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Establishing a cost model when estimating product cost in early design phases

GKN AEROSPACE

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Abstract

About 75% of the total product cost is determined in the early design phase, which means that the possibilities to affect costs are relatively small when the design phase is completed. For companies, it is therefore vital to conduct reliable cost estimates in the early design phase, when selecting between different design choices. When conducting a cost estimate there are many uncertainties. The aim with this study is therefore to explore how uncertainties regarding product cost can be considered when estimating product cost and how expert's knowledge can be integrated within cost estimation. A case study has been conducted within the aerospace industry at the company GKN Aerospace Sweden (GAS) in Trollhättan, from which a model to estimate product cost has been developed. The model is developed for space turbines, but can with modifications be used for other products. Space turbines are highly advanced products, produced in small batches with complex manufacturing processes and high costs. Because of the heavy capital investment, long lead times and high risks, cost estimates become very important, which made GAS suitable for the case study.

The new cost estimation model (NCEM) developed is a combination between intuitive, analogical and analytical cost estimation techniques. Product cost at GAS is built up by the following cost elements; raw material, purchased parts, material surcharge, manufacturing cost, manufacturing surcharge, outsourced operations, method support, delivery cost, warranty and scrap, which are studied more in depth. The material cost is estimated based on historical data and a list of previous purchased alloys is created. The manufacturing cost is determined more in detail where the cost for each operation is estimated, based on operation time, amount of removed material or welding speed. The method support cost is estimated based on a study of an internal prognosis where the amount of time from each discipline needed to support the product is determined. Included in the NCEM is also a risk assessment.

The main insights from this study is that transparency is vital when estimating product cost. It is important to state what assumptions that have been made. Breaking down the product cost into smaller units and create awareness about the cost drivers will identify risks and reduce uncertainness. Experts possess a great deal of knowledge about cost drivers and should be integrated when estimating product cost.

Keywords: *Cost estimation, Product cost, Design Phase, Uncertainties, Expert knowledge*

Sammanfattning

Omkring 75 % av den totala produktkostnaden fastslås i den tidiga designfasen. Detta innebär att möjligheterna att påverka produktkostnaden är reducerad när designfasen är avslutad. Det är därför viktigt för företag att kunna göra tillförlitliga kostnadsestimat i designfasen när val mellan olika designkoncept görs. Inom kostnadsestimering finns det många osäkerheter och syftet med den här studien är därför att undersöka hur hänsyn kan tas till dessa osäkerheter när produktkostnadsestimeringar ska göras, samt hur expertkunskap kan integreras i kostnadsestimat.

En fallstudie har gjorts inom rymdindustrin på företaget GKN Aerospace Sweden (GAS) i Trollhättan, där en modell för att estimera produktkostnaden har utvecklats. Modellen är utvecklad för rymdturbiner, men kan även modifieras för att passa andra produkter. Rymdturbiner är avancerade produkter med höga kostnader som är tillverkade i små serier med komplexa tillverkningsprocesser. Den stora kapitalinvesteringen, långa ledtider och höga risker, gjorde GAS till ett lämpligt företag att utföra fallstudien på.

Den utvecklade kostnadsestimeringsmodelen (NCEM) är en kombination av intuitiva, analoga och analytiska kostnadsestimeringstekniker. Produktkostnaden är uppbyggd av följande kostnadsenheter; råmaterial, inköpta delar, materialpålägg, tillverkningskostnad, tillverkningspålägg, utlagda operationer, metodstöd, leveranskostnad, garanti och skrot. I NCEM baseras materialkostnaden på historiska data och en lista har skapats över tidigare inköpa legeringar. Tillverkningskostnaden bestäms mer i detalj där kostnaden för varje operation uppskattas baserat på operationstid, mängden borttaget material eller svetshastigheten. Metodstödet bestäms genom en jämförelse med en prognos för en turbin där antalet timmar som behövs från varje roll för att stödja en produkt under tillverkning är framtaget. Inkluderat i NCEM finns också ett riskbedömningsunderlag.

De viktigaste insikterna från den här studien är att transparens är vitalt vid produktkostnadsestimering. Det är viktigt att framföra vilka antaganden som har gjorts i uppskattningen och vilken information data är baserat på. Genom att bryta ner produktkostnaden i mindre enheter skapas kännedom om kostnadsdrivare, samt identifierar risker och minskar osäkerheter. Experter innehar stor kunskap om kostnadsdrivare och bör integreras vid produktkostnadsestimering.

Nyckelord: *Kostnadsestimering, Produktkostnad, Designfasen, Osäkerheter, Expertkunskap*

Preface

This Master's Degree Thesis was carried out at GKN Aerospace Sweden (GAS), Trollhättan, and at the Department of Industrial Economics, Blekinge Institute of Technology (BTH) from January 2017 to June 2017 under supervision of lector Henrik Sällberg. This Master's Degree Thesis is an outcome from the master program, Industrial Management and Engineering 2012 at the Department of Industrial Economics at BTH.

First, a great thank you to our supervisor at BTH Henrik Sällberg, who has provided us with valuable and essential information during the project.

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Nomenclature

Acronyms

GAS	GKN Aerospace Sweden
NCEM	New Cost Estimation Model
WC	Work Center
CAD	Computer Aided Design

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1 INTRODUCTION

In this chapter, the subject and the problem is introduced. The chapter begins with a background description of the aerospace industry and a problem discussion which describes the relevance of the work. Thereafter the case company is presented and the objectives and delimitations is stated.

1.1 Background

The world is becoming more globalized which increases competition within the manufacturing industry and puts extra pressure on companies to survive and remain profitable (Niazi et al., 2006). This leads to higher pressