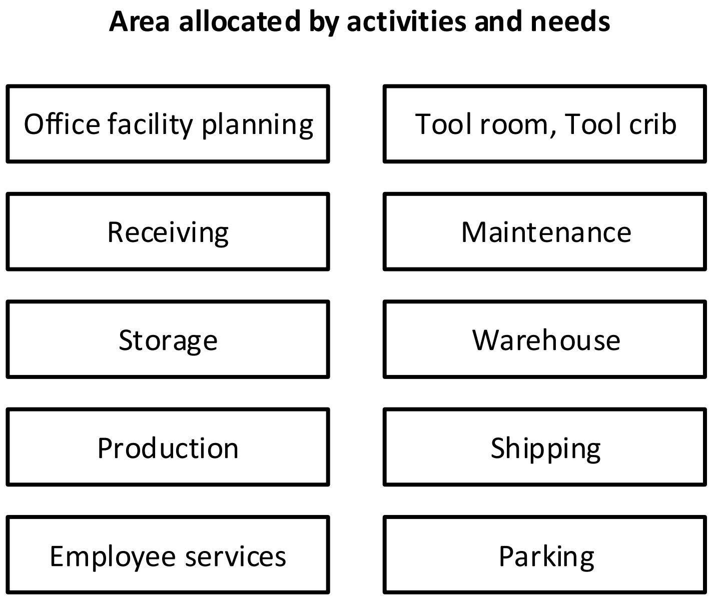

Figure 4-48 Areas and facilities of a production plant (Hiregoudar and Reddy, 2007)

Also Schenk et al. (2010) in the book "Factory planning manual" have listed the main elements of a factory or production facilities:

- Personnel/workforce:
    - number, gender
    - qualifications, skills
- Machinery and equipment:
    - manufacturing and assembly equipment:
      machinery/workstation including fixtures/auxiliary equipment and tools
    - logistics facilities: transport, handling, storage and order picking facilities including auxiliary warehouse and transport equipment
    - quality assurance equipment: measuring and testing equipment, jigs and fixtures/ auxiliary equipment
    - control, information and communication systems
    - safety, emissions and interference suppression systems
    - supply and disposal systems for utilities, power; raw materials and auxiliary materials; waste and residual materials
- Technical systems (in conjunction with their structures):

- structural equipment: supporting structures, foundations, pillars, beams, roof structure
- envelope: facades, roofs including windows, doors, gates
- interior: flooring, ceilings, dividing walls, openings
- building systems: heating, ventilation, air conditioning, sanitary facilities
- supply and disposal systems for utilities: power, gas, water (drinking and industrial water), electricity, raw materials, auxiliary, waste and residual materials

- Operating materials:
    - liquid materials (fluids, media): water, oils and greases, coolants, acids and bases, solvents, cleaners, polishing materials and abrasives, fuels, paints, biological materials
    - gaseous materials: technical gases, technical fuel gases, gas mixtures, steam
    - solid materials: fuel, paper and cardboard, glass, administrative equipment

According to the data collected, a process has been developed for the factory set-up cost estimation. The process includes steps and decisions to be taken to obtain estimation for the factory set-up cost. The process is shown in Figure 4-49.

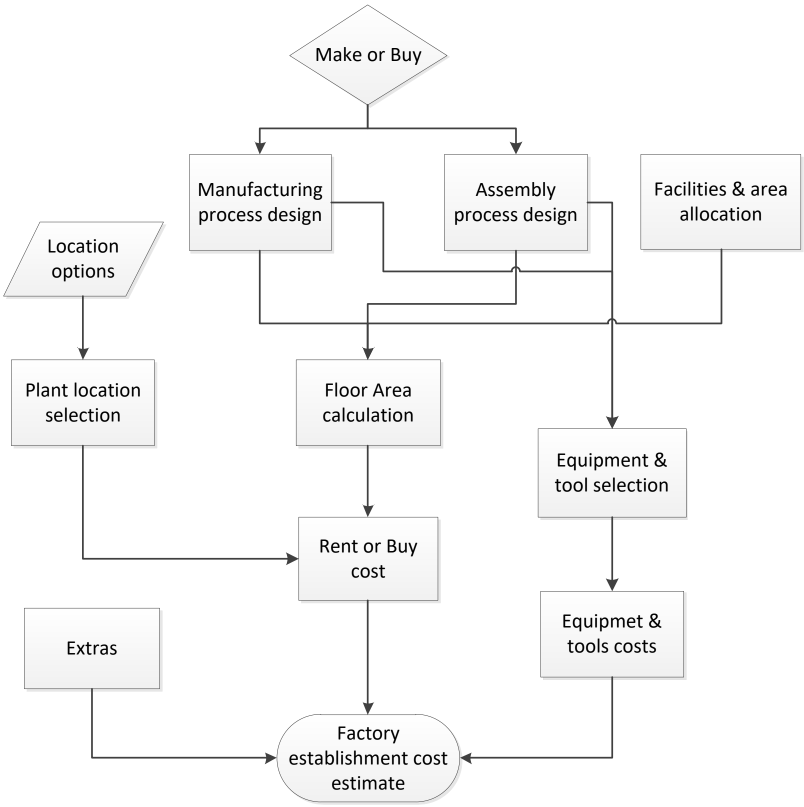

Figure 4-49 Factory set-up cost estimation process

4.5.4 Case study

The developed process has been implemented in the collaborating company. The result of the case study was used for future production planning and also negotiations with suppliers.

The following are the requirements of the collaborating company:

- There would be an Increase of production from 1000 units for the first year to 100000 units in 5 years.
- The production plant would consist of an assembly line with the lowest capital requirement
- Agreements would be made with suppliers to have the parts ready in 24 hours
- Complex manufacturing processes such as moulding and casting are not considered for in-house manufacturing process

The assumptions used for the case study are as follows:

- The estimate is done for the factory setup costs without any activity being started in the plant
- Purchase costs of equipment are not considered.
- Cost of equipment set-up and any modification to the building would be considered as a percentage of other costs.
- The estimation is based on data collected on September, 2014
- The gender of the employee is assumed to be 10 male and 6 female workers

The facilities needed in the factory are identified as following:

- Offices
- Kitchen
- Production area
- Quality check area
- Warehouse
- Storage
- Parking and loading area
- Test cells (For development purposes)
- Toilets, showers and changing rooms

4.5.4.1 Offices

Numbers and roles of office workers are shown in Table 4-37.

Table 4-37 Employee roles and number list

Role	Number of employee
Managers	3
Engineers	4
Business & marketing	2
Others	2
Total	11

The area minimum office area size is calculated as following.

According to Health and Safety Executive (2011b), the minimum working area for each person should be at least 11 m^3 (All or part of a room over 3.0 m high should be counted as 3.0 m high)

If ceiling height be 2.6m $\frac{11}{2.6} = 4.23\ \mathrm{m}^2$

Total area size: $11 \times 4.23 = 46.53\ \mathrm{m}^2$

4.5.4.2 Kitchen

Factory kitchen area is a place for the employee to reheat food, make hot drinks and to have their food.

The kitchen area allocation is as follows:

- 1x microwave
- 1x washing basin,
- 2x sets of cupboard,
- 1x under counter fridge
- 2x sets of 4 person tables

Typical cupboard size is 670 mm depth and the width for a sink cabinet is typically 80 mm and for normal cabinets is 60 mm. (Typical sizes from ikea.com)

$$Cabinet\ area\ occupation = (0.80 \times 0.67 + 2 \times 0.60 \times 0.67) = 1.34\ \mathrm{m}^2$$

Dining tables area = each size

$135 \times 85\ \mathrm{cm} + Margin\ around\ table\ for\ sitting\ (200\% \times table\ area)$

$$A = 2 \times (1.35 \times 0.85) = 2.295\ \mathrm{m}^2$$

$$Table\ \&\ sitting\ Area: A + 2 \times A = 6.885\ \mathrm{m}^2$$

$$Walking\ area\ around\ tables = 50\%\ of\ Table\ and\ sitting\ area$$

$$B = (2.295 + 6.885)$$

$$Total\ area\ size: B + 0.5 \times B = 13.77\ \mathrm{m}^2$$

4.5.4.3 Toilets and changing areas

According to Health and Safety Executive (2011a) there are minimum number of toilets and washbasins according to minimum number of workers at any one time at the workplace. The minimum number of toilets and washbasins is shown in Table 4-38 and Table 4-39.

Table 4-38 Number of toilets and washbasins for mixed use (or women only) (Health and Safety Executive, 2011a)

Number of people at work	Number of toilets	Number of washbasins
1-5	1	1
6-25	2	2
26-50	3	3
51-75	4	4
76-100	5	5

Table 4-39 Toilets used by men only (Health and Safety Executive, 2011a)

Number of men at work	Number of toilets	Number of urinals
1-15	1	1
16-30	2	1
31-45	2	2
46-60	3	2
61-75	3	3
76-90	4	3
91-100	4	4

Minimum toilet size is $30\ \mathrm{inch}\ \times 60\ \mathrm{inch} = 1800\ \mathrm{inch}^2 = 1.161\ \mathrm{m}^2$ (International code council, 2012)

Minimum of one emergency shower is needed.

Also According to International code council (2012) there shall be at least 533 mm clearance in front of a lavatory to any wall, fixture or door.

It is assumed that the size of each wash basin is 500 mm X 350 mm and the minimum area for shower according to International code council (2012) is $90\ \mathrm{inch}^2 = 0.581\ \mathrm{m}^2$.

According to above reference, men and women should have separate facilities unless each facility is in a separate room with a lockable door and is for use by only one person at a time.

The areas considered for restroom (Toilet, shower and changing room together) areas are as following:

- 2 restroom areas (1 male area and 1 female area)
- For male's restroom: 2 toilets, 1 shower, 2 wash basins and 1 changing room.
- For lady's restroom, 1 toilet, 1 shower, 1 wash basin and 1 changing room
- Toilet area = 1.161 m^2
- Shower area = 0.58 m^2

- Wash sink area = $0.50 \times 0.60 = 0.3\ \mathrm{m}^2$
- 100% of the sum of the above areas would be considered for walking area
- And 100% of the sum of the above areas would be considered for changing room

Male's room:

$$C = 2 \times 1.61 + 0.58 + 2 \times 0.3 = 4.4\ \mathrm{m}^2$$

$$Area: C + 1 \times C + 1 \times C = 13.2\ \mathrm{m}^2$$

Female's room:

$$D = 1 \times 1.61 + 0.58 + 1 \times 0.3 = 2.49\ \mathrm{m}^2$$

$$Area: D + 1 \times D + 1 \times D = 7.47\ \mathrm{m}^2$$

4.5.4.4 Parking and loading area

The parking standards are being determined by local councils and there might be differences in the standards for different locations. As a reference the current location of the company, Milton Keynes, would be considered for parking standards. According to Milton Keynes Council (2015) the minimum parking space sizes should be as Table 4-40.

Table 4-40 Recommended parking bay dimensions (Milton Keynes Council, 2015)

	Bay dimension	
	Length (m)	Width (m)
Car	5.0	2.5
Transit/Van	7.5	3.5
Rigid	12.0	3.5
Articulated	17.0	3.5
Coach	15.0	4.0
Minibus	8.0	4.0

And the recommended two-way drive way for a car park is 6 m.

If number of parking bays for the factory is considered to be 10 and have 1 loading bay which could accommodate an articulated lorry, the total area size would be calculated as following A minimalistic design has been drawn for the parking and loading area which can be seen in Figure 4-50, but as the plant would not be designed and built from scratch, for any plant selection the minimum number of bays should be considered regardless of the design.

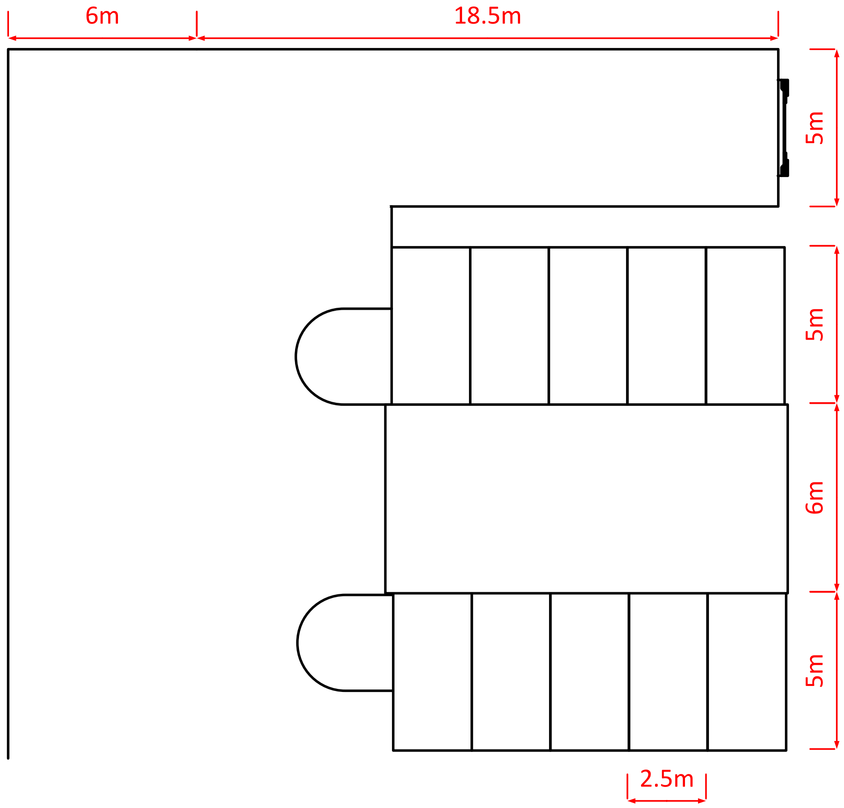

Figure 4-50 An example of a parking and loading area with minium bay sizes

- Number of car parks: 10
- Number of loading bays: 1

$$Each\ car\ bay\ area: 5 \times 2.5 = 12.5\ \mathrm{m}^2$$

$$Each\ loading\ bay\ area: 18.5 \times 5 = 92.5\ \mathrm{m}^2$$

$$Driving\ aisle\ area: 6 \times 12 = 72\ \mathrm{m}^2$$

$$Total\ parking\ area: 10 \times 12.5 + 1 \times 92.5 + 72 = 289.5\ \mathrm{m}^2$$

4.5.4.5 Storage and warehouse

For the storage it is assumed that an area for 3 rows and 4 columns of pallets is required.

The area of each pallet is:

$$Individual\ Pallet\ area = Width \times Depth \quad \textbf{(4-20)}$$

$$0.80 \times 1.20 = 0.96\ \mathrm{m}^2$$

Total area for all pallets:

$$Total\ pallet\ area = Number\ of\ pallets \times Individual\ pallet\ area \quad \textbf{(4-21)}$$

$$12 \times 0.96 = 11.52\ \mathrm{m}^2$$

The minimum aisle width for standard forklifts is $11\ \mathrm{feet} \approx 3.36\ \mathrm{m}$ (Piasecki, 2013).

A sample design for the warehouse is made according to the minimum required size which is shown in Figure 4-51. In reality when looking for a plant to buy or rent, the minimum area size of the warehouse area should be considered in the decision.

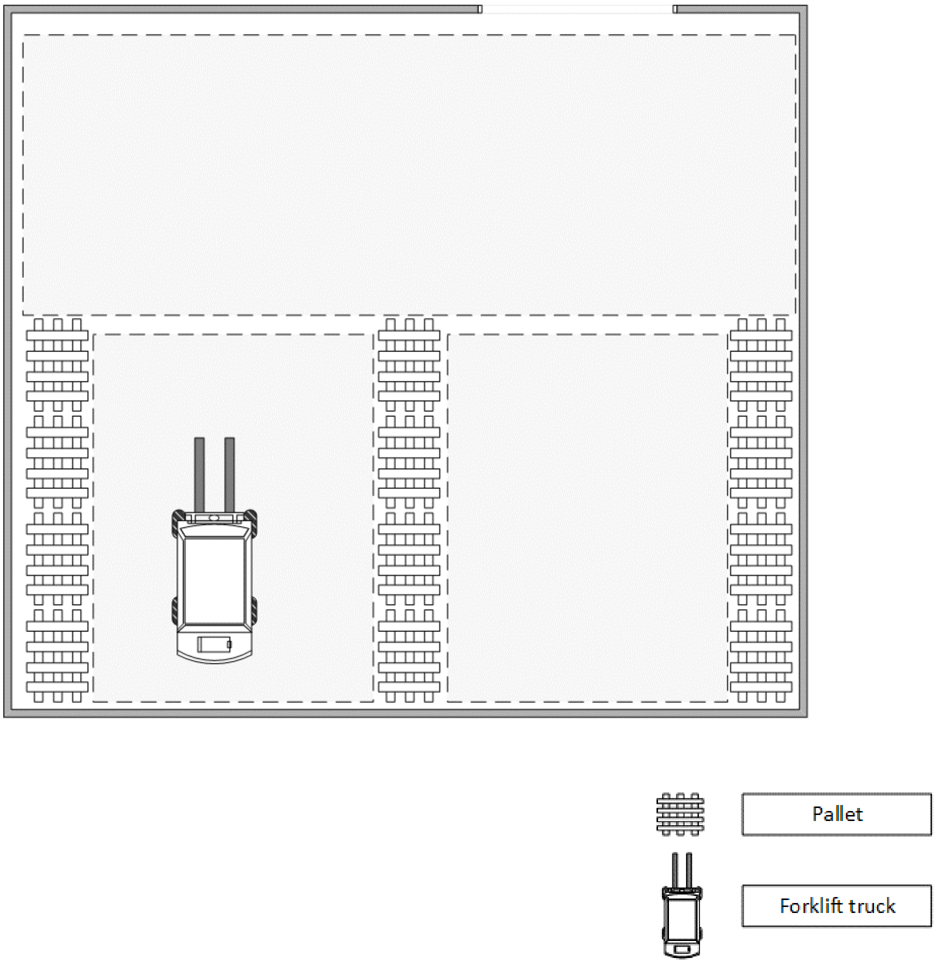

Figure 4-51 A sample design of the warehouse area

$$Aisles\ area = Pallet\ width \times Number\ of\ pallet\ per\ aisle\ length \times Aisle\ width \times (Number\ of\ pallet\ rows - 1) \tag{4-22}$$

$$0.80 \times 4 \times 3.36 \times (3 - 1) = 21.504\ \mathrm{m}^2$$

$$Head\ way\ area = (Number\ of\ pallet\ rows \times Pallet\ depth + Number\ of\ aisle \times Aisle\ width) \times Head\ way\ width \tag{4-23}$$

$$(3 \times 0.80 + 2 \times 3.36) \times 3.36 = 30.65\ \mathrm{m}^2$$

$$Total\ area = Pallets\ area + aisles\ areas + head\ way\ area \tag{4-24}$$

$$11.52 + 21.504 + 30.65 = 63.68\ \mathrm{m}^2$$

4.5.4.6 Assembly line

By using the results from Assembly line design in Chapter 4.4, the minimum assembly area size is calculated.

The assembly line would be consisted of 5 stations. The 5th station would be the testing and packaging station. In order to have the minimum area size, a U-shape assembly line would be selected. The design of this area is shown in Figure 4-52.

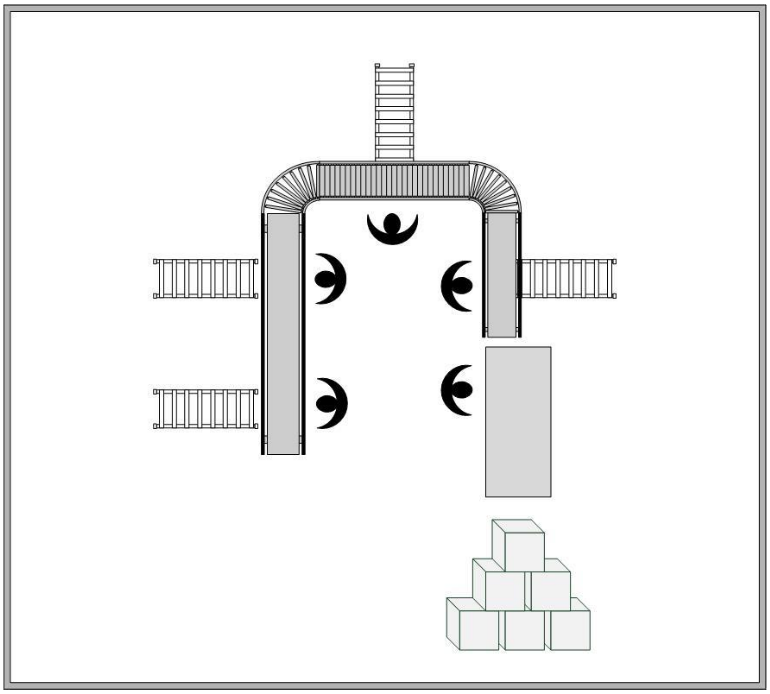

Figure 4-52 Assembly area layout based on U-shape layout

The last station would be considered a double station in terms of size as the testing and packaging area requires more space than assembling stations. 100% of the total assembly line would be added for extra walkway area around the line.

The assembly line area calculation is presented in Table 4-41.

Table 4-41 Assembly line area size

Number of workstations	6
Number of operators	6
Each Persons area	3.67 m^2
Each workstation area	2.00 m^2
Number of shelves	5
Shelf area	1 m^2
Doorway area (2 doors)	0.78 m^2
Assembly line area	39.78
Number of assembly areas	2
Percentage added for walk way	100%
Total assembly line area	159.14 m^2

The detail of calculation is as follows:

$$\begin{aligned} Assembly\ area\ size &= Number\ of\ assembly\ lines \\ &\times (Number\ of\ workstations \\ &\times Individual\ workstation\ area + Number\ of\ operators \\ &\times Individual\ operators\ area + Number\ of\ shelves \\ &\times Each\ shelf\ area + Doorway\ area) \times 2 \end{aligned} \quad \textbf{(4-25)}$$

$$2 \times (6 \times 2 + 6 \times 3.67 + 5 \times 1 + 0.78) \times 2 = 159.14\ \mathrm{m}^2$$

4.5.4.7 Production area

By considering the current needs of the company, a production area is considered for the factory for any modifications, repair works and prototyping for the research and development activities. The company has built up the facilities for this purpose and the capabilities would remain the same for the next few years.

The list of the manufacturing equipment is show in Table 4-42.

Table 4-42 Manufacturing equipment list

Equipment
CNC milling machine
Air compressor
Lathe
Press drill
MIG welder
TIG welder
Milling machine
Grinding machine
Sheet metal cutter & roller
Desk
Workbench
Mobile tool box
Trolley

The total area size needed for all the equipment is shown in Table 4-43. The measurement is done with two different measurement methods. In the first method, the sample equipment shapes available in the Microsoft Visio software were used to obtain the total area. The equipment were arranged in the software to obtain the plan of the workshop and to achieve the area size. The workshop plan diagram is shown in Figure 4-53.

Table 4-43 Manufacturing area size

Total area (m^2)	**Measurement method**
11 x 7.6	Microsoft Visio
	Sample measurement

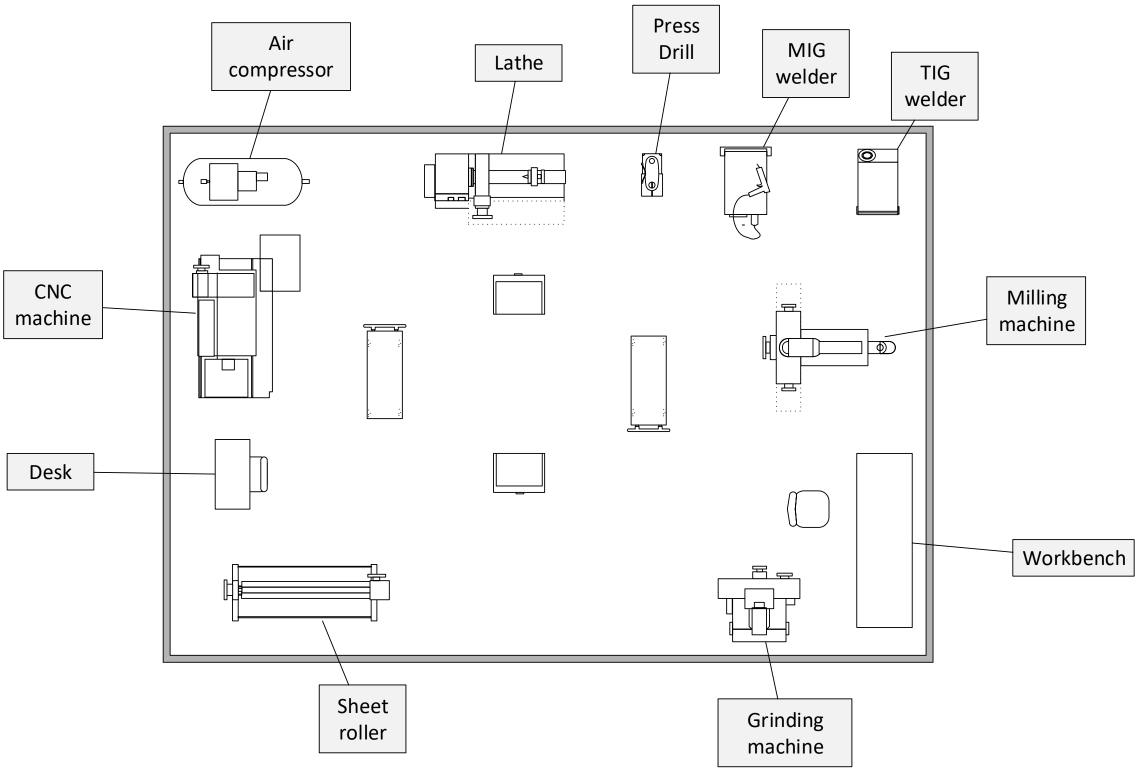

Figure 4-53 Proposed production area layout and possible equipment and machinery

For the sample measurement, the current equipment and machinery available in the workshop were used as sample references for the sizes and for the equipment which were not available, sample equipment were looked for on the internet. The list of individual equipment area is shown in Table 4-44.

Table 4-44 Individual Equipment areas

Equipment	Area (m^2)
CNC machine	16
Air compressor	13
Lathe	15
Press drill	2
MIG welder	2
TIG welder	2
Milling machine	12
Grinding machine	9
Sheet metal cutter & roller	6
Desk	3
Workbench	3.5
Mobile tool box	4×0.5
Trolley	4×0.5

4.5.4.8 Tell cell area

The test cell consists of the test cell room, control desk and demo heating system. The test cell is an enclosed air-conditioned and ventilated space with power, water and gas supply into the cell. The cell should have windows with impact resistant glasses for visual sight of the system from outside the cell during tests. For testing the product of the collaborating company, temperature control system and ventilation is needed. The size of the test cell should be large enough to accommodate two test products and have enough space for assembling and disassembling parts onto the under test systems. A space for electronic and control systems desk or racks is required.

The control desk would be located outside the test cell, behind the windows so that the engineers would have a view of inside the test cell. The control desk would have all the necessary equipment for controlling and monitoring the tests. Computers, data acquisition systems and control units would be some equipment which would be located on the test cell.

The demo heating system is a replica of a house heating system, including a hot water cylinder, water pump and few radiators. The purpose of the heating system is to demonstrate the heating performance of the systems in under test.

Figure 4-54 Picture of the current test cell of the collaborating company. (Image courtesy of Samad Power Ltd.)

The current test cell size is 4500mm × 4500mm. The space required for the control area is 3000mm × 3000mm. The heating demo system requires a minimum area size of 7500mm × 1500mm which is recommended to be along a wall for the purpose of mounting radiators. The current plan of the testing area is shown in Figure 4-55. By using the current layout, the total area size for the test cell would be 7500mm × 7500mm.

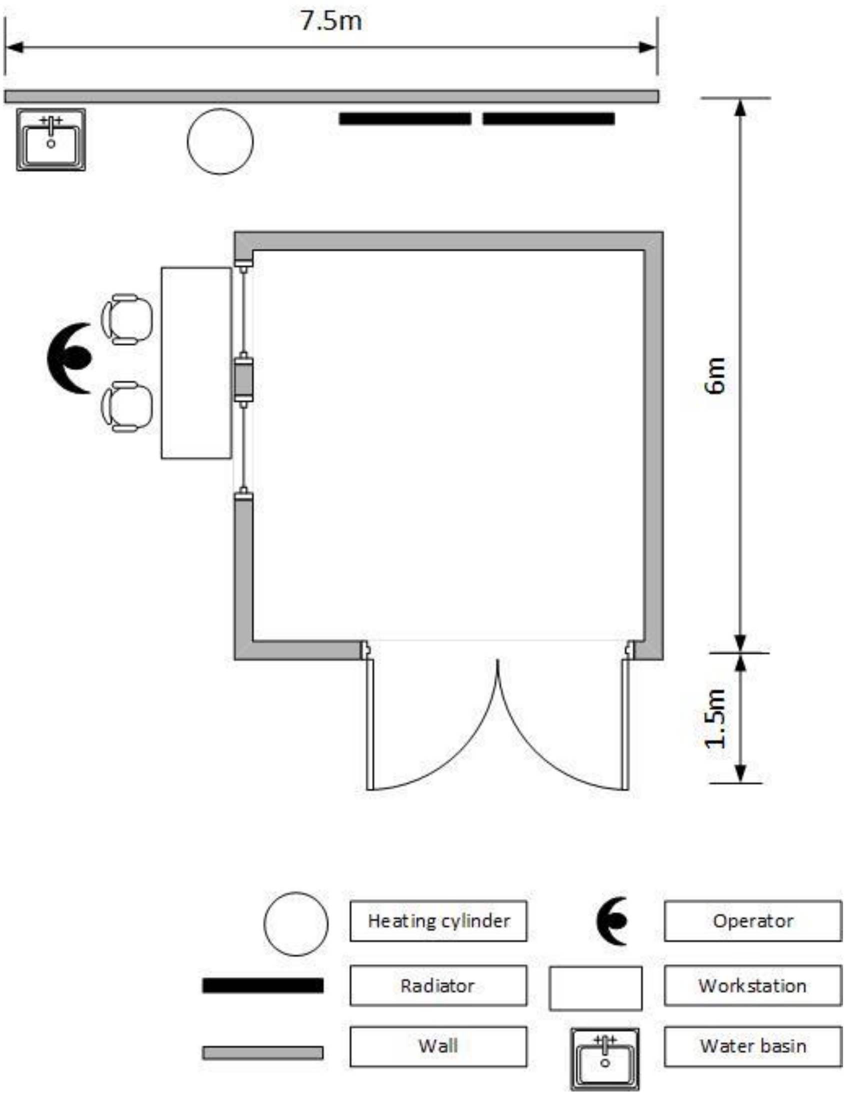

Figure 4-55 Testing area current plan

4.5.4.9 Total area

The total area required for the production can be obtained by the sum of the entire individual area sizes; although when looking for a plant, each area size has to be looked for separately and each area size requirement should be met separately.

The total area calculation is shown in Table 4-45.

Table 4-45 Total area calculation

Area	**Area size (m^2)**
Offices	46.53
Kitchen	13.77
Assembly area	159.14
Production area	105
Quality check area	25
Storage & warehouse	63.68
Parking & loading area	289.5
Test cells	56.25
Toilets, showers & changing areas	20.67
Total	669.453

4.5.5 Discussion

The factory set-up cost estimation tool is developed to help SMEs in primary decision making in early product development stage, this would help them to have an approximate view of the production stage and production capabilities. Knowing the required plant size would help the managers in making decisions in terms of location of the production plant as well as gives them guidance in terms of the capital needed for acquiring or renting a production plant.

As there is no plan to design and build a factory from scratch, it would be difficult to find a building with exactly same facilities and areas. So there should be a degree of flexibility in the area size and layouts and the areas need to be prioritised. For this study case, the production, office and warehouse are the key areas. A decision making method could be proposed for prioritising the areas. Also alternative layouts for areas need to be considered to facilitate the decision making process.

As mentioned earlier, the focus should be on individual area sizes rather than total area size of the factory. For example, when searching for a plant, it should be assessed that if the parking area would meet the minimum area size requirement rather than just considering the total factory area size.

In estimating the assembly area, it is important to consider how the workstations are spread on the floor. If a U-shape layout is chosen a squarer area is needed and if a straight line is selected more rectangular area is needed. So in addition to the area size, the shape of the area is important as well. A room with 400 m^2 area can be a '20m×20m' room or can be '10m×40m' or many other configurations. A proposed line might fit into one configuration, but might not fit into another, both with the same area size.

5 VALIDATION AND VERIFICATION

5.1 Introduction

This chapter performs a detailed industrial verification and validation of the framework and methods developed in Chapter 4. The chapter is organised in the following structure. In Section 5.2, a background of the theory behind validation and verification is presented. In Section 5.3, the research methodology is presented for verification and validation of the framework. In Section 5.4.1 a detailed verification is carried out on the framework models by carrying out an empirical study in the collaborating company, utilising the cost reduction framework in the small company based on real world data. In Section 5.4.2 a validation process is performed on the framework models by presenting the framework model to experts. Section 5.5 concludes the chapter with the chapter summary and key observations.

5.2 Background

Research can be done using 3 types of methods: a qualitative perspective (Denzin & Lincoln, 2005), a quantitative perspective (Shadish, Cook, & Campbell, 2002), or a mixed methods combination of the two perspectives (Tashakkori & Teddlie, 1998).” (Dellinger and Leech, 2007)

For this study a mixed method is used. Due to the nature of the study which is multi-disciplinary, qualitative and quantitative methods have been employed. For the purpose of validation, appropriate validation methods relative to the research method should be used.

In order for any research results to be valid, they should have validity in different levels. Internal and external validity are the top levels of validity. Internal validity is divided into statistical validity and construct validity which construct validity is divided into three main areas of face validity, method validity and procedure validity.

The criteria for validation in qualitative and quantitative research are different. Dellinger and Leech (2007) have reviewed validation theories and proposed a validation framework for mixed method research. Figure 5-1 shows elements of construct validation in quantitative and qualitative research as well as in mixed method research.

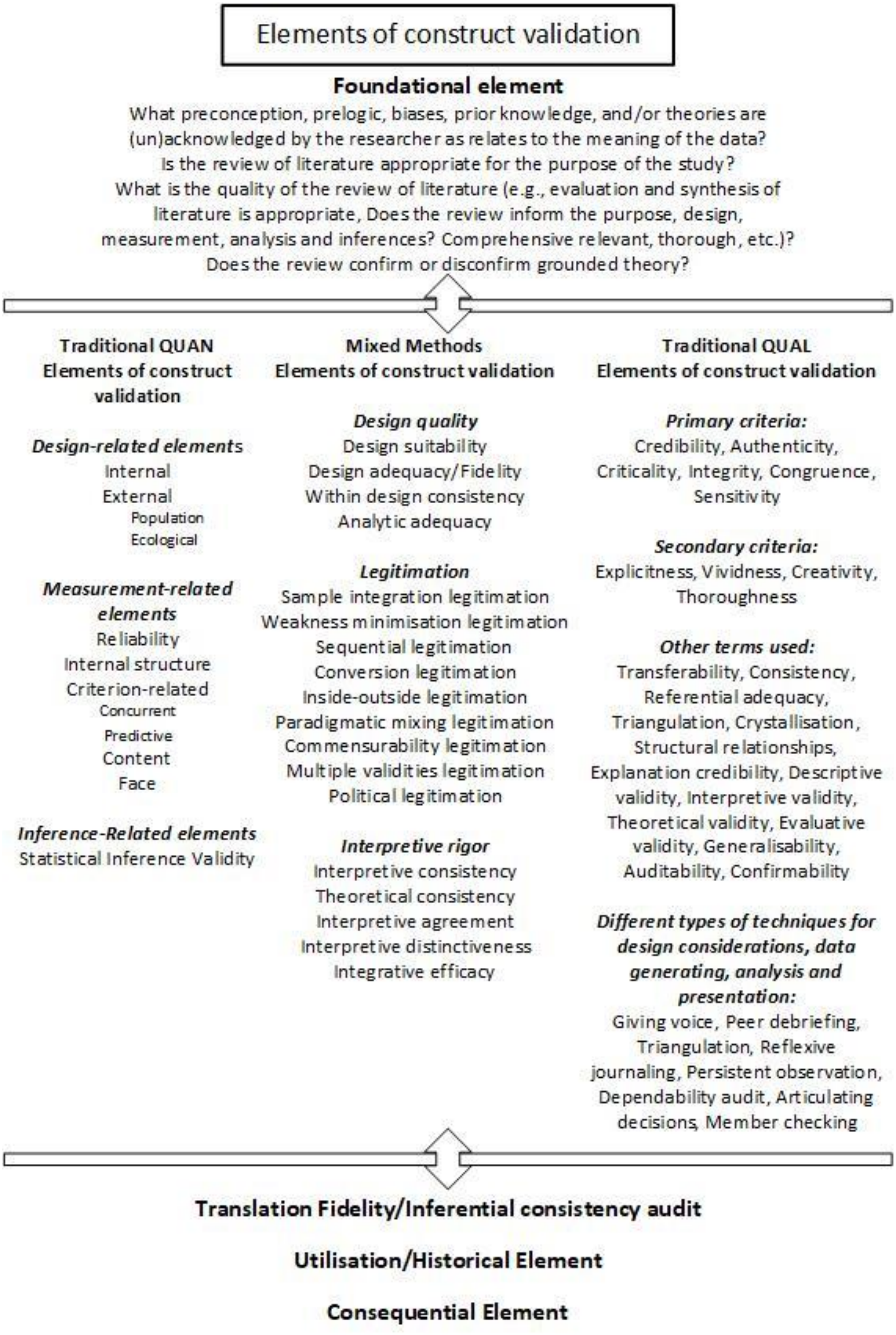

Figure 5-1 Elements of construct validation (Dellinger and Leech, 2007)

A strategy to make sure the collected data are valid is Respondent validation. In order to make sure that the collected data are valid the data where checked and the results of any case study where presented to relevant company staff. So a systematic feedback approach was taken for making sure the collected data where valid.

5.3 Method

For the validation and verification, methods have been employed to verify and validate the developed method and the results. In this research both validation and verification of the research have been considered. Validation has been done to check if the 'right system' has been developed and verification has been done to ensure that the system is 'built right' (Roy, 2001). The verification and validation steps done in this research are illustrated in Figure 5-2. The detailed verification involved verifying the framework using actual case study data from the studied SME by the empirical study.

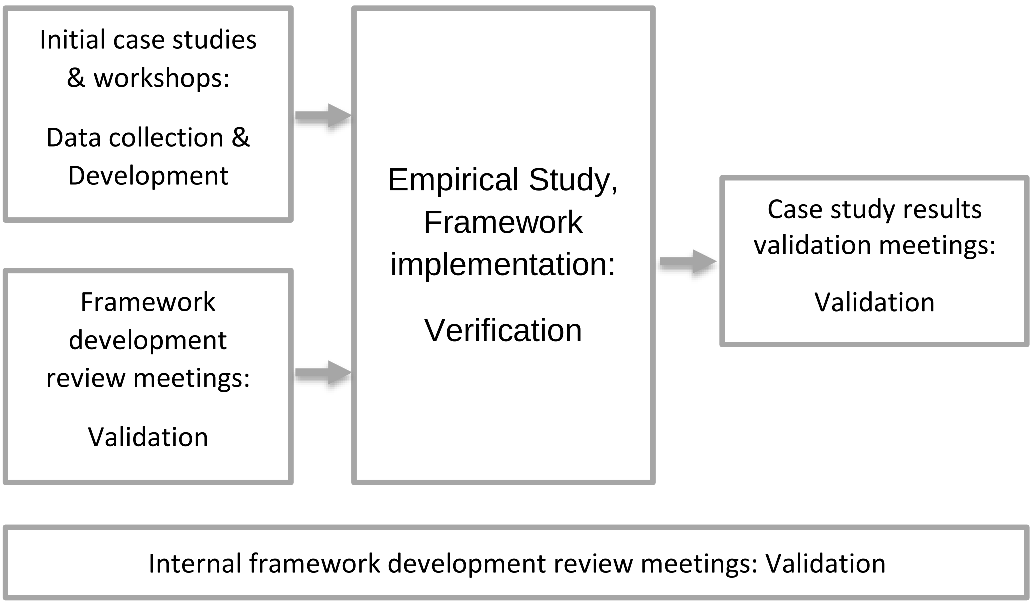

Figure 5-2 - Verification and validation steps

Every method of the framework has been verified separately as well as the framework in general. The verification has been done in the form of implementation of the developed method in a real case. It has been done by performing case studies in the collaborating company. It involved the complete implementation of the framework in the SME for the reason of verification of the framework against formal specifications, although the results obtained from the case study will be included in the final tool. As the project has two aspects of academic and industrial, in validation planning satisfying the criteria of both aspects should be considered.

The validation involved interviews with experts within the collaborating company, within the university and outside experts. In addition to interviews, other methods were employed to ensure the validity of data. Utilising various data collection methods was a method to ensure the validity of collected data. Also, due to the nature of the data, various data sources had to be used for data collection. Triangulation or using various data sources, especially non-human sources, helps to reduce systematic bias. For the interviews a semi-structured strategy was followed. The interviews started with an introduction to the project though a short presentation about the research topic and the work done and planned for the research and the results. Then they followed by few structured questions and continued with unstructured discussions in continue of the structured questions. The questions were focus on the intention of obtaining feedback about the project topic, results and methodology and also obtain data and information for the methods development.

Since the start of the project, case studies were done in parallel to the framework development. The purposes of the case studies were to firstly implement academic best practices in the collaborating company to help them in cost reduction early in product development cycle. As the collaborating company had a project plan and had to meet deadlines and more importantly had design freeze points, in order to help them to achieve the required cost reduction, case studies were done during the length of the PhD project, since the start of the project.

For the case studies, as explained in Section 3.4, the researcher was present in the company and participated in some of the company tasks, while he had direct access to many design data regarding the studied product. The direct access to data eliminates the need for some time consuming data collection activities such as surveys and interviews. In this process the data and the results were verified by the technical manager of the company by reviewing and authorising the data usage.

In order to validate if the right system has been developed the framework has been presented to experts from academia and industry in Cost Engineering or SMEs related fields. Validation was done against the formal specification of the developed framework. The focus of the interviews were on validating the suitability, usability, practicality, quality and completeness of the developed framework. Whether the framework has covered some of the main SMEs requirement and the level of appropriateness of the framework for SMEs with the terms explained in Section 4.1 have been discussed in the validation meetings.

In the data collection stage by using appropriate methods it was ensured that the collected data were valid. The involvement of the researcher in the collaborating company and his awareness of various aspects of the on-going product development add an extra measure of validity of data.

The researcher was in direct contact with the company staff and the data collected using various sources were checked with the related staff. Several meetings were arranged during the course of the project which part of the meetings was spent for presenting the progress of work and presenting the findings.

In order to get an unbiased view and reduce the possibility of systematic bias views of the internal human data sources, the results were presented to the supervisors and independent experts from inside the university and outside. Validation was done against the formal specification of the developed framework.

5.4 Results

In this sections the results of Verification and Validation (V&V) of the developed framework are presented. This section is divided into two sub sections of Verification results and Validation results.

5.4.1 Verification

Verification has been done in the form of implementation of the framework in a SME. The results of the case studies that have been done for each objective are presented under each objective section in Chapter 4. In this section a general overview of the results and validation of the framework is presented.

5.4.1.1 Cost estimation

As a part of the V&V process for the framework a case study is done for the developed cost estimation method. The aim of this case study is to follow the developed cost estimation method for two of the main parts of the gas turbine. The data are collected from internal and external sources and Microsoft Excel spreadsheets are used for data analysis. The internal sources for collecting data are the technical team and the managing director, in addition to the unlimited direct access of the researcher to the parts and engineering drawings. Also, the participation of the researcher in design tasks has developed internal knowledge about the parts. The external sources of data are tier one suppliers and partners. Data are mainly extracted from CAD drawings and physical and visual analysis and measurement of the actual product and are in the format of engineering drawings, material information, manufacturing processes, factory data, physical part and part specifications. Some of the data such as engineering drawings, material information and part specifications may not be released by the OEMs for the off-the-shelf parts. In Figure 5-3 The type of data used for this case study are illustrated. The case study has been described in more detail in Section 4.2.

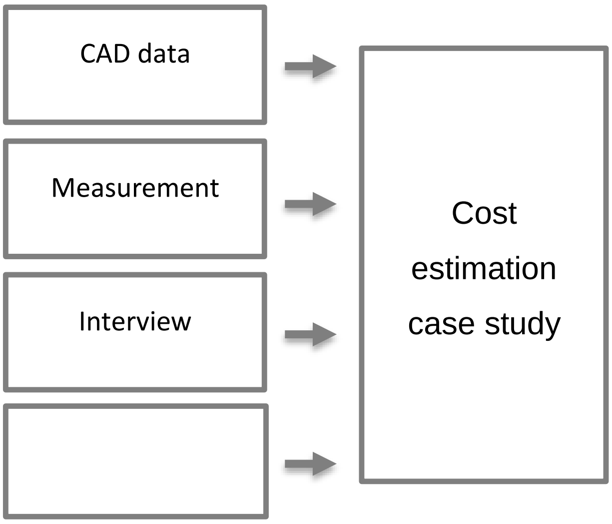

Figure 5-3 - Multiple data sources for the cost estimation case study

For the case study two main parts were chosen; the compressor wheel and the shaft. The reason for this selection is the two different fabrication processes that these parts are made with.

5.4.1.2 Make or buy

A case study has been done for validation of the method developed for 'Make or buy' decision making. In this designed case study, a part of the system would be selected and the developed method would be implemented on the part to reach a decision on the part.

The part selected for the case study is the Shaft of the TGB system. The product under study is a turbo machinery (rotary) system and the shaft is the core (physical core) of the system, which most components are assembled onto the shaft. Although considered in the system, it won't give a major competitive advantage. Because the technology used is not a high tech and novel technology. The material and manufacturing processes are not novel or high tech.

By looking at the cost comparison it can been seen that if only cost would be considered, doing both design and fabrication in-house would be more cost efficient, but only with the condition that the capability and knowledge would be available in-house.

If the fabrication machinery and tools would not be available, the cost comparison would have a different form, and the cost of acquiring the machinery and tools should be added to the in-house cost. If those machinery would be only used for the production of the shaft and no other part, the cost of the machinery has to be distributed over the production size. This means that the in-house cost would be much higher than the current calculated cost and it would be higher than outsourcing cost. In that case outsourcing fabrication would be more cost effective than in-house fabrication.

The experience of working at the collaborating company showed that if you choose in-house manufacturing, the workers would have less motivation to finish their assigned job on-time. One of the identified reasons is that they are being paid monthly and not based on project results. On the other hand, for the case of outsourced fabrication, the payment is based on completed jobs and in-order for them to be able to get more jobs in a fix time frame, they have to finish their jobs as soon as possible and without effecting the quality.

5.4.1.3 Assembly line design

There were two stages for the case study done during the project for the area of assembly line design; one case study was done earlier in the project to help the collaborating company for preliminary decision makings at that point and a detailed case study was done later as the main case study for the purpose of validating the developed method.

5.4.1.3.1 Case study 1

For the first case study a factory design proposed by the CEO of the collaborating company was reviewed and validated. For this purpose, the design was compared to assembly line design theory, in addition, the design was presented to an expert in this field for validation purpose.

5.4.1.3.2 Case study 2

In the case study, the planned figures for production were entered into the developed method to compare various assembly line design options.

The production requirements of the company are as follows:

- Production of 1000 units for the first year and increase up to 100,000 units in 5 years
- An assembly line with the lowest capital requirement

In the first step, the time needed to produce each unit was calculated based on 1,000 units and 100000 units per year. In the next step the product assemblies and subassemblies were determined and product breakdown structure diagram was developed.

In order to make the use of the diagram easier a simple number coding system was used where all top level subsystems were given a unique number or letter. Also, the parts were given a unique number or letter. The combination of the two codes would define a part in the system.

For the next step a list of assembly tasks was defined. In addition to the part code, a task code was defined for each assembly task. The next major step was defining the precedence graph.

Determining the task times was the next step in the assembly line design. The task times were determined either by time study of the tasks or expert knowledge and experience. For this case study an estimation of task times was used based on experience and expert knowledge.

In addition to the tasks times, there are other times that have to be added to the assembly time. For a cell system, Initial set-up time, supply racks filling up time, walking time, testing time, packaging time and transfer to warehouse time are the times that can be added.

For an assembly line, initial set-up time, work piece line transfer time, testing time, packaging time and transfer to warehouse time were the times that needed to be added to the task times.

In the next step, the assembly system capability for an unbalanced linked line assembly system was calculated

The calculation continued with the calculation of the number of assembly lines needed to meet 1000 units per year and 100,000 units per year production capacity.

The next set of calculations were for a balanced assembly line.

The process used for balancing is explained briefly as follows:

- Reassign tasks to stations with the aim to decrease idle time.
- In order to have minimum idle time, negative idle time would be accepted
- So the bottleneck can be identified
- So, in order to eliminate negative cycle time and bottlenecks, cycle time has to be adjusted to the highest station time

In order to be able to compare the performance and effectiveness of the lines, the line efficiencies were compared.

By comparing the 3 different assembly lines, the line with the highest efficiency was the balanced line with heuristic method.

5.4.1.4 Factory cost estimation

The developed process for factory set-up cost estimation was implemented in the collaborating company. The result of the case study was used for future production planning and also negotiations with suppliers.

The following requirements of the collaborating company were used for the study:

- There would be an Increase of production from 1000 units for the first year to 100000 units in 5 years.
- The production plant would consist of an assembly line with the lowest capital requirement
- Agreements would be made with suppliers to have the part supplies ready in 24 hours
- Complex manufacturing processes such as moulding and casting are not considered for in-house manufacturing processes

Due to uncertainties for some of the data, some assumptions were used for the case study which are as follows:

- The estimate is done for the factory setup costs without any activity being started in the plant
- Purchase costs of equipment are not considered.
- Cost of equipment set-up and any modification to the building would be considered as a percentage of other costs.
- The estimation is based on data collected on September, 2014.
- The gender of the employee is assumed to be 10 male and 6 female workers.

The facilities needed in the factory were identified as following:

- Offices
- Kitchen
- Production area
- Quality check area
- Warehouse
- Storage
- Parking and loading area
- Test cells (For development purposes)
- Toilets, showers and changing rooms Total area

The total area required for the production can be obtained by the sum of the entire individual area sizes; although when looking for a plant, each area size has to be looked for separately and each area size requirement should be met separately.

5.4.1.5 The framework

After performing the case studies of implementing the framework in the SME, the case studies were evaluated for meeting the initial list of requirements of a tool for an SME. By applying the method it was seen that the needs of SME was addressed by providing them with tools that helps them in Cost Engineering needs such as cost estimation of products in the design stage which is required for early decision makings and cost reduction at the design stage as discussed in Section 4.2.

The tools provided to the SME were designed to be easy to use and require little expert knowledge. For example, the data required for obtaining the cost estimate where either readily available in the company such as engineering drawings or could be obtained internally such as by measurement of part dimensions. The step by step guided process would help the engineers to follow the Cost Engineering methods through to end with little Cost Engineering knowledge required.

The above mentioned simplicity and availability of input data results in less time consuming processes to obtain results quickly for quick decision makings at the design stage. Being a not time consuming process with little human resources requirement (one-man job) results in a cost effective method for a company with limited financial requirements.

Quality and accuracy of data is another aspect that need to be evaluated. The accuracy of obtained cost data needs to be investigated by considering the context. The stage at which the cost analysis is being made and the level of uncertainties at that stage are important factors to take into consideration. The quality and accuracy have been further discussed in the validation section.

5.4.2 Validation

In this section the meetings, interview and surveys performed for the reason of validation are presented. As explained in section 3.5, more than 25 number of meetings with more than 40 hours were held during the course of this project. As illustrated in Figure 5-2, a number of the interviews were held before the framework development and a number of them where held after the development.

A number of the meetings were held with the focus on development of separate framework methods, while a number of the meetings were held for validating the framework in general.

The aim of the validation meetings was to evaluate if the developed models have fulfilled the specified requirements for SMEs and how accurate are the results. The meetings were held in the format of semi-structured and structured interviews.

5.4.2.1 The framework

The first set of validation meetings presented in this Section are validation meeting within the collaborating company. These meetings were held with the managing director and the technical manager of the SME. In separate meetings with the managing director of the company and the technical manager, the framework was presented and a structured interview was performed after the presentation.

The questions asked in these meetings were about ‘to what extent has the framework fulfilled the specified requirements of an SME’. Questions regarding what is the level of suitability, usability, practicality, quality and completeness of the developed framework were asked in these interviews.

The managing director believed that the framework is very helpful for start-up small enterprises, because it can transfer a high degree of knowledge in a quick way to the management of the company. These are knowledge that might take years to gain through experience. The structure of the framework helps in the flow of product development and is a step by step guide for a company to go through the Cost Engineering methods. The framework can be a considerable decision support tool for a SME manager, because it provides the manager with major elements required for decision making at the design stage.

The way that the framework would be available to SMEs is important. It is suggested that the framework could be implemented into Microsoft Excel software and utilise a user friendly interface to make it easier for users to use it. Having information in a graphical way would help in transferring knowledge compared to pure text. It should be considered that managers in small companies are very occupied by management tasks, so using the tool should not need much time.

Some methods of the framework are very specific. For example, the Cost estimation method is manufacturing process specific. There are many other manufacturing processes that have not been addressed in this method.

The technical manager in general saw the framework very helpful for a small company. He believed that there is a significant amount of knowledge covered in the framework for a SME. For a start-up company these information are very valuable and would take experience and cost to be obtained.

He had some slight corrections to some inputs of the case studies and commented on the results of the case studies. He suggested that an interface should be designed for the framework to make it more user-friendly. It was suggested that a guide should be prepared in order to help the user towards using the framework. The comments about the case study inputs and results were implemented where applicable. Lack of a method for design modification for cost reduction purpose can be seen in the framework. In terms of Simplicity, the technical manager believed that still for following some of the methods such as Cost Estimation, help from an expert was required. The advantages and disadvantages of the framework in the view of the collaborating company are summarised in Table 5-1.

Table 5-1 - Advantages and disadvantages of the framework from the point of view of the collaborating company

Advantage	Disadvantage
Is very useful for start-up SMEs	Appearance and interface
Quick transfer of high degree of knowledge	Time consuming
Well structure framework	Context specific
Guided & step by step process	Lack of written guide
Simplicity	Lack methods for product design modification
A considerable decision support tool	

In addition to validating with parties from the collaborating company, meetings were held with independent external individuals.

A meeting was held on 5rd March 2013 with Expert 5, an expert in Cost Engineering. He was working as the Process Improvement Manager at National Grid with several years of experience in Cost Engineering.

In the 1.5 hour meeting, the framework was presented to the expert and semi-structured questions were asked. The focus of the questions were on SMEs Cost Engineering requirements and to what extend the framework has addressed SMEs problems. The expert believed that the major issue that causes problems for SMEs is cash flow crisis, other issues come second. He mentioned that most of the SMEs failures he had encountered was due to lack of cash flow. So SMEs need help and guidance in terms of cash flow management and acquiring funds. Although he believed that the areas covered in the framework were among the major areas that SMEs would need help with.

Another meeting was held with an experienced cost engineering expert, Expert 9 was a cost engineering senior manager at Jaguar Land Rover Company. The framework was presented to the expert in detail and semi-structured questions were asked. The framework was seen useful for both SMEs and large companies as it helps transferring knowledge in a structured way. Running all the methods will be demanding and time consuming and might not be of interest of an SME. There were few correction suggestions about the details of the framework.

5.5 Summary

In this chapter the verification and validation of the cost reduction framework for SMEs were presented. In Section 5.2 a background of V&V was presented by reviewing the theory of V&V in the literature. In Section 5.3 the detailed research methodology was presented, including explaining the 5 stages for V&V during this project. The project has been supervised by two academic experts in Cost Engineering and coherent review meetings were held with them. Also few review meetings were held with another internal expert in the field, Expert 10. In addition to the review meetings, by careful considerations, it was ensured that the collected data are valid. Direct and coherent contact of the researcher with company managers helped in this process.

The results were also presented to academic and industrial experts. The knowledge and experience of the experts helps to validate the results to ensure that the objectives are met. The main objective to be met is the usefulness of the framework for targeted SMEs.

For quantitative verification, the framework was implemented through case studies, in the company. The case studies were done is real world environments on a real product and the results had effects on the collaborating company.

The framework was developed through an iterative method. The development started with initial objectives and as the development was proceeded, based on the feedbacks, the objectives were refined. The iterative method also covered the developed methods. As more interaction was done with the studied company and more data were collected about SMEs requirements, the objectives and in more detail, methods were modified to suite those requirements.

In Section 5.4.1, the results of implementing the framework in a real work situation were presented. This verified the framework against formal specifications. And in Section 5.4.2, the validation interviews held for validating the results were presented. The feedback from the experts were evaluated and where applicable, corrections were made to the details of the framework and case study results.

6 DISCUSSION, CONCLUSION & FUTURE WORKS

6.1 Introduction

This chapter starts with the discussion of the key research findings and identifying the primary contributions to knowledge. In this section results of each objective are discussed and it is shown how the original research aim and objective were addressed. This chapter continues with the evaluation and discussion of the research limitations. And it is concluded with future works recommendations and final concluding remarks.

6.2 Discussions

This section starts with the discussion of key findings of this research and continues with the presentation of the achievement of research aim and objectives and finishes with the discussion of research limitations.

6.2.1 Discussion of key findings

In this section a summary of the key findings and observations are discussed. The structure of this section follows the thesis structure.

6.2.1.1 Literature review

Because of the areas covered in the objectives of the project mentioned in Section 3.1 and additionally because of the exploratory nature of the research, the literature review has covered a number of main areas of SMEs' characteristics, Cost reduction methodologies, Cost estimation methods & tools, Make or buy decision making, Factory cost estimation and Factory design. By evaluating the Cost Engineering methods developed for SMEs, lack of Cost Engineering knowledge for SMEs is identified. By reviewing SME related research it has been observed that minimal research has been carried out on the development of cost reduction methods specifically developed for SMEs. There is minimal research on how to standardise Cost Engineering in start-up SMEs by introducing best practices in the form of tools and subsequently observing the results of using them on a case study design.

Several general cost reduction methods were observed covering various conventional cost reduction methods. Most of these papers have combined several conventional cost reduction methods such as DFMA, VE and QFD. Many of the papers in this area have studied the implementation of traditional cost reduction methods in real world companies in different contexts and different industries. A significant lack of methods specifically developed for SMEs considering SME characteristics and requirements, is identified. There are a large number of papers focusing on subjects related to SMEs which many are related to management, economics and business of SMEs which have been presented in Section 2.3. Out of the searched papers a small number are related to cost reduction for SMEs. Most of these papers are case studies which focus on implementing conventional cost reduction methods in SMEs and studying the effects. Many of the case study papers were country specific with studying SMEs in a specific country and in some cases SMEs in a specific industry.

SMEs possess a very low number of research topics in these areas compared to larger and more complex firms. Most of the available tools and methods are applicable to SMEs as well as large companies, but studying the impact of using such methods on SMEs hasn't been of much focus in the literature.

A lack of research was seen in the topic of characteristics of SMEs and studying and comparing different categories of SMEs. As the specific tools need to be tailored for SMEs based on their specific characteristics which separates them from other types of enterprises, it makes studying characteristics of SMEs more significant. A portion of SME related papers have studied SMEs characteristics and requirements in the form of surveys of SMEs in a country or in a specific industry and in-depth study of individual SMEs are the main themes of these papers. But these studies were context specific and did not differentiate between the different types and categories of SMEs.

6.2.1.2 Research methodology

The development of the research methodology is described in Chapter 3. Due to the different areas covered in the aims and objectives a mixed research methodology was required. In this research methodology design, qualitative and quantitative methods were utilised. An exploratory research method was employed to identify requirements of the studied company. Participation and observation were the main data collection methods for developing the framework which helped with the exploratory nature of the research. A case study was done to implement the developed framework in a real world situation.

There was one company in the study, not a range of companies. However, this allowed an in-depth work to take place in detail including a significant amount of expert opinion from the company, and the focus on one novel design and development project.

Case studies were running throughout the project in parallel to the framework development. Part of the data achieved through case studies was used in framework development.

Initial steps of the case studies were to help the SME as soon as possible. By holding early cost reduction workshops with the company, some early thought of cost reduction idea was introduced to the company. Therefore workshops for Value engineering and DFMA have been held for the company in the early stages of the research project.

The case studies in later stages of the project were mainly focused on validating the results of framework development and they included the implementation of best practice methods in the company.

Some of the results from the case studies helped to understand the requirements of the SME in terms of cost reduction methods.

The case studies also helped to develop a better understanding of the environment and activities of the SME and helped to understand the product in more depth.

As the researcher was participating in the case company's design tasks, there was the advantage of accessing product design data directly which facilitated data collection for case studies. Although as discussed earlier due to the development nature of the project the design data was changing quickly and it was difficult to rely on the design data for long term decision making.

One of the challenges the researcher was facing was managing the research work with the case company. It included keeping the balance between research related work and non-research work directly related to the company while being present in the company. As a part of the observation and participation research methodology, the researcher spent a major proportion of the research time in the case company, participating as a normal staff member. In total this participation resulted in a close observation of an SME and direct and immediate access to data and management staff.

These lead to quicker data collection, on the go feedback from the company, and quicker transfer of knowledge to the company.

The downsides of this methodology are that informal and unstructured interviews with the staff may result in inaccurate or out of context answers. In addition, regular presence of the researcher in the company and the nature of SMEs work lead to requests for work tasks which were unrelated to research work. Work such as workshop works, system assembly and testing, CAD design and general office works.

The change of environment from the industrial environment of the company to the academic environment of the university office was a challenge for the researcher. Adapting to the different conditions needed some time which occupied part of the research time.

Being close to the company has increased the possibility of bias and an objective view of how to implement cost engineering might have been influenced. By collecting data from various data sources in the company and evaluating the findings with other researcher's findings and validating the data with experts and reviewing the findings with internal experts, it has been tried to minimise the possibility of bias in the research.

Part of the case studies were planned to follow the SME in development stage and it was tried to match the case studies and workshop plans with the case company's development plan. But due to the nature of business, there were changes to the company plans which lead to mismatching between the research plan and company's plan which in turn lead to some research plan adjustments.

The research provided a range of cost engineering tools across the new product development cycle. The alternative of focussing on one aspect of cost engineering was not a possibility because of the ongoing commercial requirement of the company. This provided best practices to a focussed but limited extent which might have been possible because of the SME level of the research. A single aspect may have led to a possible lack of significance in cost reduction research contribution.

6.2.1.3 Framework development

The framework was developed based on SMEs characteristics and requirements for Cost reduction with the focus on start-up SMEs developing a novel product. In Chapter 2 lack of Cost Engineering methods for SMEs was observed in the literature. In Section 4.1, SME characteristics, by studying an SME, significant lack of Cost Engineering knowledge was observed which was confirmed by the studies of other researchers as shown in Section 2.3.

In the study of the SME in Section 4.1 it was seen that for most Cost Engineering requirements 'Gut feeling' and 'rule of thumb' was the method of choice, rather than well-developed methods. This reemphasised the need for transferring Cost Engineering knowledge including state-of-art methods to SMEs.

The analysis of the AS IS model of the SME and by considering general requirement of SMEs and by studying state-of-art methods a process map of the cost reduction framework was developed. The framework was validated by implementing it in the collaborating company and was modified and improved based on results from ongoing case studies.

In achieving any cost reduction results for the SME numerous main obstacles were faced.

- Lack of information about the final product:

  As the product is under development and many parts are not finalised yet and the product is a novel product with very few similar products on the market which due to competitive sensitivity very little cost information are available, so there was lack of information in some areas. Many conventional tools and methods require accurate data about the product or comparative products to produce accurate results.

- Unconventional design process:

  The product development process that the collaborating company has used to have a low cost product relies on using commercial-off-the-shelf parts as many as possible. This strategy, despite many advantages, but limits the possibility of design changes for cost reduction purposes.

Using COTS parts is not the best strategy for cost reduction, since an off the shelf part has not specifically been designed for the developing product.

It is possible that cost reduction principles have not been considered in the COTS part design. This may cause difficulties in matching the purchased parts with other parts which would result in higher assembly time and consequently higher assembly cost.

Also matching various COTS components in terms of technical compatibility, coming from different products, may become time consuming as well and may result in design modification of the parts and consequently may require further tests and experiments to come up with a final, ready to market product.

One way to overcome these issues is to use a COTS component as the base for designing a new component which would match the system. Which neither has the disadvantages of designing a part from scratch and nor the disadvantages of using a COTS part directly.

- Time and resource constraints

The product development project had a very compact project plan and due to competition reasons and limited financial resources there was the necessity for quick time to market. Also, due to financial constraints, there was lack of human resources and the current resources were overloaded with various responsibilities. The described situation made any contribution of team members in any cost reduction workshops or cost reduction activities difficult. Also, any changes or modification that required spending time or involvement of any staff was very challenging. Any distraction from normal workflow seemed unfavourable in the company.

- Instability in SMEs Management

Due to the nature of their work, a large degree of instability exists in SME management and business aspects. Although the high degree of flexibility in SMEs is seen as an advantage compared to large companies, sometimes this characteristic becomes a routine and changes become the first solution for any problem. The changes happen in various aspects. Changes could happen to project plan or changes could happen to staff roles especially in management roles. Firefighting has been seen as the main cause of quick changes in the SME.

- More focus on technology demonstration rather than cost reduction

As a company that develops a novel product, it is important to prove that the idea that the product is being developed on, actually works. Any person or organisations that are going to invest into an idea need to see the idea working. So it is very important for the company to prepare their product for technology demonstration. Focusing on this aspect of work and with the addition of tight time to market and ever progressing competitors, leaves smaller attention for cost reduction. When a company is designing a component or looking for an off-the-shelf component, the focus is mainly of technical performance rather than other cost attributes.

- Decisions made based on owner's knowledge

In the SME the business has been formed on a business idea of the founder of the company and the founder which is also the managing director of the company, manages the business based on its own knowledge and judgement. Consequently, the main decision maker of the company is the managing director and any decisions need to be approved by the managing director which slows down any cost reduction activity in the company. Only if the mind-set of the managing director has been changed towards cost reduction, then the task of implementing cost reduction methods would be facilitated.

- Lack of documentation and standard processes

  Because of the nature of the start-up SME, standards, processes and documentations have not been implemented yet and these make finding up-to-date data difficult and time consuming. Due to the importance of standardisation the researcher was involved in defining standards for CAD data and drawings.

The framework is useful for an SME in terms of firstly addressing the key problems the SME is facing. Secondly the step by step process of the framework requires minimal expert knowledge. Thirdly selected best practice methods have been selected based on the ease of use for SMEs which don't have access to cost engineering experts.

6.2.2 Achievement of Research Aim and Objectives

This section is focusing on defining the success of achieving the aim and objective of this thesis. The aim has been defined in Chapter 3 as:

"*To develop a cost reduction tool for SMEs developing a novel product.*"

The aim of the research has been successfully achieved. The Objectives of this research have been defined in Section 3.2, and the level of success of each objective has been evaluated in the following:

The objective 'To identify challenges that SMEs are facing introducing a new product to the market' was focused on studying the collaborating company and reviewing other researcher's studies about SMEs to understand characteristics of SMEs and identify current practices and Cost Engineering requirements.

The evaluation started in Chapter 2 was a detailed review of literature and how cost reduction was performed. In this chapter the current status of SMEs and their Cost Engineering requirements were identified. In Section 4.1, by close studying of an SME, the day to day challenges and characteristics were identified. The current practices of the company were mapped and by interviews and observations, their requirements were recorded. The analysis of the findings in Section 4.1 resulted in the development of other objectives.

The second objective was the development of a cost reduction framework. As discussed in Section 2.11 no cost engineering method was identified in the literature developed based on SMEs characteristics. The framework development was based on findings from the first objective. The framework is detailed in Chapter 4 and the framework is fulfilled by developing a cost reduction framework. The framework includes methods that would fulfil a number of the major requirements of SMEs developing a novel product. The framework was verified through implementation in a real world case and validated by presenting to and interviewing Cost Engineering and SME experts. These indicated the lack of such methods in the industry and re-emphasised the need of SMEs for Cost Engineering knowledge to be able to compete in the market.

The third objective was to develop a detailed cost estimating method and a process for 'Make or buy' decision making. Based on the identified requirement of the SME a detailed cost estimating method was required for supporting decision making at the design stage of the product development cycle. The cost estimating method should be run with minimal Cost Engineering knowledge as one of the identified characteristics of SMEs identified in Section 4.1 was lack of Cost Engineering knowledge. The development of the Cost Estimation model is explained in Section 4.2 . The development of the Cost estimation model follows with the development of a 'Make or buy' decision making process. The model was developed as a decision support tool for the SMEs. The need for such a method was captured in studying the SMEs in Section 4.1 . The development of this method is part of knowledge transfer to SMEs which lack or have limited Cost Engineering knowledge. As discussed in Chapter 2.11 similar methods developed for SMEs were not identified in the literature.

The fourth objective required tools for supporting production line designs. In Chapter 4.4 it was discussed that in order to have a low cost production, a low cost production line needs to be designed. In the case of the collaborating company, the production would be focused on assembling parts, so a method for assembly line design was developed. As detailed in Section 4.2.2, selecting an appropriate manufacturing process, helps in having a low cost product design. In addition, for a low cost production line design, an appropriate manufacturing process should be selected.

The fifth objective required an estimating tool for factory set-up cost. The tool was developed to estimate costs at design stage for set-up of a low cost production plant. The tool is a decision support tool at product design stage to support designing a low cost product. It provides cost data for decision making and planning at the design stage. As discussed in Section 2.9, by reviewing the literature no similar tools were identified and a requirement of such a tool for SMEs is discussed in Section 4.5.

The sixth objective was met by performing case studies of all the objectives and validating the results with academic and industrial experts as discussed in Chapter 5. The case studies were running through the project in the form of implementing the developed methods in an SME and the results were presented to experts for validation. The development of the framework and conformity of the framework with SME characteristics and requirement has been validated through the project with internal and external academic and industrial experts.

6.2.3 Research limitations

The framework has been developed specifically for start-up Small to Medium sized Enterprises developing a novel product. The focus of the development has been a start-up small company developing an engineering product in the boiler sector with micro gas turbine technology. Although the framework can be used by other industries as a guideline for cost reduction, but specific considerations have to be considered for appropriateness of detailed methods.

The research has considered a case where the company is willing to have minimum fabrication facilities and focus production capabilities on assembling outsourced parts.

The researcher has considered SMEs in the UK, so the results might be country specific and might not be generalised globally.

The cost reduction method was focused on production cost whereas other areas of cost reduction could be explored. SMEs are in need of support in the form of knowledge transfer and in addition to knowledge transfer, further interaction is required to result in mind set and strategy changes in companies.

The research has been done based on SMEs' characteristics and requirements identified through a literature review, interviews with experts and studying an SME. Due to the research scope and limited time frame further study of other SMEs was not possible. By studying more SMEs developing a novel product a more general understanding of industry requirements could be obtained which would help to develop a more universal framework. Hence the requirements of all start-up SMEs developing a novel product could not be addressed.

The case company could not afford to implement the entire framework, because of the high risk of implementing academic research results directly into industry. Accordingly, for some parts of the framework, instead real world scenarios were defined to advance the case studies.

Because of some uncertainties at the development stage of a novel product, some of the data used for the case studies are based on the current status of the product and these might change at later stages where the product design would be modified for mass production.

For a company developing a novel product at early design stages, reaching the technology demonstration stage was vital. Therefore a great amount of effort was placed on technical tasks to reach that stage. The future life of the company was dependent on demonstrating the acclaimed technology, which took most of the focus of the company and left less attention for cost reduction activities.

As discussed in Chapter 4.1 many start-up companies struggle with cash flow and a great amount of their focus is on managing cash flow and obtaining funds. Trying to initiate the thought of importance of cost reduction at early design stages is a challenge. Lack of human resources and the focus of everyone on technical tasks is added to the challenges of implementing Cost Engineering in start-up SMEs.

The methods developed in this research could be expanded further to address more universal requirements, but due to the limited time frame and limited scope of the project these have been limited. The developed Cost Estimation method could be expanded by having cost estimation processes for other common manufacturing processes. There are many variations of machinery and tools with different capabilities in the industry that would defer the general cost estimation assumptions and equations. For example, a conventional CNC lathe machine would machine a part in C-axis and X-axis, whereas CNC lathe machine are available which have milling capabilities built in the machine. These machine would have capability of machining in Y-axis and Z-axis as well. This additional capability can reduce setup and operation times significantly. However, as discussed in Section 4.2, it should be considered that the aim of producing the cost estimation at early design stages is producing quick cost estimates to support decision making. Due to a high number of uncertainties at those stages accuracy of estimates are not expected.

6.3 Future works

The title includes SMEs, but SMEs includes a broad range of companies in terms of sizes and financial level and each have their own characteristics and therefore unique requirements. There is the potential to study the companies under SMEs in more detail and categorise them in more detailed levels.

In addition to the areas covered in this research for cost reduction, there are other potential areas for cost reduction. Other stages of the life cycle cost can be covered for cost reduction. There are cost reduction potentials in the way a company is managed especially during resource management.

A topic that can be further investigated is academic research in collaboration with industry in general and SMEs specifically. From the experience that the researcher gained through this research it was realised that because of the specific conditions of the SMEs, working and collaboration with SMEs requires further considerations. Methods of knowledge transfer to SMEs in another topic can be further investigated in more detail.

A user friendly interface can be designed and developed for the developed framework, also for ease of use, the framework could be designed into a website or be cloud based for ease of access. A written or an interactive guide can be designed for the framework. In addition, the results of the research can be formed into a workbook or a guide book that can be useful by SMEs. The workbook could include step-by-step guide through the framework and with having instructions for implementing methods with the focus of knowledge transfer to SMEs.

6.4 Conclusion

In this section the key contributions to knowledge and the research findings are presented and the section is end by the concluding remarks.

6.4.1 Key contributions to knowledge

The research has contributed to increase the understanding about start-up SME characteristics and their Cost Engineering requirements. The understanding has resulted in developing a novel framework to address the identified requirements, using methods that would comply with the identified characteristics of start-up SMEs. It has also helped to increase the understanding of collaborating with an SME in a research setting. The knowledge obtained through applying the methods in the specific setting and on the specific product has created new knowledge.

The key research contributions are summarised as follows:

- One of the major novelties of the research was the novel application of the conventional methods to a novel product and the results obtained from the implementation of these methods. The product which the company is developing is a novel product and also because of the situation of the company which is a start-up SME, the results obtained from the implementation of framework are novel.
- Based on the research findings and the developed tools and methods, a novel framework was developed to transfer Cost Engineering knowledge to SMEs in a structured method. The framework has been developed to address a number of major identified requirements of SMEs in the target field. The novel framework has been designed with the aim to be used by companies with minimal Cost Engineering knowledge. The framework is a structured set of best practices to be delivered to SMEs.
- This research identified the lack of Cost Engineering knowledge in SMEs through a state of the art literature review. It was realised that SMEs are in need of Cost Engineering knowledge to be able to compete in the market. Lack of research was seen in the area of SME characteristics, but the in-depth study of the collaborating SME gave a better understanding of characteristics of a certain type of SME. The SME in this research is a small start-up enterprise with less than 20 employees developing a novel product.

In addition of the key contributions to knowledge, key findings and achievements of this research are listed below:

- In this research a set of tools and methods were identified to meet the identified SMEs requirements and comply with their characteristics. Where no appropriate tools were identified in the literature, a specific tool was developed in this research.

- In this research a factory set-up cost estimation has been developed based on the identified requirements of SMEs. Literature was reviewed for any available tools, but no tool or method could be found to estimate, in the design stage, the cost of setting-up a production plant.
- As a result of the research findings, a cost estimation process was required as a decision support tool in the design stage. A detailed cost estimation process was developed for estimating the cost of fabricated parts using available state-of-art cost estimation methods identified through literature review.
- The research identified the need for a ‘Make or buy’ decision making tool for the SME. A novel tool was compiled using best available tools in the literature to meet the requirements of an SME for a decision making tool at the design stage.

6.4.2 Concluding remarks

In this chapter a novel cost reduction methodology has been developed for start-up SMEs developing a novel product. The methodology has been developed in the form of a framework including methods addressing target SMEs’ requirement. The framework has been successfully validated and verified in a small start-up company developing a technology intensive product. It was validated that the framework had addressed a number of major requirements of start-up SMEs. The aim and objectives have successfully been achieved. Implementing the framework in SMEs would transfer necessary Cost Engineering knowledge to SMEs that need them and helps to implement the methods in a guided process.

REFERENCES

Aarts, F. M. and Vos, E. (2001), "The impact of ISO registration on New Zealand firms' performance: A financial perspective", *TQM Magazine,* vol. 13, no. 3, pp. 180-191.

Abbey forged products (2018), *655M13 – 3.25% Ni – Cr Case Hardening Steel*, available at: http://www.abbeyforgedproducts.co.uk/images/downloads/PDF/655M13.pdf (accessed September 2018).

Abdul-Halim, H., Ahmad, N. H. and Ramayah, T. (2012), "Unveiling the motivation to outsource among SMEs", *Business Strategy Series,* vol. 13, no. 4, pp. 181-186.

Abdullah, T. A., Popplewell, K. and Page, C. J. (2003), "A review of the support tools for the process of assembly method selection and assembly planning", *International Journal of Production Research,* vol. 41, no. 11, pp. 2391-2410.

Agustin, R. O. and Santiago, F. (1996), "Single-minute exchange of die", Anon (ed.), in: *Proceedings of the 1996 7th Annual IEEE/SEMI Advanced Semiconductor Manufacturing Conference, ASMC 96,* 12 November 1996 through 14 November 1996, Cambridge, MA, USA, IEEE, Piscataway, NJ, United States, pp. 214.

Amenudzi, E. Y. (2009), *A structured literature review of make or buy decisions in manufacturing industries* (unpublished M.Sc. thesis), Cranfield University. School of Management.

Anderson, E. and Anderson, M. (2000), "Are your decisions today creating your future competitors? Avoiding the outsourcing trap", *The Systems Thinker,* vol. 11, no. 7, pp. 1-5.

Auer, M. and Biffl, S. (2004), "Increasing the accuracy and reliability of analogy-based cost estimation with extensive project feature dimension weighting", *Proceedings - 2004 International Symposium on Empirical Software Engineering, ISESE 2004,* 19 August 2004 through 20 August 2004, Redondo Beach, CA, pp. 147.

Azzeh, M., Neagu, D. and Cowling, P. I. (2011), "Analogy-based software effort estimation using Fuzzy numbers", *Journal of Systems and Software,* vol. 84, no. 2, pp. 270-284.

Barber, J., Metcalfe, J. S. and Porteous, M. (1989), *Barriers to growth in small firms,* Routledge.

Bayati, A. and Taghavi, A. (2007), "The impacts of acquiring ISO 9000 certification on the performance of SMEs in Tehran", *TQM Magazine,* vol. 19, no. 2, pp. 140-149.

Bayrak, T. (2013), "A decision framework for SME Information Technology (IT) managers: Factors for evaluating whether to outsource internal applications to Application Service Providers", *Technology in Society,* vol. 35, no. 1, pp. 14-21.

Bell, D. N. and Blanchflower, D. G. (2011), "Young people and the Great Recession", *Oxford Review of Economic Policy,* vol. 27, no. 2, pp. 241-267.

Bennedsen, M. and Wolfenzon, D. (2000), "The balance of power in closely held corporations", *Journal of Financial Economics,* vol. 58, no. 1-2, pp. 113-139.

Benton, W. C. (2010), *Purchasing and supply chain management,* 2nd ed, McGraw-Hill, Boston, Mass.; London.

Bharara, A. and Lee, C. (1996), "Implementation of an activity-based costing system in a small manufacturing company", *International Journal of Production Research,* vol. 34, no. 4, pp. 1109-1130.

Blocher, E. J., Chen, K. H., Cokins, G. and Lin, T. W. (2005), *Cost management a strategic emphasis,* McGraw-Hill, New York.

Boeker, W. (1989), "The development and institutionalization of subunit power in organizations", *Administrative Science Quarterly,* pp. 388-410.

Boothroyd, G., Dewhurst, P. and Knight, W. A. (2002), *Product design for manufacture and assembly,* 2nd ed, Marcel Dekker, New York.

Boysen, N., Fliedner, M. and Scholl, A. (2007), "A classification of assembly line balancing problems", *European Journal of Operational Research,* vol. 183, no. 2, pp. 674-693.

Brown, C., Hamilton, J. and Medoff, J. (1990), *Employers Large and Small,* Harvard University Press, Cambridge, Massachusetts.

Brunninge, O. and Nordqvist, M. (2004), "Ownership structure, board composition and entrepreneurship: Evidence from family firms and venture-capital-backed firms", *International Journal of Entrepreneurial Behaviour & Research,* vol. 10, no. 1/2, pp. 85-105.

Buchowicz, B. S. (1991), "A process model of make-vs.-buy decision-making; The case of manufacturing software", *IEEE Transactions on Engineering Management,* vol. 38, no. 1, pp. 24-32.

Canel, C. and Das, S. R. (2002), "Modeling global facility location decisions: Integrating marketing and manufacturing decisions", *Industrial Management and Data Systems,* vol. 102, no. 1-2, pp. 110-118.

Cantarello, S., Nosella, A., Petroni, G. and Venturini, K. (2011), "External technology sourcing: Evidence from design-driven innovation", *Management Decision,* vol. 49, no. 6, pp. 962-983.

Carney, M. (2005), "Corporate Governance and Competitive Advantage in Family-Controlled Firms", *Entrepreneurship Theory and Practice,* vol. 29, no. 3, pp. 249-265.

Castagne, S., Curran, R. and Collopy, P. (2009), "Implementation of value-driven optimisation for the design of aircraft fuselage panels", *International Journal of Production Economics,* vol. 117, no. 2, pp. 381-388.

Chang, SI., Yen, DC., Ng, CSP. and Chang, WT. (2012), "An analysis of IT/IS outsourcing provider selection for small- and medium-sized enterprises in Taiwan", *Information and Management,* vol. 49, no. 5, pp. 199-209.

Chesbrough, H. W. (2003), "The era of open innovation", *MIT Sloan Management Review,* vol. 44, no. 3, pp. 35-41.

Cheung, J., Scanlan, J., Wong, J., Forrester, J., Eres, H., Collopy, P., Hollingsworth, P., Wiseall, S. and Briceno, P. (2010), "Application of Value-Driven Design to commercial aero-engine systems", *10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference,* September 2010, Ft Worth, TX, American Institute of Aeronautics and Astronautics.

Chiesa, V. (2001), *R & D strategy and organisation: managing technical change in dynamic contexts,* Imperial college press.

Chowdhury, S. R. (2011), "Impact of global crisis on small and medium enterprises", *Global Business Review,* vol. 12, no. 3, pp. 377-399.

Coase, R. H. (1937), *Economica,* vol. 4, no. 16, pp. 386-405.

Collopy, P. (1997), "Surplus Value in Propulsion System Design Optimization", American Institute of Aeronautics and Astronautics, *97-3159*.

Collopy, P. D. and Eames, D. J. (2001), "Aerospace manufacturing cost prediction from a measure of part definition information", *SAE Technical Paper*, no. 2001-01-3004.

Collopy, P. D. and Hollingsworth, P. M. (2011), "Value-driven design", *Journal of Aircraft,* vol. 48, no. 3, pp. 749-759.

Cooper, R. and Kaplan, R. S. (1988), "Measure costs right: make the right decisions", *Harvard business review,* vol. 66, no. 5, pp. 96-103.

Cooper, R. and Slagmulder, R. (1997), *Target costing and value engineering,* Productivity Press, Portland, OR.

Cowling, M. (2003), "Productivity and corporate governance in smaller firms", *Small Business Economics,* vol. 20, no. 4, pp. 335-344.

Creece, R. C. (1992), *Estimating and costing for the metal manufacturing industries,* M. Dekker, New York.

Creese, R. C. (2001), "Cost management in lean manufacturing enterprises and the effects upon small and medium enterprises", *Manufacturing Information Systems,* Aalborg, Denmark, pp. 144–151.

Curran, R., Abu-Kias, T., Repco, M. J. F., Sprengers, Y. L. J., Van Der Zwet, P. N. C. S. and Beelearts, W. (2010), "A value operations methodology for value driven design: Medium range passenger airliner validation", *48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition,* 4 January 2010 through 7 January 2010, Orlando, FL.

Curran, R., Raghunathan, S. and Price, M. (2004), "Review of aerospace engineering cost modelling: The genetic causal approach", *Progress in Aerospace Sciences,* vol. 40, no. 8, pp. 487-534.

Daganzo, C. F. and Blumenfeld, D. E. (1994), "Assembly system design principles and tradeoffs", *International Journal of Production Research,* vol. 32, no. 3, pp. 669-681.

Daim, T. U. and Kocaoglu, D. F. (2008), "Exploring technology acquisition in Oregon, Turkey and in the U.S. electronics manufacturing companies", *Journal of High Technology Management Research,* vol. 19, no. 1, pp. 45-58.

Dale, B. and Cunningham, M. (1984), "The importance of factors other than cost considerations in make or buy decisions", *International Journal of Operations & Production Management,* vol. 4, no. 3, pp. 43-54.

David, M. and Sutton, C. D. (2011), *Social Research: An Introduction,* Second ed, SAGE publications, UK.

Dellinger, A. B. and Leech, N. L. (2007), "Toward a unified validation framework in mixed methods research", *Journal of Mixed Methods Research,* vol. 1, no. 4, pp. 309-332.

Department for business, innovation and skills (2013), *SME business barometer - June 2013,* BIS/13/P75B, Department for Business, Innovation & Skills.

Department of business, innovation and skills (10/09/2012)*, SME business barometer: June 2012*, available at: http://www.bis.gov.uk/assets/biscore/enterprise/docs/s/12-p75c-sme-business-barometer-june-2012 (accessed 07/11/2012).

Department of energy and climate change (DECC) (2011)*, Carbon Emissions Reduction Target (CERT)*, available at: http://www.decc.gov.uk/en/content/cms/funding/funding_ops/cert/cert.aspx (accessed October 2011).

Duverlie, P. and Castelain, J. M. (1999), "Cost estimation during design step: Parametric method versus case based reasoning method", *International Journal of Advanced Manufacturing Technology,* vol. 15, no. 12, pp. 895-906.

El Adl, M. K., Rodriguez, A. A. and Tsakalis, K. S. (1996), "Hierarchical modeling and control of re-entrant semiconductor manufacturing facilities", Anon (ed.), in: *Proceedings of the 35th IEEE Conference on Decision and Control. Part 4 (of 4),* Vol. 2, 11 December 1996 through 13 December 1996, Kobe, Jpn, pp. 1736.

Ellram, L. M. and Maltz, A. B. (1995), "The use of total cost of ownership concepts to model the outsourcing decision", *The International Journal of Logistics Management,* vol. 6, no. 2, pp. 55-66.

EPSRC (2015), *EPSRC Centres for Innovative Manufacturing*, available at: https://epsrc.ukri.org/research/centres/innovativemanufacturing/ (accessed 01/09/2018).

EPSRC (10/2016)*, Innovative Manufacturing Research Centres (IMRCs)*, available at: https://www.epsrc.ac.uk/research/centres/imrcs/ (accessed 20/10/2016).

EPSRC (06/06/2006)*, Innovative Manufacturing Research Centres*, available at: ftp://ftp.cordis.europa.eu/pub/ist/docs/europ/rob-plat-25.pdf (accessed 09/11/2012).

Erel, E. and Sarin, S. C. (1998), "A survey of the assembly line balancing procedures", *Production Planning and Control,* vol. 9, no. 5, pp. 414-434.

European Commission (2011), *Annual Report on EU Small and Medium sized Enterprises 2010/2011*, available at: http://ec.europa.eu/enterprise/policies/sme/facts-figures-analysis/performance-review/files/supporting-documents/2010-2011/annual-report_en.pdf (accessed 07/2013).

European Commission (16/04/2012), *What is an SME? - Small to medium sized enterprises (SME) - Enterprise and industry*, available at: http://ec.europa.eu/enterprise/policies/sme/facts-figures-analysis/sme-definition/index_en.htm (accessed 29/10/2012).

European Union (15/10/2012), *Small and medium sized enterprises in 2011: situations per EU Member State*, available at: http://europa.eu/rapid/press-release_MEMO-12-783_en.htm?locale=en#PR_metaPressRelease_bottom (accessed 07/11/2010).

Everaert, P. and Bruggeman, W. (2002), "Cost targets and time pressure during new product development", *International Journal of Operations and Production Management,* vol. 22, no. 12, pp. 1339-1353.

Everaert, P., Sarens, G. and Rommel, J. (2007), "Sourcing strategy of Belgian SMEs: Empirical evidence for the accounting services", *Production Planning and Control,* vol. 18, no. 8, pp. 716-725.

Farsi, J. Y. and Hakiminezhad, N. (2012), "The integration of QFD technique, Value Engineering and design for manufacture and assembly (DFMA) during the product design stage", *Advances in Environmental Biology,* vol. 6, no. 7, pp. 2096-2104.

Fassoula, E. D. and Rogerson, J. H. (2003), "Management tools for SMEs", *Total Quality Management and Business Excellence,* vol. 14, no. 10, pp. 1143-1158.

Fiegener, M. K. (2005), "Determinants of board participation in the strategic decisions of small corporations", *Entrepreneurship Theory and Practice,* vol. 29, no. 5, pp. 627-650.

Fine, C. H. (2000), "Clockspeed-Based Strategies for Supply Chain Design1", *Production and Operations Management,* vol. 9, no. 3, pp. 213-221.

Fombrun, C. J., Gardberg, N. A. and Barnett, M. L. (2000), "Opportunity platforms and safety nets: Corporate citizenship and reputational risk", *Business and Society Review,* vol. 105, no. 1, pp. 85-106.

Ford, R. H. (1988), "Outside directors and the privately-owned firm: Are they necessary", *Entrepreneurship Theory and Practice,* vol. 13, no. 1, pp. 49-57.

Francis, R. L. and White, J. A. (1974), *Facility layout and location: an analytical approach,* Prentice-Hall, Englewood Cliffs, N.J.

Freel, M. (2000), "External linkages and product innovation in small manufacturing firms", *Entrepreneurship and Regional Development,* vol. 12, no. 3, pp. 245-266.

Freeman, S. (2001), "Industry environment: influence on performance of smallmedium sized enterprise in Asia Pacific markets", *Asian Academy of Management Journal,* vol. 5, no. 2, pp. 96-113.

Friedman, A. L. and Miles, S. (2002), "Developing stakeholder theory", *Journal of management Studies,* vol. 39, no. 1, pp. 1-21.

Fuller, T. (2003), "Small business futures in society", *Futures,* vol. 35, no. 4, pp. 297-304.

Galorath Inc. (2011)*, SEER for Manufacturing*, available at: http://www.galorath.com/index.php/products/manufacturing/C6/ (accessed 28 October 2011).

George, G., Wiklund, J. and Zahra, S. A. (2005), "Ownership and the internationalization of small firms", *Journal of Management,* vol. 31, no. 2, pp. 210-233.

Gibb, A. A. (2000), "SME policy, academic research and the growth of ignorance, mythical concepts, myths, assumptions, rituals and confusions", *International Small Business Journal,* vol. 18, no. 3, pp. 13-35.

Gong, J., Prabhu, V. V. and Liu, W. (2011), "Simulation-based performance comparison between assembly lines and assembly cells with real-time distributed arrival time control system", *International Journal of Production Research,* vol. 49, no. 5, pp. 1241-1253.

Goodstein, J. and Boeker, W. (1991), "Turbulence at the top: A new perspective on governance structure changes and strategic change", *Academy of Management Journal,* vol. 34, no. 2, pp. 306-330.

Goss, D. (1991), *Small business and society,* Routledge London.

Grant, R. M. (1991), *The resource-based theory of competitive advantage: implications for strategy formulation,* California Management Review, University of California.

Gray, D. E. (2009), *Doing Research in the Real World,* 2nd ed, SAGE publications, Cornwall, GB.

Greening, D. W. and Turban, D. B. (2000), "Corporate social performance as a competitive advantage in attracting a quality workforce", *Business & Society,* vol. 39, no. 3, pp. 254-280.

Gupta, K. M. and Gunasekaran, A. (2005), "Costing in new enterprise environment: A challenge for managerial accounting researchers and practitioners", *Managerial Auditing Journal,* vol. 20, no. 4, pp. 337-353.

Hamaker, J. (1995), "Parametric estimating", in Stewart, R. D., Wyskida, R. M. and Johannes, J. D. (eds.) *Cost estimator's reference manual,* 2nd ed, John Wiley & Sons, Inc., USA, pp. 233-265.

Health and Safety Executive (2011a)*, Welfare at work: Guidance for employers on welfare provisions*, available at: http://www.hse.gov.uk/pubns/indg293.pdf (accessed 20/12/2015).

Health and Safety Executive (2011b)*, Workplace health, safety and welfare: A short guide for managers*, available at: http://www.hse.gov.uk/pubns/indg244.pdf (accessed 20/12/2015).

Henrekson, M. and Johansson, D. (1999), "Institutional Effects on the Evolution of the Size Distribution of Firms", *Small Business Economics,* vol. 12, no. 1, pp. 11-23.

Hewitt-Dundas, N. (2006), "Resource and capability constraints to innovation in small and large plants", *Small Business Economics,* vol. 26, no. 3, pp. 257-277.

Hill, C. W. and Snell, S. A. (1988), "External control, corporate strategy, and firm performance in research-intensive industries", *Strategic Management Journal,* vol. 9, no. 6, pp. 577-590.

Hiregoudar, C. and Reddy, B. R. (2007), *Facility planning and layout design,* 1st ed, Technical publications Pune, India.

Hobson, W. K. (1992), *Maynard's industrial engineering handbook,* 4th ed, McGraw-Hill.

Hoskisson, R. E., Eden, L., Lau, C. M. and Wright, M. (2000), "Strategy in emerging economies", *Academy of management journal,* vol. 43, no. 3, pp. 249-267.

Hundal, M. S. (1997), "Product costing: A comparison of conventional and activity-based costing methods", *Journal of Engineering Design,* vol. 8, no. 1, pp. 91-103.

Huse, M. (2000), "Boards of directors in SMEs: A review and research agenda", *Entrepreneurship & Regional Development,* vol. 12, no. 4, pp. 271-290.

Ilkay, M. S. and Aslan, E. (2012), "The effect of the ISO 9001 quality management system on the performance of SMEs", *International Journal of Quality and Reliability Management,* vol. 29, no. 7, pp. 753-778.

International code council (2012), *2012 International Plumbing Code*, available at: http://publicecodes.cyberregs.com/icod/ipc/index.htm (accessed 20/12/2015).

International Organization for Standardization, *ISO 9000 - Quality management*, available at: http://www.iso.org/iso/iso_9000 (accessed 10/2012).

Januszewski, A. (2008), "Activity-based costing system for a small manufacturing company: A case study", *Encyclopedia of Decision Making and Decision Support Technologies,* vol. 2.

Jenkins, H. (2004), "A critique of conventional CSR theory: an SME perspective", *Journal of General Management,* vol. 29, pp. 37-57.

Jinks, S., Scanlan, J., Reed, P. and Wiseall, S. (2010), "Utilising dynamic factory simulation to improve unit cost estimation and aid design decisions", *2010 43rd Winter Simulation Conference, WSC'10,* 5 December 2010 through 8 December 2010, Baltimore, MD, pp. 1758.

Jung, JY. (2002), "Manufacturing cost estimation for machined parts based on manufacturing features", Journal of Intelligent Manufacturing, vol. 13, no. 4, pp. 227-238.

Karana, E., Hekkert, P. and Kandachar, P. (2008), "Material considerations in product design: A survey on crucial material aspects used by product designers", *Materials & Design,* vol. 29, no. 6, pp. 1081-1089.

Kelton, W. D. (2010), *Simulation with Arena,* 5th ed, McGraw-Hill, Boston.

Khan, A. and Day, A. J. (2001), "A knowledge based design methodology for manufacturing assembly lines", *Computers and Industrial Engineering,* vol. 41, no. 4, pp. 441-467.

Khozein, A. and Royaee, R. A. (2011), "Effectiveness Implementing and Lunching the Target Costing System", *International Research Journal of Finance & Economics*, no. 70, pp. 197-204.

Kim, H., Seo, Y. and Hyun, C. (2012), "A hybrid conceptual cost estimating model for large building projects", *Automation in Construction,* vol. 25, no. 0, pp. 72-81.

Kimberly, J. R. and Bouchikhi, H. (1995), "The dynamics of organizational development and change: how the past shapes the present and constrains the future", *Organization Science,* vol. 6, no. 1, pp. 9-18.

Korpi, E. and Ala-Risku, T. (2008), "Life cycle costing: A review of published case studies", *Managerial Auditing Journal,* vol. 23, no. 3, pp. 240-261.

Kramer, T., Klimpke, L. and Heinzl, A. (2013), "Outsourcing decisions of small and medium-sized enterprises: A multiple-case study approach in the German software industry", *46th Annual Hawaii International Conference on System Sciences, HICSS 2013,* 7 January 2013 through 10 January 2013, Wailea, Maui, HI, pp. 4236.

Krarup, J. and Pruzan, P. M. (1983), "The simple plant location problem: Survey and synthesis", *European Journal of Operational Research,* vol. 12, no. 1, pp. 36-81.

Kumar, A., Antony, J. and Dhakar, T. S. (2006), "Integrating quality function deployment and benchmarking to achieve greater profitability", *Benchmarking,* vol. 13, no. 3, pp. 290-310.

Landström, H. (1990), "Co-operation between venture capital companies and small firms", *Entrepreneurship & Regional Development,* vol. 2, no. 4, pp. 345.

Law, A. (2000), *Simulation modeling and analysis,* 3rd ed, McGraw-Hill, New York.

Lee, H., Lee, S. and Park, Y. (2009), "Selection of technology acquisition mode using the analytic network process", *Mathematical and Computer Modelling,* vol. 49, no. 5-6, pp. 1274-1282.

Li, L. and Qian, G. (2007), "Partnership or self-reliance: prescriptions for small and medium-sized enterprises", *Journal of business strategy,* vol. 28, no. 6, pp. 29-33.

Li, H., Shen, Q. P. and Love, P. E. D. (2005), "Cost modelling of office buildings in Hong Kong: An exploratory study", *Facilities,* vol. 23, no. 9-10, pp. 438-452.

Liao, Y., Liao, K. and Hutchinson, R. (2010), "A conceptual framework for prototyping outsourcing in new product development: A knowledge-based view", *Journal of Manufacturing Technology Management,* vol. 21, no. 1, pp. 122-138.

Madan, J., Rao, P. V. M. and Kundra, T. K. (2007), "System for early cost estimation of die-cast parts", *International Journal of Production Research,* vol. 45, no. 20, pp. 4823-4847.

Markt, P. L. and Mayer, M. H. (1997), "WITNESS simulation software a flexible suite of simulation tools", Andradottir S., Healy K.J., Withers D.H., et al (eds.), in: *Proceedings of the 1997 Winter Simulation Conference,* 7

December 1997 through 10 December 1997, Atlanta, GA, USA, IEEE, Piscataway, NJ, United States, pp. 711.

Mayer, R. J., Menzel, C. P., Painter, M. K., deWitte, P. S., Blinn, T. and Perakath, B. (2010)*, Information integration for concurrent engineering (iice) idef3 process description capture method report*, available at: http://www.idef.com/pdf/Idef3_fn.pdf (accessed 24th October 2011).

McIvor, R. (2005), *The outsourcing process: strategies for evaluation and management,* Cambridge University Press, Cambridge.

McLaney, E. J. and Atrill, P. (2012), *Accounting: an introduction,* 6th ed, Pearson, Harlow, England; New York.

Melo, M. T., Nickel, S. and Saldanha-da-Gama, F. (2009), "Facility location and supply chain management – A review", *European Journal of Operational Research,* vol. 196, no. 2, pp. 401-412.

Meyers, F. E. and Stephens, M. P. (2005), *Manufacturing facilities design and material handling,* Pearson, New Jersey.

Michaels, J. V. and Wood, W. P. (1989), *Design to cost,* John Wiley & Sons.

Milton Keynes Council (2015)*, Parking standards*, available at: http://www.milton-keynes.gov.uk/assets/attach/29608/Consultation%20summary%20doc%20and%20question.pdf (accessed 20/12/2015).

Minh, N. D. (2011), "Empirical make-or-buy decision making model in the Japanese automobile industry", *2011 Winter Simulation Conference, WSC 2011,* 11 December 2011 through 14 December 2011, Phoenix, AZ, pp. 647.

Moradi, E. and Bidkhori, M. (2009), "Single facility location problem", in Zanjirani Farahani, R. and Hekmatfar, M. (eds.) *Facility location: concepts, models, algorithms and case studies,* Physica, Heidelberg, pp. 37-68.

Moses, A. (2011), "Cross-functional make or buy decision process ownership", *Management Research Review,* vol. 34, no. 9, pp. 1042-1060.

MRT castings ltd (2018), *Aluminium Casting Alloy LM16*, available at: https://www.mrt-castings.co.uk/design_lm16.html (accessed September 2018).

Muller, P., Caliandro, C., Peycheva, V., Gagliardi, D., Marzocchi, C., Ramlogan, R. and Cox, D. (2015), *Annual Report on European SMEs - 2014 / 2015 - SMEs start hiring again*, European Commission, European Union.

Mustakallio, M., Autio, E. and Zahra, S. A. (2002), "Relational and contractual governance in family firms: Effects on strategic decision making", *Family Business Review,* vol. 15, no. 3, pp. 205-222.

Myint, S. and Tabucanon, M. T. (1994), "A multiple-criteria approach to machine selection for flexible manufacturing systems", *International Journal of Production Economics,* vol. 33, no. 1–3, pp. 121-131.

NASA (2010)*, 2008 NASA cost estimating handbook*, available at: http://ceh.nasa.gov/ceh_2008/2008.htm (accessed 01/2012).

Needy, K. L., Nachtmann, H., Roztocki, N., Warner, R. C. and Bidanda, B. (2003), "Implementing activity-based costing systems in small manufacturing firms: A field study", *Engineering Management Journal,* vol. 15, no. 1, pp. 3-10.

Niazi, A., Dai, J. S., Balabani, S. and Seneviratne, L. (2006), "Product cost estimation: Technique classification and methodology review", *Journal of Manufacturing Science and Engineering, Transactions of the ASME,* vol. 128, no. 2, pp. 563-575.

Nordgren, W. B. (2003), "Flexsim simulation environment", Chick S.E., Sanchez P.J., Ferrin D., et al (eds.), in: *Proceedings of the 2003 Winter Simulation Conference: Driving Innovation,* Vol. 1, 7 December 2003 through 10 December 2003, New Orleans, LA, pp. 197.

Nordqvist, M. and Melin, L. (2002), "6 The dynamics of family firms", *Understanding the small family business,* vol. 8, pp. 94.

Ou-Yang, C. and Lin, T. S. (1997), "Developing an integrated framework for feature-based early manufacturing cost estimation", *International Journal of Advanced Manufacturing Technology,* vol. 13, no. 9, pp. 618-629.

Parry, G., James-Moore, M. and Graves, A. (2006), "Outsourcing engineering commodity procurement", *Supply Chain Management,* vol. 11, no. 5, pp. 436-443.

Petley, G. and Edwards, D. (1995), "Further developments in chemical plant cost estimating using fuzzy matching", *Computers & Chemical Engineering,* vol. 19, pp. 675-680.

Pham, D. T. and Ji, C. (1999), "A concurrent design system for machined parts", *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* vol. 213, no. 8, pp. 841-846.

Piasecki, D. (2013)*, Lift Truck Basics*, available at: http://www.inventoryops.com/lift_truck_basics.htm (accessed 20/12/2015).

Platts, K. W., Probert, D. R. and Cáez, L. (2002), "Make vs. buy decisions: A process incorporating multi-attribute decision-making", *International Journal of Production Economics,* vol. 77, no. 3, pp. 247-257.

Pratt, D. J. (2011), *Fundamentals of construction estimating,* 3rd ed, Wadsworth Cengage Learning, Boston, MA.

Probert, D. (1997), *Developing a Make or Buy: Strategy for Manufacturing Business,* IET.

Qian, L. and Ben-Arieh, D. (2008), "Parametric cost estimation based on activity-based costing: A case study for design and development of rotational parts", *International Journal of Production Economics,* vol. 113, no. 2, pp. 805-818.

Quinn, J. B. and Hilmer, F. G. (1994), "Strategic Outsourcing", *MIT Sloan Management Review,* vol. 35, no. 4, pp. 43-55.

Rekiek, B. and Delchambre, A. (2006), *Assembly line design*, Springer, London.

Rhodes, C. (2017), *Briefing paper - Business statistics,* 06152, House of commons library, UK.

Roberts, S., Lawson, R. and Nicholls, J. (2006), "Generating regional-scale improvements in SME corporate responsibility performance: Lessons from responsibility Northwest", *Journal of Business Ethics,* vol. 67, no. 3, pp. 275-286.

Robertson, M., Swan, J. and Newell, S. (1996), "The role of networks in the diffusion of technological innovation", *Journal of Management Studies,* vol. 33, no. 3, pp. 333-359.

Robson, C. (2011), *Real world research: a resource for users of social research methods in applied settings,* 3rd ed, Wiley, Chichester, West Sussex.

Roper, S. and Hewitt-Dundas, N. (2001), "Grant assistance and small firm development in Northern Ireland and the Republic of Ireland", *Scottish Journal of Political Economy,* vol. 48, no. 1, pp. 99-117.

Rothwell, R. (1985), *Reindustrialization and technology,* Longman, London.

Roy, R. and Sackett, P. (2003), *Cost engineering: The practice and the future,* Computer and Automated Systems Association of the Society of Manufacturing Engineers.

Roy, R. (ed.). (2001), *Industrial knowledge management: a micro-level approach,* Springer, London.

Roy, R., Colmer, S. and Griggs, T. (2005), "Estimating the cost of a new technology intensive automotive product: A case study approach", *International Journal of Production Economics,* vol. 97, no. 2, pp. 210-226.

Roy, R., Souchoroukov, P. and Shehab, E. (2011), "Detailed cost estimating in the automotive industry: Data and information requirements", *International Journal of Production Economics,* vol. 133, no. 2, pp. 694-707.

Roztocki, N., Porter, J. D., Thomas, R. M. and Needy, K. L. (2004), "A procedure for smooth implementation of activity-based costing in small companies", *Engineering Management Journal,* vol. 16, no. 4, pp. 19-27.

Sarkandi, M., Baguley, P. and Tiwari, A. (2013), "Analysis of the “Make Or Buy” Decision Process in a Research and Development SME", Shehab, E., Ball, P. and Tjahjono, B. (eds.), in: *Proceedings of the 11th International Conference on Manufacturing Research*, 19th - 20th September 2013, Cranfield University, UK, Cranfield University Press, UK, pp. 473.

Sarkandi, M., Baguley, P. and Tiwari, A. (2012), "Factory set-up cost estimation tool for SMEs", Baines, T. S., Clegg, B. T. and Harrison, D. K. (eds.), in: *Proceedings of the 10th International Conference on Manufacturing Research (ICMR2012)*, Vol. 1, 11th – 13th September 2012, Aston Business School, UK, Aston Business School, pp. 285.

Satty, T. L. (1996), *Decision making with dependence and feedback: The analytic network process* (Vol. 4922). RWS Publication.

Schenk, M., Wirth, S., and Muller, E., (2010), *Factory planning manual*, Springer, Berlin; London.

Selvaraj, P., Radhakrishnan, P. and Adithan, M. (2009), "An integrated approach to design for manufacturing and assembly based on reduction of product development time and cost", *International Journal of Advanced Manufacturing Technology,* vol. 42, no. 1-2, pp. 13-29.

Sengupta, K. and Jacobs, F. R. (2004), "Impact of work teams: A comparison study of assembly cells and assembly line for a variety of operating environments", *International Journal of Production Research,* vol. 42, no. 19, pp. 4173-4193.

Sharma, J. R., Sharma, D. K. and Rawani, A. M. (2006), "Quality driven product development", *Manufacturing Engineer,* vol. 85, no. 3, pp. 38-41.

Shehab, E. M. and Abdalla, H. S. (2001), "An integrated prototype system for cost-effective design", *Concurrent Engineering Research and Applications,* vol. 9, no. 4, pp. 243-256.

Shepperd, M. and Schofield, C. (1997), "Estimating software project effort using analogies", *IEEE Transactions on Software Engineering,* vol. 23, no. 11, pp. 736-743.

Shingō, S. (1985), *A revolution in manufacturing: the SMED system,* Productivity Press, London.

Shtub, A. and Dar-El, E. (1989), "A methodology for the selection of assembly systems", *THE INTERNATIONAL JOURNAL OF PRODUCTION RESEARCH,* vol. 27, no. 1, pp. 175-186.

Slack, N., Chambers, S. and Johnston, R. (2007), *Operations management,* 5th ed, Financial Times, Prentice Hall, Harlow, Essex.

Sledgianowski, D., Tafti, M. H. A. and Kierstead, J. (2008), "SME ERP system sourcing strategies: A case study", *Industrial Management and Data Systems,* vol. 108, no. 4, pp. 421-436.

Soares, C. (2007), *Microturbines: applications for distributed energy systems,* Butterworth-Heinemann, Oxford.

Steckler, A., McLeroy, K. R., Goodman, R. M., Bird, S. T. and McCormick, L. (1992), "Toward integrating qualitative and quantitative methods: an introduction", *Health education quarterly,* vol. 19, no. 1, pp. 1-8.

Stevenson, W. (2009), *Operations management,* 10th ed, McGraw-Hill Irwin, Boston.

Stewart, R. D. (1995), "Fundamentals of cost estimating", in Stewart, R. D., Wyskida, R. M. and Johannes, J. D. (eds.) *Cost estimator's reference manual,* 2nd ed, John Wiley & Sons, Inc., USA, pp. 1-40.

Storey, D. J. (1994), *Understanding the small business sector*.

Swift, K. G. and Booker, J. D. (2013), *Manufacturing process selection handbook,* Butterworth-Heinemann.

Swift, K. G., Booker, J. D. and Edmondson, N. F. (2004), "Strategies and case studies in assembly system selection", *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* vol. 218, no. 7, pp. 675-688.

Tansel, B. C., Francis, R. L. and Lowe, T. J. (1983), "Location on Networks: A Survey. Part II: Exploiting Tree Network Structure", *Management Science*, pp. 498-511.

Tayles, M. and Drury, C. (2001), "Moving from make/buy to strategic sourcing: The outsource decision process", *Long range planning,* vol. 34, no. 5, pp. 605-622.

Tushman, M. L., Virany, B. and Romanelli, E. (1985), "Executive succession, strategic reorientations, and organization evolution: The minicomputer industry as a case in point", *Technology in Society,* vol. 7, no. 2, pp. 297-313.

United States. Government Accountability Office, Richey, K., Echard, J. and Cha, C. (ed.). (2009), *GAO cost estimating and assessment guide: best practices for developing and managing capital program costs,* United States Govt. Accountability Office, Washington, DC.

Value-Driven Design Institute*, Value-Driven Design*, available at: http://www.vddi.org/vdd-home.htm (accessed 10/2012).

van Dam, F. and Pruijsen, G. (2008), *Target costing and value analysis,* van Dam Orenda, Borne, Netherlands.

van Echtelt, F. E. A., Wynstra, F., van Weele, A. J. and Duysters, G. (2008), "Managing supplier involvement in new product development: A multiple-case study", *Journal of Product Innovation Management,* vol. 25, no. 2, pp. 180-201.

Wallace, T. (2008), "Cycles of production: From assembly lines to cells to assembly lines in the Volvo Cab Plant", *New Technology, Work and Employment,* vol. 23, no. 1-2, pp. 111-124.

Wang, E. -., Su, T. -., Tsai, D. -. and Lin, C. -. (2013), "Fuzzy multiple-goal programming for analysing outsourcing cost-effectiveness in hi-tech manufacturing", *International Journal of Production Research,* vol. 51, no. 13, pp. 3920-3944.

Wang, Q., Owen, G. W. and Mileham, A. R. (2007), "Determining numbers of workstations and operators for a linear walking-worker assembly line", *International Journal of Computer Integrated Manufacturing,* vol. 20, no. 1, pp. 1-10.

Ward, J. L. (1991), *Creating effective boards for private enterprises: Meeting the challenges of continuity and competition,* Jossey-Bass.

Webb, A. (1993a), "Value engineering. I", *Engineering Management Journal,* vol. 3, no. 4, pp. 171-175.

Webb, A. (1993b), "Value engineering. II", *Engineering Management Journal,* vol. 3, no. 5, pp. 231-235.

Weil, R. L. and Maher, M. W. (2005), *Handbook of cost management,* 2nd ed, Wiley, Hoboken, N.J.

Weng, W. and Fang, D. (2011), "Cost-based Plant Location Decision Model from the View of Entire Supply Chain", *Energy Procedia,* vol. 13, no. 0, pp. 9859-9865.

Wild, R. (1975), "On the selection of mass production systems.", *International Journal of Production Research,* vol. 13, no. 5, pp. 443-461.

Wilkinson, N. (2005), *Managerial economics: a problem-solving approach,* Cambridge University Press, Cambridge.

Williamson, O. E. (1975), *Markets and hierarchies: analysis and antitrust implications: a study in the economics of internal organization,* Free Press; Collier Macmillan, New York.

Williamson, O. E. (1985), *The economic institutions of capitalism,* Simon and Schuster.

Yamada, T., Satomi, K. and Matsui, M. (2006), "Strategic selection of assembly systems under viable demands", *Assembly Automation,* vol. 26, no. 4, pp. 335-342.

Yaman, R. (2008), "An assembly line design and construction for a small manufacturing company", *Assembly Automation,* vol. 28, no. 2, pp. 163-172.

Yang, C. L., Chuang, S. P., Huang, R. H. and Tai, C. C. (2008), "Location selection based on AHP/ANP approach", *2008 IEEE International Conference on Industrial Engineering and Engineering Management, IEEM 2008,* 8 December 2008 through 11 December 2008, Singapore, pp. 1148.

Yang, Q. Z., Ng, R. S. and Song, B. (2008), "A production economics model for predictive cost assessment in manufacturing", *2008 IEEE International Conference on Industrial Engineering and Engineering Management, IEEM 2008,* 8 December 2008 through 11 December 2008, Singapore, pp. 292.

Zanjirani Farahani, R. and Hekmatfar, M. (2009), "Facility location: concepts, models, algorithms and case studies", in Zanjirani Farahani, R. and Hekmatfar, M. (eds.) *Contributions to management science,* Physica, Heidelberg, pp. 1-4.

Zarinbal, M. (2009), "Distance functions in location problems", in Zanjirani Farahani, R. and Hekmatfar, M. (eds.) *Facility location: concepts, models, algorithms and case studies,* Physica, Heidelberg, pp. 5-17.

Zengin, Y. and Ada, E. (2010), "Cost management through product design: Target costing approach", *International Journal of Production Research,* vol. 48, no. 19, pp. 5593-5611.

Zenz, G. J. (1994), *Purchasing and the management of materials,* 7th ed, Wiley, New York; Chichester.

Zha, X. F., Lim, S. Y. E. and Fok, S. C. (1998), "Integrated intelligent design and assembly planning: A survey", *International Journal of Advanced Manufacturing Technology,* vol. 14, no. 9, pp. 664-685.

Appendix A - Figures

A.1 IDEF0 function modelling diagram

In this section, all the diagrams prepared using IDEF0 function modelling method are shown.

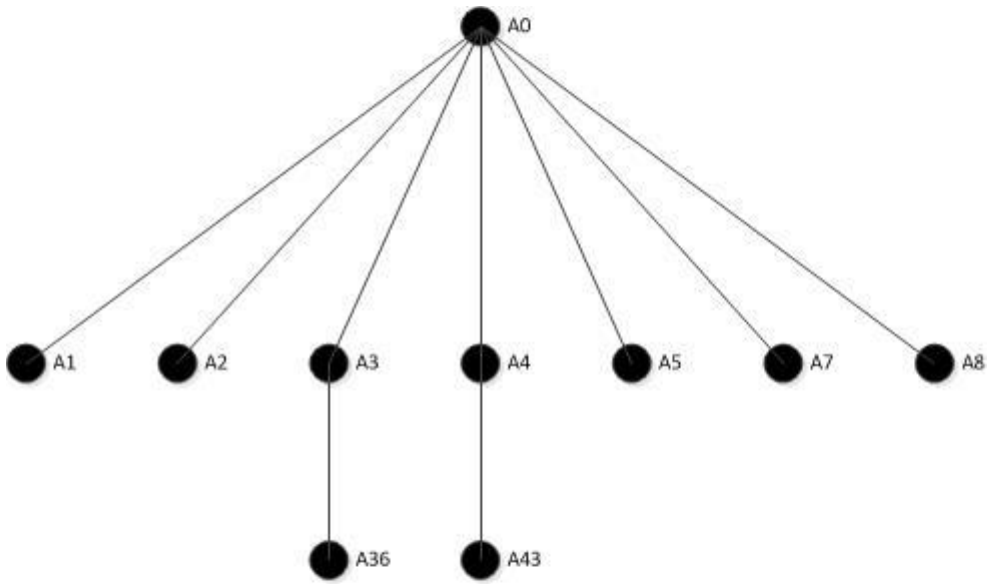

Figure A-1 - Node tree for IDEF0 diagram

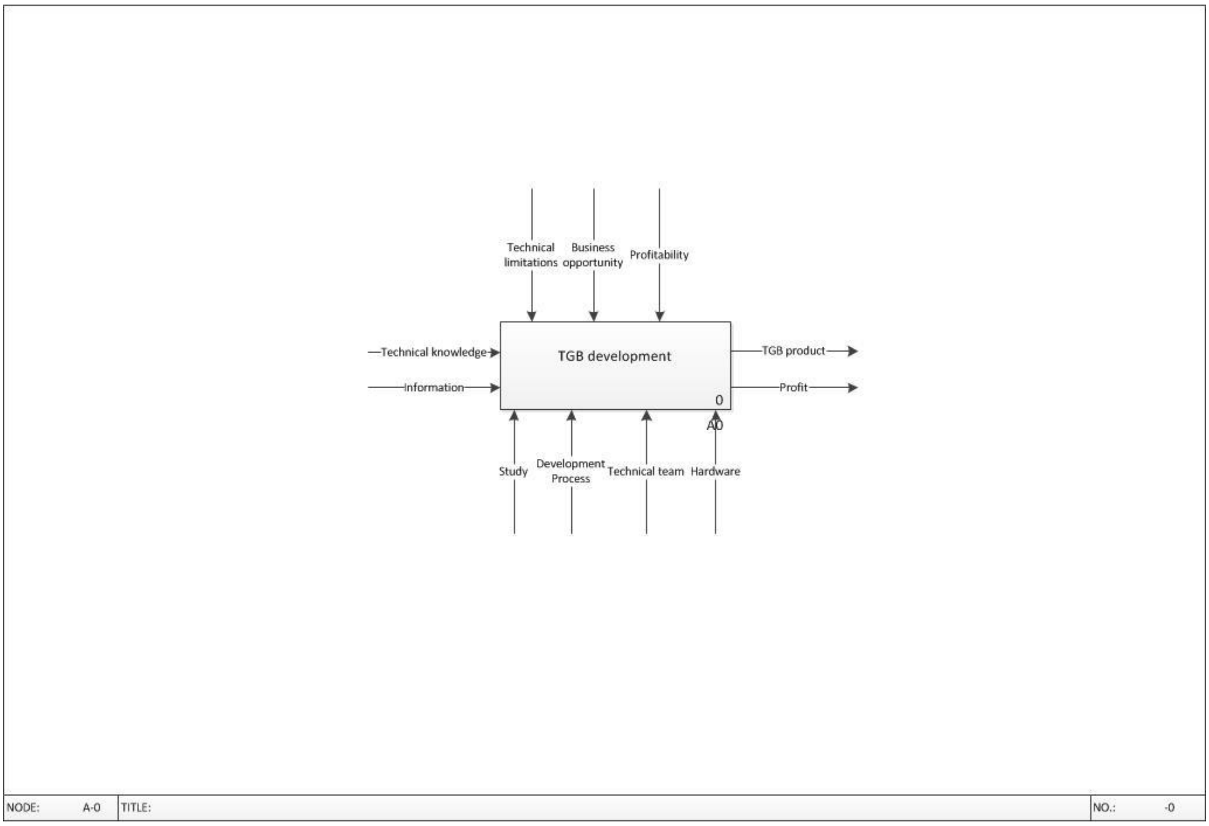

Figure A-2 First level IDEF0 diagram developed based on a product development function

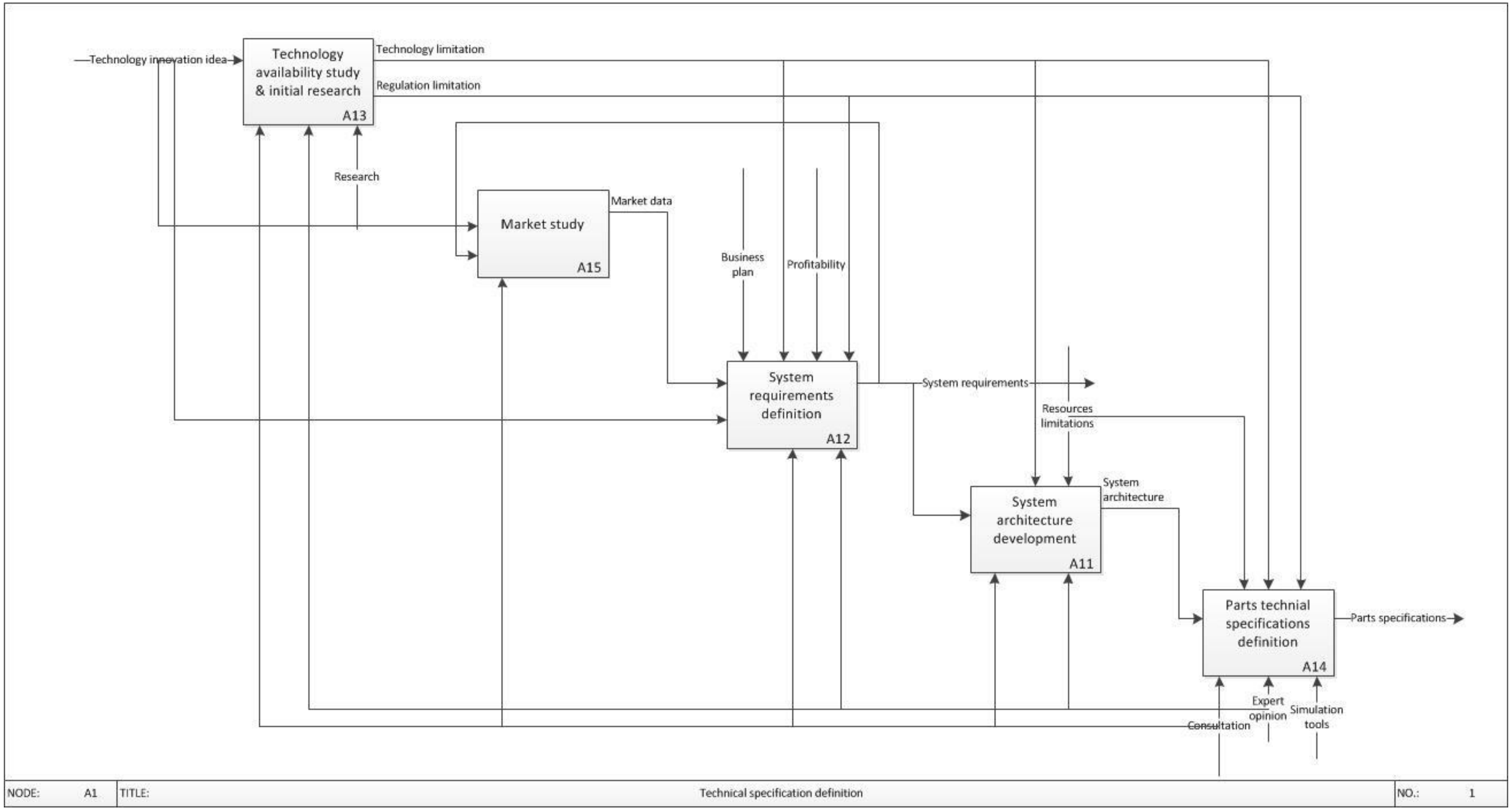

Figure A-3 A second level IDEF0 diagram based on a product development function

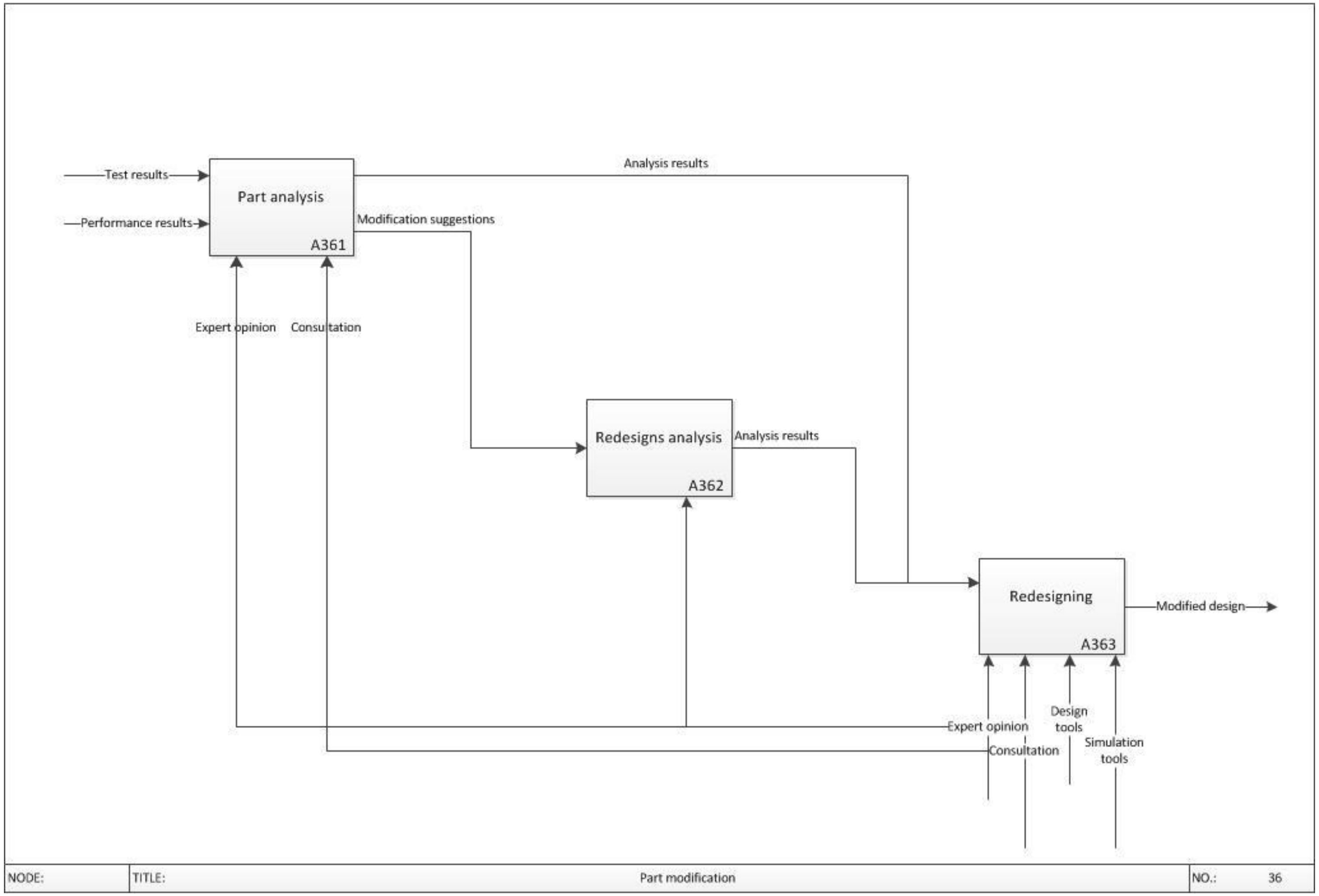

Figure A-4 A third level IDEF0 diagram based on a product development function

A.2 Process identification

Samad's Make or buy process identification:

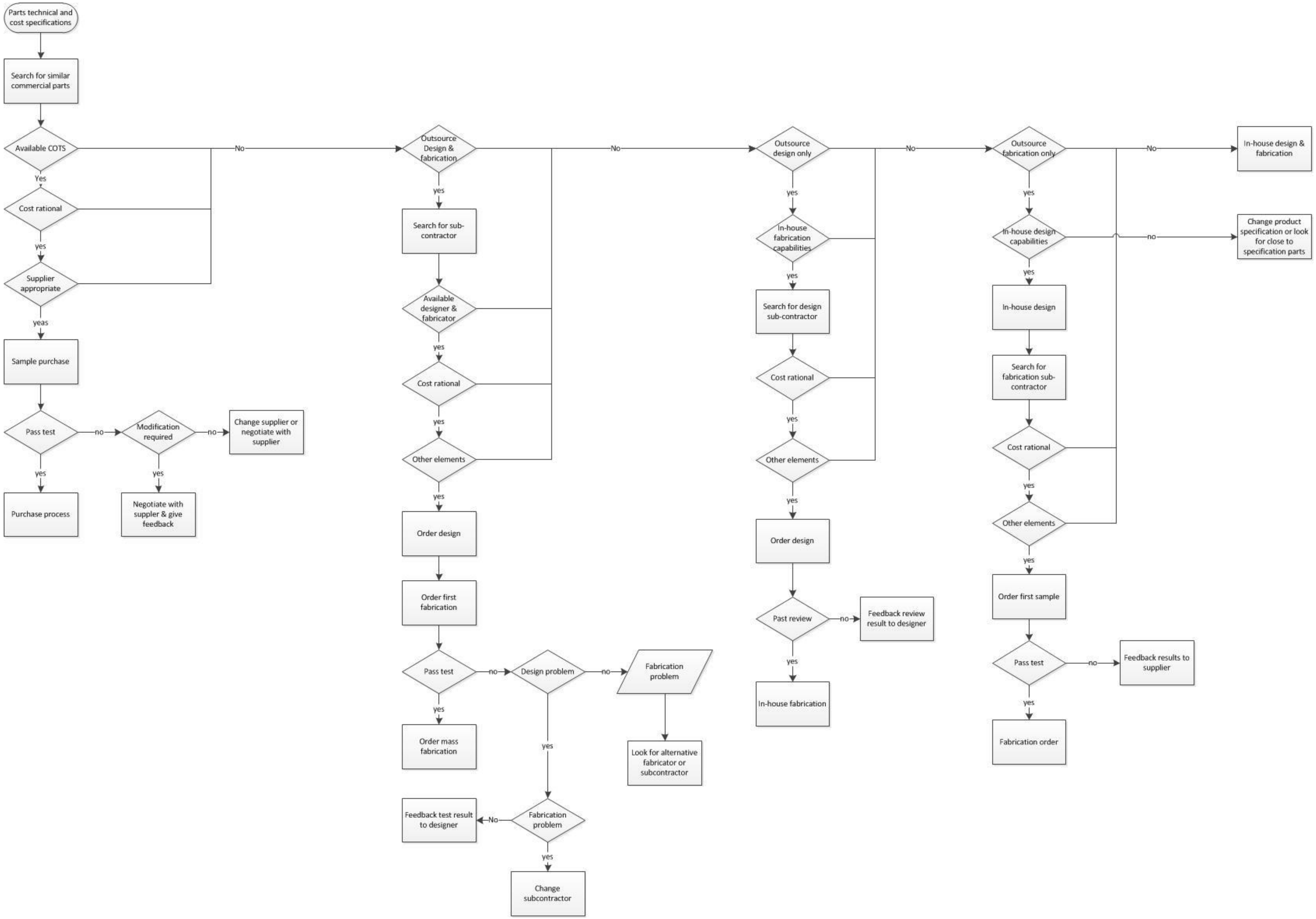

Figure A-5 Identified 'Make or buy' process at the collaborating company

Appendix B – Method development mind maps

In this section the mind maps developed for the purpose of identifying topics related to each framework title are shown.

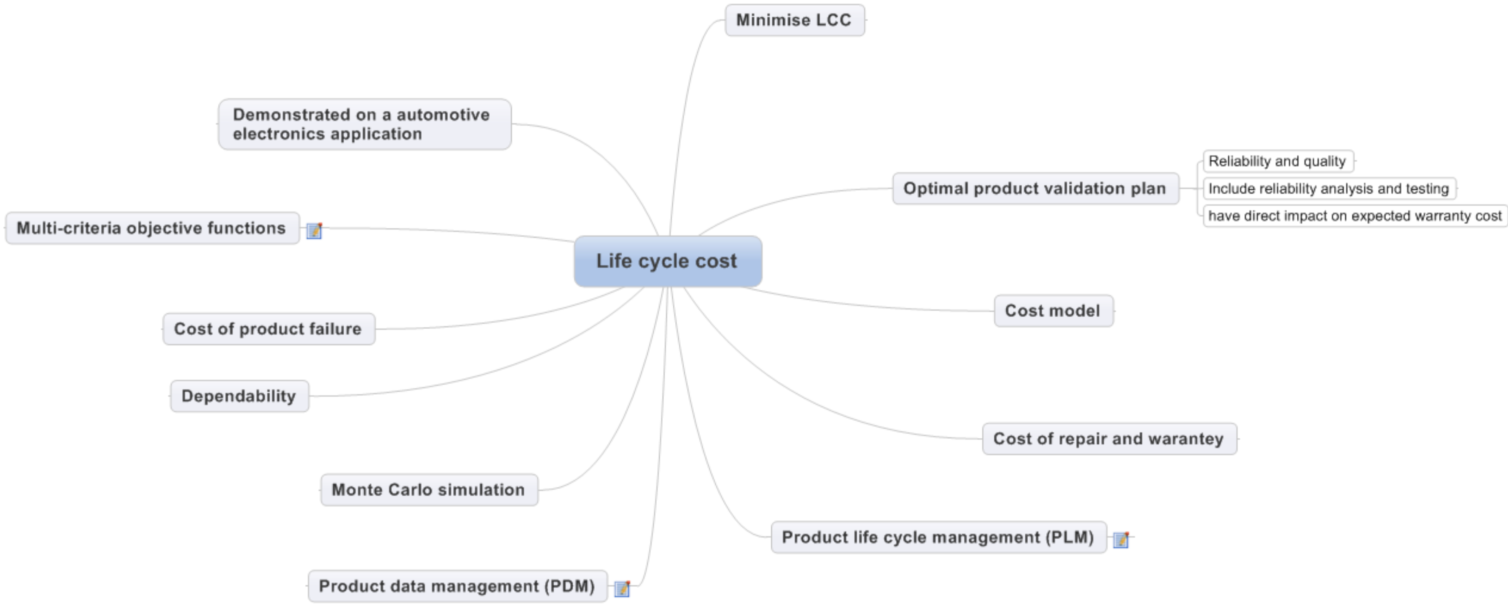

Figure A-6 Mind map developed for identifying the area of Life cycle costing

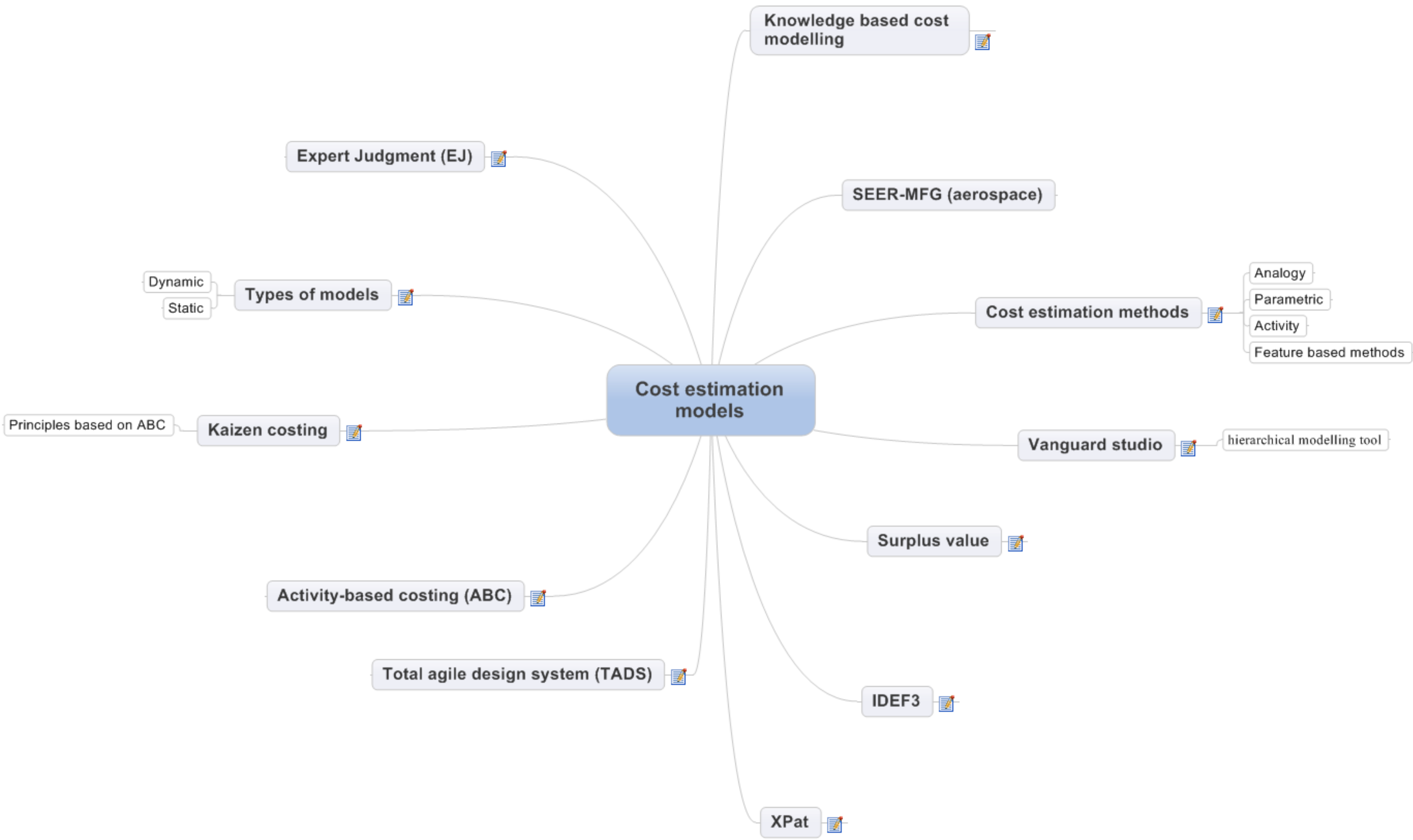

Figure A-7 Mind map developed for exploring the area of Cost estimation models

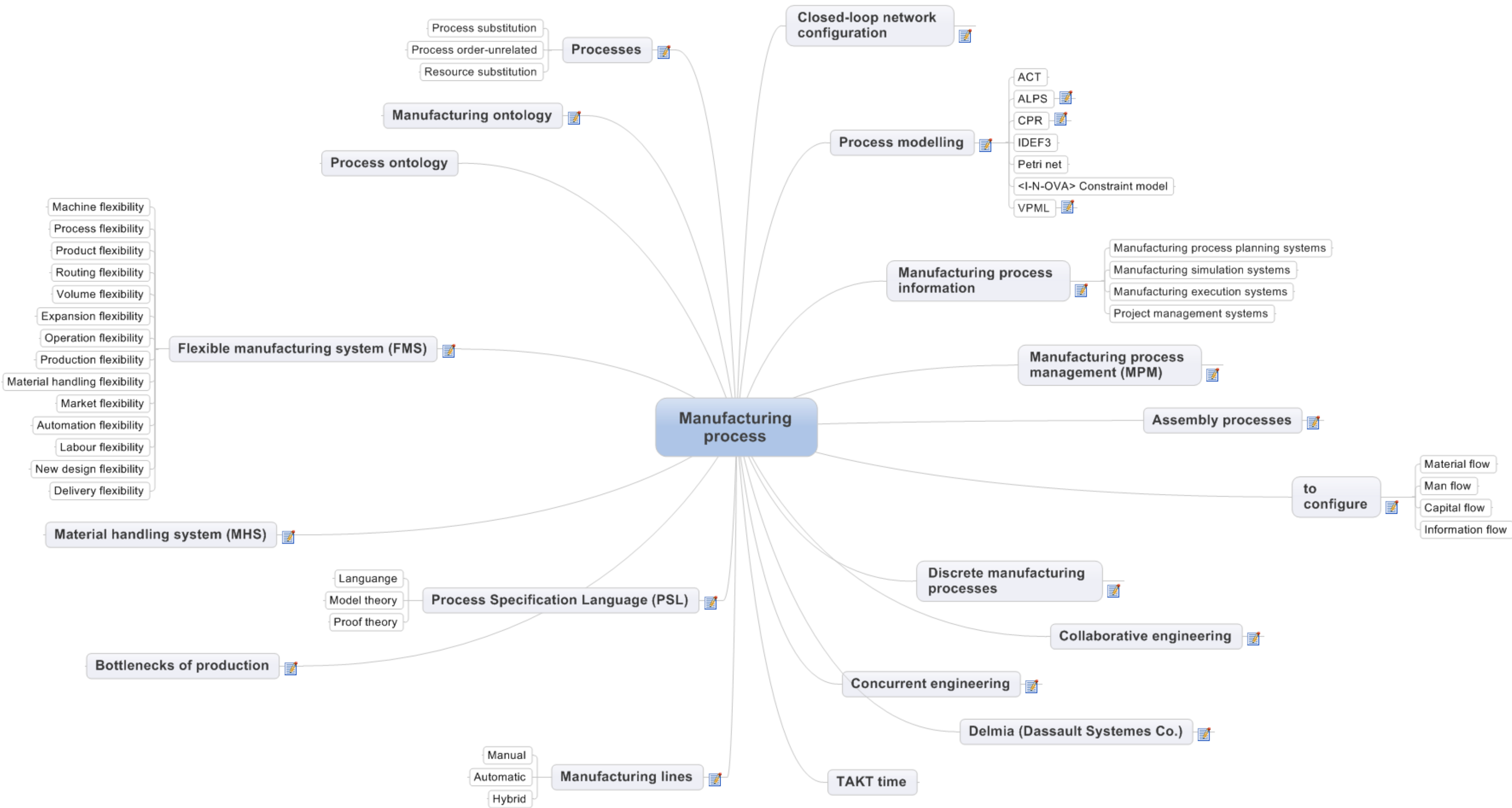

Figure A-8 Mind map developed for exploring the area of Manufacturing processes

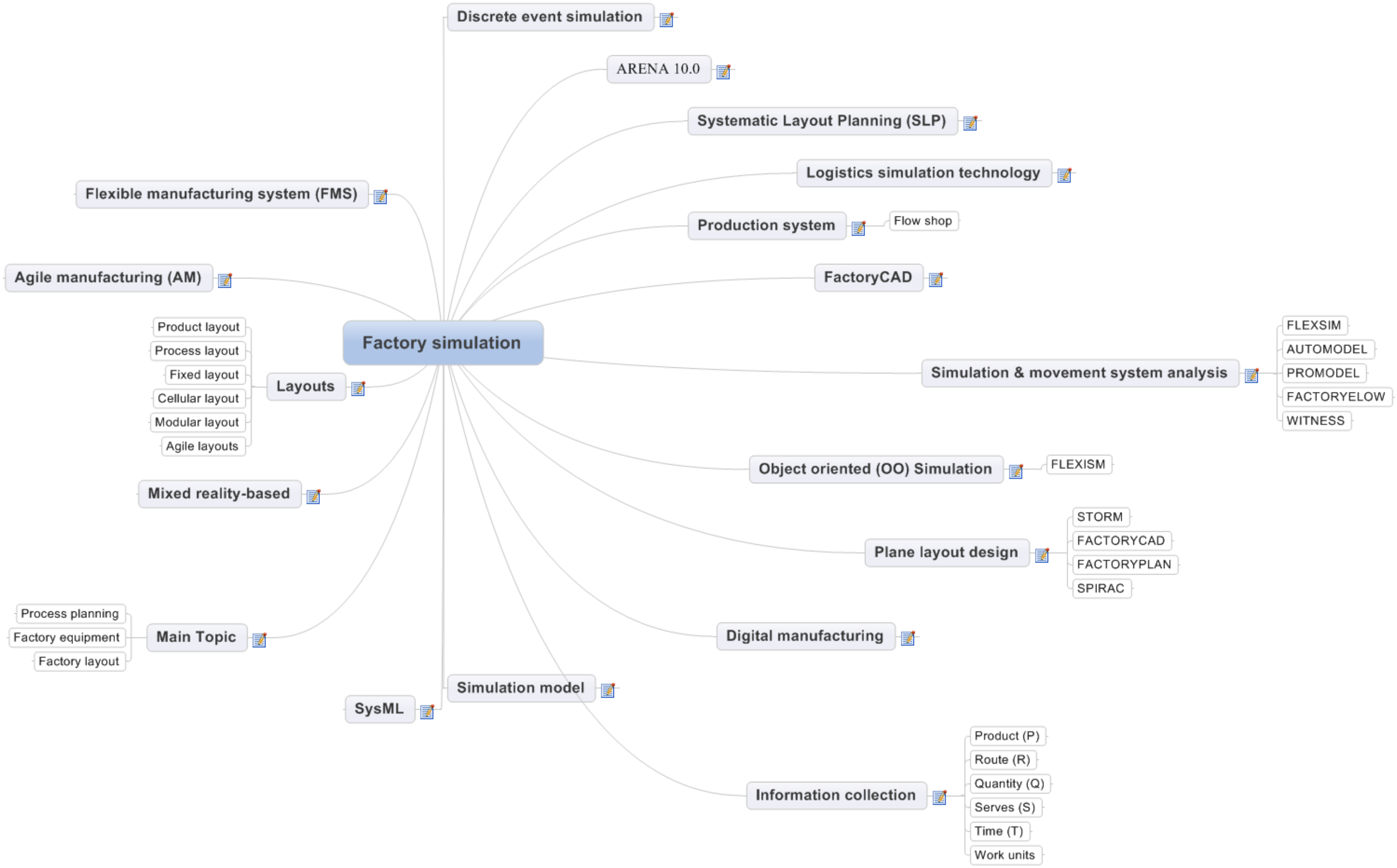

Figure A-9 Mind map developed for exploring the area of Factory simulation

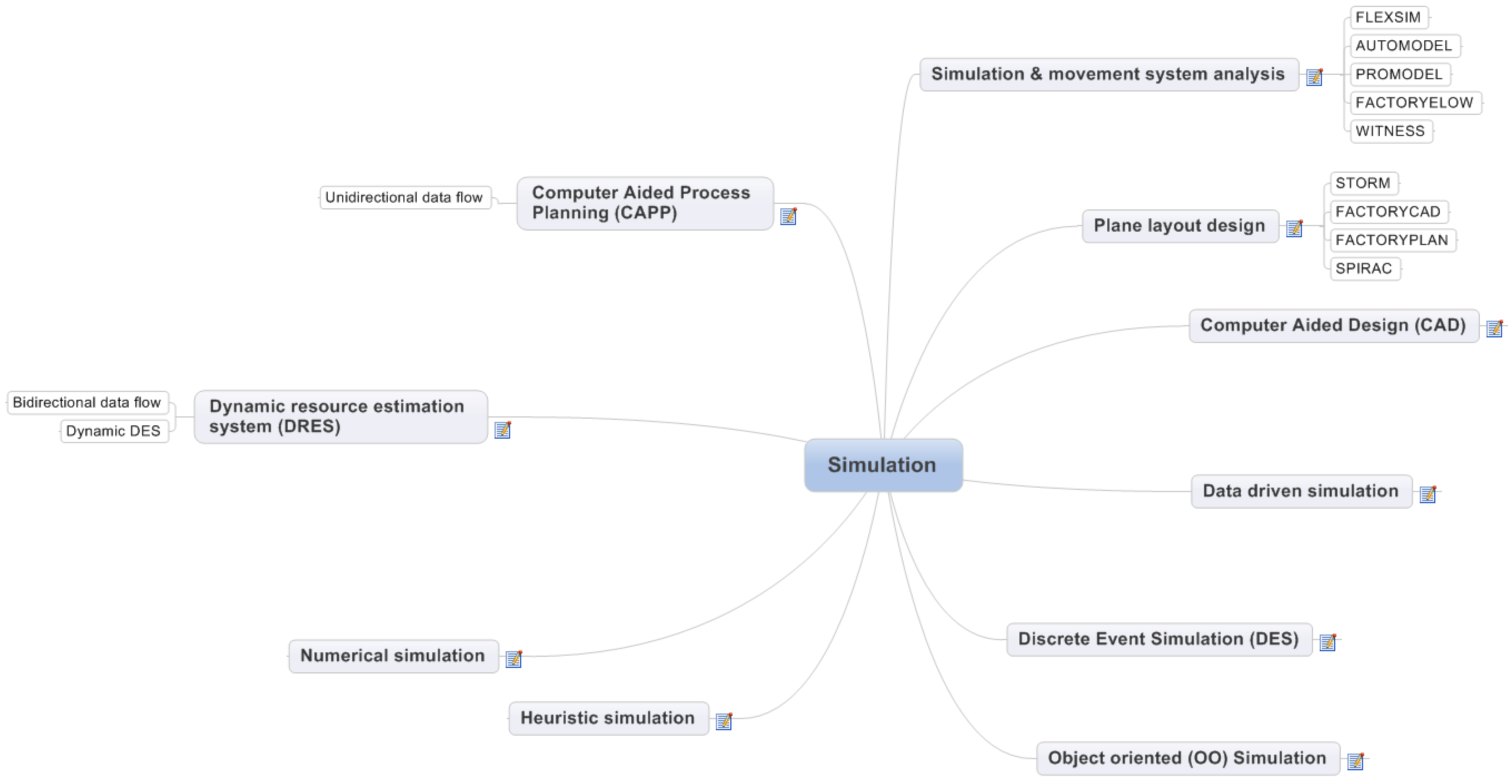

Figure A-10 Mind map developed for exploring the area of Simulation methods

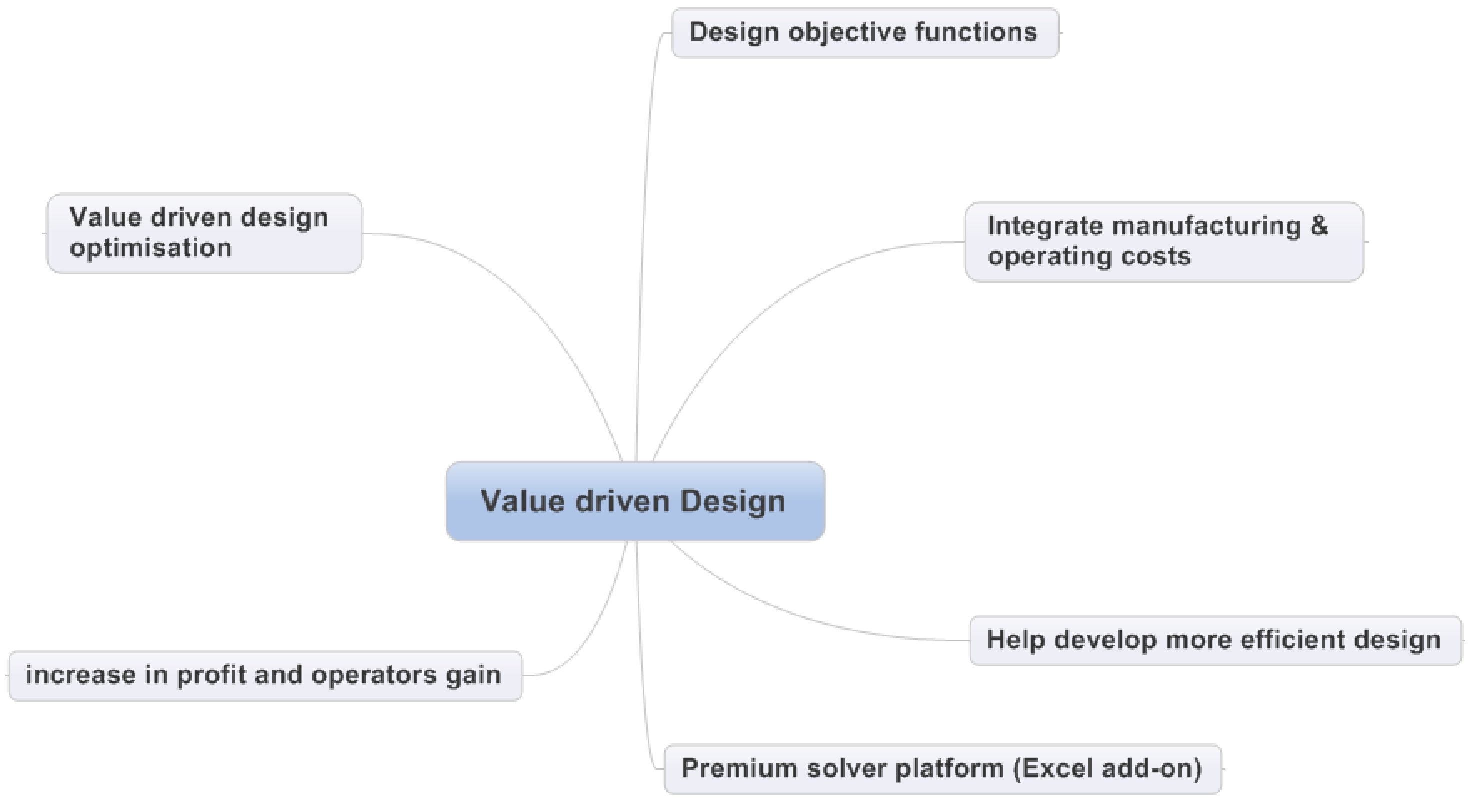

Figure A-11 Mind map developed for exploring the area of Value driven design

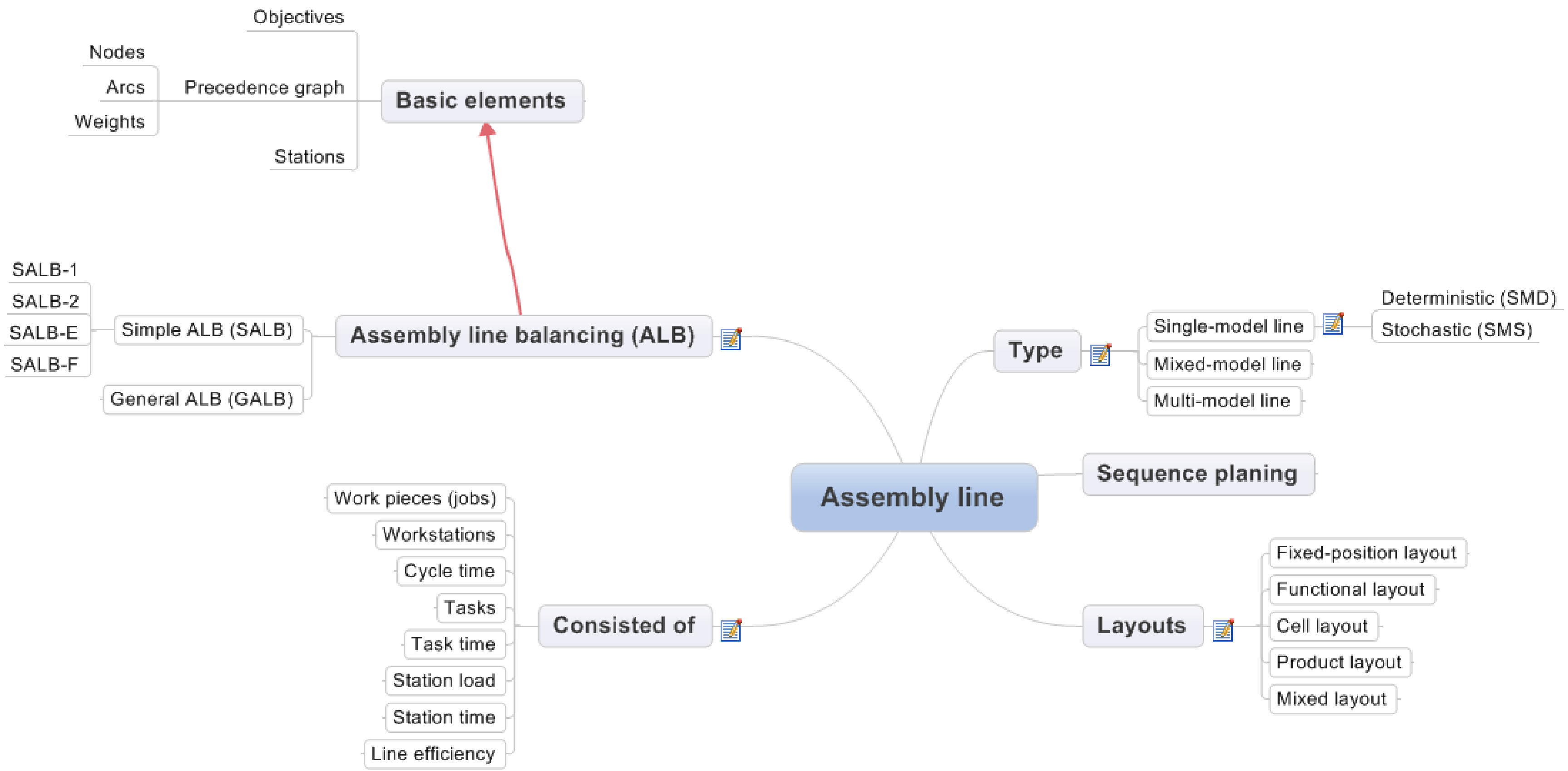

Figure A-12 Mind map developed for exploring the area of Assembly line

Appendix C - Workshop reports

In this section a report written as a result of holding several sessions of VE & DFMA workshops with the collaborating company is presented.

C.1 VE & DFMA workshops report

One the main Objectives of the project is to study cost reduction methods and Implement the best cost reduction techniques to reduce costs and add value to the product. In order to do this task, workshops with company should be done. Until this stage of the project two workshops where done with collaborating company. In this section a short report of the workshops and the results are presented. These results are the first deliverables of this project.

The first workshop was done on 1st October at QUBIC and the attendees were the researcher, the CE of the collaborating company and the supervisor.

The subject of this workshop was introduction to value engineering and DFMA In the meeting a presentation about VE and Cost analysis was facilitated by the supervisor.

And the rest of the meeting was consisted of talks and discussion about implementing cost reduction methods to the product. In the meeting it was decided that for start, function analysis was to be done which is the basic for Value analysis.

After the meeting work on function analysis started. In order to identify the functions of the system, a list of all parts of the system where obtained from collaborating company. Secondly the function of each part was listed in a table.

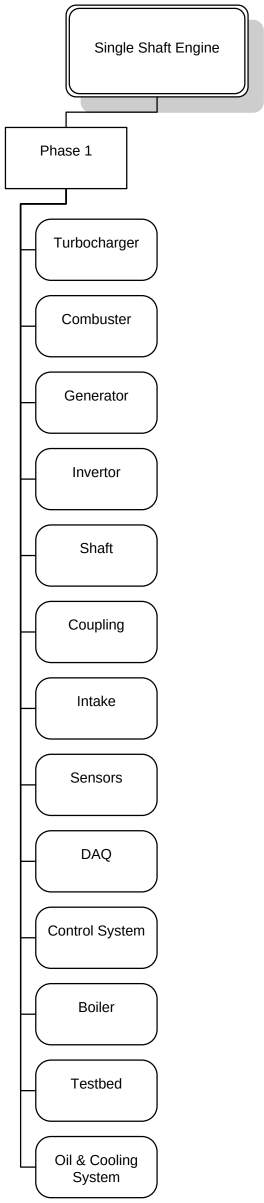

Figure 1 - TGB parts list

The next step was to construct a FAST (function analysis system technique) diagram. In order to do so, the method explained in the (Bytheway, 2007) was used.

Parts	Functions
Turbine	Convert energy
Compressor	Compress air
Generator	Convert energy
Invertor	Convert electrical current
Shaft	Transmit torque
Coupling	Transmit torque
Intake	Generate uniform air stream
Sensors	Sense properties
Control system	Control the system
Boiler	Heat water
Oil system	Lubricate surfaces
Mounting and testbed	Hold system
Starter	Produce rotational power
TGB	Generate heat
TGB	Generate electricity

Table 1 - Part functions

The functions should be formatted as Verb + Noun.

By following the method mentioned in the book, the following result is reached.

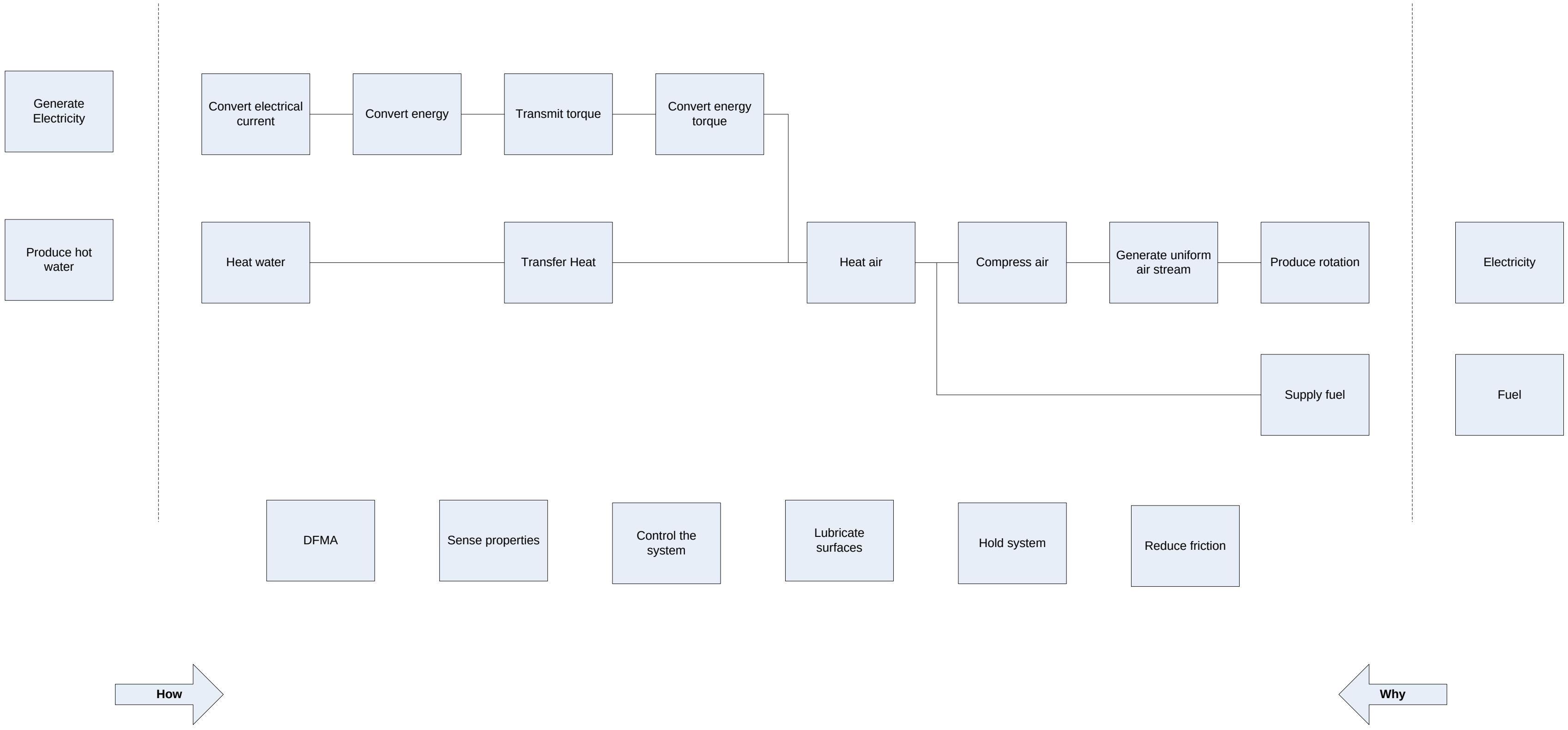

Table 2 - FAST diagram

To check the diagram and see if it’s correct, the question how should be asked by starting from left, for example, we have to ask, how to heat water? The answer is by heat transfer which is a correct answer. By transferring heat to water, the water’s temperature increases. And also this process has to be repeated from right to left, but this time with asking why.

For example, we should ask, why to transfer heat? And the answer is to heat water.

The second workshop was done on 27th of September 2011 and the venue was Cost studio in building 50. The attendees were CEO of the collaborating company, the supervisor and the researcher. In the start presentation of my three month work was done by me. And next, a presentation on SEERF-MFG and cost engineering was done by the supervisor and after that, a group task was done on DFMA.

In this group work, all the parts of the TGB were listed and an assembly drawing of the system was done and then the parts where listed in the order of disassembly and then an DFMA methodology was implemented to check if the parts are necessary or if any changes can be done to any parts.

The results of this workshop can be seen in the following table.

Number	**Part**
1	Intake
2	Coupling
3	Generator shaft
4	Rotor
5	Cooling system of generator
6	Stator
7	Fuel pump
8	Fuel nuts
9	Fuel pipe
10	Combustor fasteners
11	Combustor
12	Housing fasteners
13	Combustor pipe
14	Oil system
15	Compressor clip
16	Compressor housing
17	Turbine clip
18	Turbine housing
19	Compressor bolt
20	Compressor
21	Turbine bolt
22	Turbine
23	Engine shaft
24	Bearing 1
25	Bearing 2
26	Core housing

Table 3 - Disassembly order

Design changes for DFMA are planned for next meetings.

Appendix D - Sample of meeting minutes with collaborating company

In this section a sample meeting minute with the collaborating company is presented. Several meeting have been held with the company for various reason, as a reference, one example of the minutes is presented in this section.

D.1 Meeting minutes 14-02-13 (Company meeting)

Attendees:

Technical Manager (J)

Senior Engineer (E)

Mohammad Ali Sarkandi (M)

Mohammad: the meeting has two aims, one is to **review the project plan** and secondly to **validate the developed framework**.

M: Second year finishes on 27 June 2013, PhD started, 27 June 2011 and has to finish 27 June 2014. 6 months before 27 June, has to start thesis writing. From now have 10 months for research.

M: We are behind schedule on SMEs survey and validation and product cost estimation. Now have to finish data collection by the end of this month (Feb 2013).

M: Make or buy data decision to finish by the end of May 2013.

M: Explained the Framework

M: Design modification till the end of August 2013. Inputs are required from the company for design modification. An initial design should be agreed.

J: For us the cost and ease of manufacture might be more important than other factors to us. We might want to have some technical features, but the design costs would be higher, so in this case we cannot compete in the market. Or for example, in terms of material, we might get a turbine from a supplier, with a material that has much higher technical specifications than our needs and has higher cost, if we get a material with lower technical specifications, close to our needs, it would cost less. Can your framework help us with these decisions?

M: how can this help you?

J: we might have several options for a part; the parts might have a higher cost material, but better in terms of life length or a lower cost material and lower life length or easier maintenance. There should be balance in these analyses. These are not related to our design. But in terms of part selections from the suppliers these can help. For example for the heat exchanger, we know it is stainless steel, but there are various types of steel, which one to choose is a matter.

M: Maintenance is out of our scope. Other stages of life cycle are very large areas. Can be done as other projects.

E: One other option, high cost option, is to ask the suppliers to make some modifications to their products for us.

M: we can consider this case in our design modifications; we can suggest design changes to the supplier to make their manufacturing cost lower.

It is very important to see what is our view point to issues. Do we consider cost or technical specifications?

J: What we do is to apply a high value technology to a low value application. It is obvious that finally what we are going to struggle with is cost. Our main focus is cost.

E: One of the reasons that why large turbo charger companies have not entered our area of work is the fact that it is not beneficial for them.

J: That is the reason we are looking at off the shelf. It is a possible solution to the cost problem.

J: One of the other possibilities to have lower prices product is to wait till the technology becomes mature and its application becomes so wide that the technology value decreases. Like electrical components like transistors. They were very expensive about 30-40 years ago, but due to increase in production and usage, they are very cheap currently.

J: Mohammad might think our main challenges are with the turbo charger components, but they are not of challenge. We can negotiate with our supplier (Garrett) and order large amount of units and have a low cost. Our challenges would be electrical components. They are expensive. For example electrical components working with high frequency are not available in the market. They are at the technology edge. The turbo machinery is used for 10s of years. And we have their prices. The problems arise were.

E: Some parameters to consider for cost are other parameters than components, for example the knowledge.

J: For example, the electrical components. When we approach different manufacturers and suppliers, none of them have ready the technology we require. So they have to design the components for us or customise their existent components. We have contacted a Swiss company for our motor drive and for our needs; we asked them to include an extra part to their existent product. For doing this, they asked for £15000 plus the cost of extra parts. £15000 for the knowledge of integrating the extra parts to their existent product, they even asked us to buy the extra parts ourselves from a German company and they will just do the integration.

E: You can categorise the components into three categories: Physical components, non-physical component (Like knowledge) and unknown components.

J: I think Mohammad needs known components (elements) for his analysis. Unknowns might be out of scope for him. Till this stage of our project, by the analysis we have done, we don’t think there be unknowns in general.

M: I know in our field of science, there is an area called, obsolescence cost. Have you considered it?

J: It possible. But for our project, we have had hours of consultancy.

M: Are you aware of technology changes going on in the world. You might be aware of things going on in UK or Europe. But what about the rest of the world? What if after developing the product, and introducing it to the market, you realise that there is another product with better features or more advanced that has occupied the market.

J: We know some unknowns. We know some of our competitors, according to their needs; have developed some new technologies for their product. But that technology is not available in the market. But the technology is not so significant, to be a key player. These technology developments are small cases and not the general field of micro CHPs. For example, all companies need to use a shaft in this technology, but how they overcome problems of shaft misalignment is different.

After these years of working in this field, we are certain about the architecture of the system and what we are currently stuck at, are fine small technological issues.

E: You can consider the uncertainties, as risk constants or unknown constants.

J: I suggest you consider the systems as fixed (unchangeable) and implement your methodology in company and on the product and once you have run the methodology, we can include the changes in other runs.

M: I think the fact that to consider the unknowns or uncertainties is important, we can mention in the report that, we know that there are uncertainties. But including them in the framework is out of our scope.

J: We now think that we are the first to develop such a product, but if after few years of development, the competitors introduce their products earlier than us, are considering these risks in your field of expertise?

M: I don't think. They are more considered in management.

There are some uncertainties like natural causes (Earthquake, Tsunami,…) or human factors or political uncertainties that cannot be estimated.

J: The first to consider is to select a name for the methodology.

Do you have a final feedback to modify your methodology?

Your framework should be a general methodology for some SMEs, and not just for Samad, otherwise it won't be a PhD.

You have to be able to show your framework in different levels of detail

Your plan is according to the company plan. I don't think you would have time problem.

But what I suggest is don't wait much for exact input from us, if you see you have to wait for exact data, just assume and do the implementation according to the assumptions; You can correct the data during write up.

M: We finalised the list of main components in the previous meeting?

E: Isn't it better that Mohammad get the data from company from one channel to have the integrity and reliability?

M: One of the important data collections is in terms of electronic components

M: Now we will move on to the methodology

E: I still have the doubt that how the methodology is going to the help the company.

J: What we want, is some suggestions on design modification, factory layout and locations.

E: The market issues are not in your scope.

We discussed about the layout design suggestions we have done with Samad Power.

J: What is the novelty of the layout design?

M: Our novelty is not the individual processes. It's the framework, and implementing these conventional processes to a start-up SMEs

J: The processes and methods in the framework should have logical relation. They should not be in isolated blocks.

In your thesis, all the chapters should be related together. They say it should be like a story book. Each chapter should be continuing of the previous chapter.

J: Do you have any work in Logistics? Because you talk about location analysis and it is directly related to logistics and supply chain topics.

M: We don't get in to details in logistics topics

J: and there are two important factory cost, one is the setup cost and one is the factory running cost (e.g. if you run the factory with 2 fewer workers you can have product cost reduction.)

J: In your framework you should not confuse it with your research methodology

In continue we discussed about the framework and cost reduction methods.

J: Do these cost reduction methods are directly intended for cost reduction? Is the aim of DFMA for cost reduction?

E: are your outputs qualitative or quantitative?

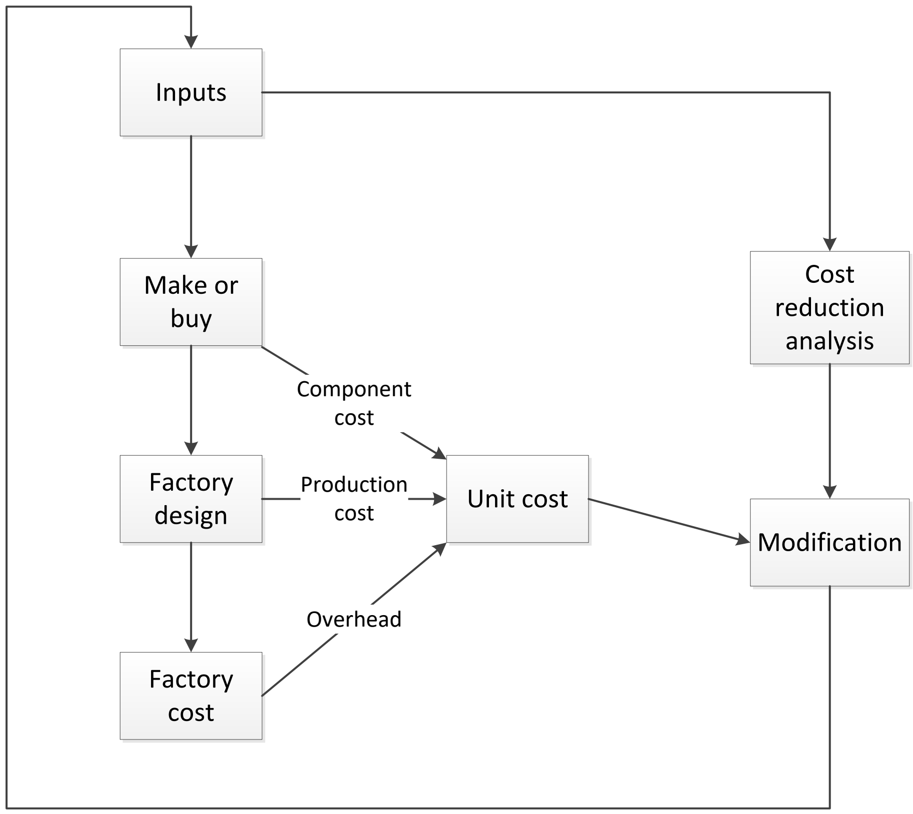

Figure 1 Modified Framework

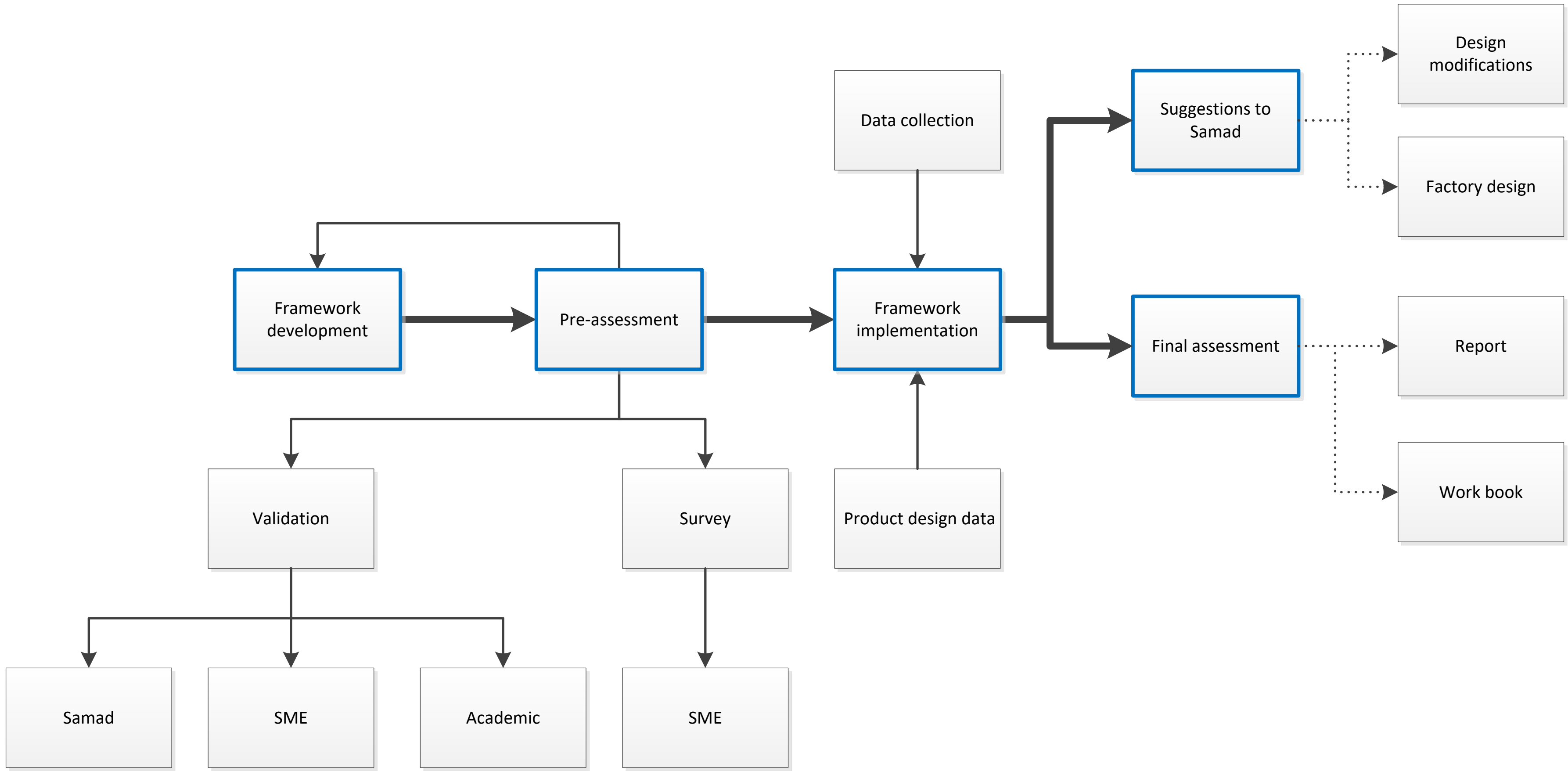

Figure 2 Modified research methodology

Appendix E - Material properties

In this section the properties of the main materials discussed in the text are shown. The two materials focused on are EN36B Steel and LM16 aluminium.

E.1 EN36B case hardening Steel

“655M13 is a 3.25% Nickel – Chromium high hardenability case hardening steel, characterised by high core strength, excellent toughness and fatigue resistance, with case hardnesses up to 62HRC when carburised, hardened and tempered.” (Abbey forged products, 2018)

The material composition and properties are show in Table , Table and Table . (Abbey forged products, 2018)

Table E-1 Typical chemical composition of EN36B Steel

Element	**Maximum value (%)**
Carbon	0.15
Silicon	0.25
Manganese	0.50
Phosphorous	<0.040
Sulphur	<0.040
Chromium	0.90
Nickel	3.50

Table E-2 Mechanical properties of EN36B - Annealed condition

Properties	**Value**
Yield	540 Mpa
Tensile Strength	700/770 Mpa
Elongation	25%
Hardness	255 HB Max

Table E-3 Typical core properties of EN36B - Carburised and oil hardened at 830ºC

Properties	Value		
Section size	11mm	30mm	63mm
Yield Strength	1030/1320 Mpa	930/1230 Mpa	880/1180 Mpa
Tensile Strength	835 Mpa	785 Mpa	735 Mpa
Elongation	9%	10%	10%
Charpy impact	55 J	55 J	-
Hardness	300-385 HB	275-360 HB	260-350 HB

E.2 Aluminium Casting Alloy LM16

Table E-4 Typical chemical composition of LM16 (MRT castings ltd, 2018)

Element	Maximum value (%)
Magnesium	0.4-0.6
Silicon	4.5-5.5
Copper	1.0-1.5
Nickel	0.25 max.
Iron	0.6 max.
Manganese	0.5 max.
Lead	0.1 max
Tin	0.05
Zinc	0.1 max.
Titanium	0.2 max.
Others total	0.15 max.

Table E-5 Mechanical properties of LM16 (MRT castings ltd, 2018)

Properties	**Value**		
Cast type	TB Sand cast	TF Sand cast	TF Gravity die cast
0.2% Proof Stress	120-140 (N/mm^2)	220-280 (N/mm^2)	250-300 (N/mm^2)
Tensile Strength	170 (N/mm^2)	230-290 (N/mm^2)	280-320 (N/mm^2)
Elongation	2%	0-1%	0-2%
Impact resistance Izod	1.4 (Nm)	1.0 (Nm)	1.4 (Nm)
Hardness	80 (HB)	100 (HB)	110 (HB)
Modulus of Elasticity (x10^3)	71 (N/mm^2)	71 (N/mm^2)	71 (N/mm^2)
Shear strength	-	200 (N/mm^2)	235 (N/mm^2)
TB: Solution heat treated and naturally aged TF: Solution heat treated and artificially aged			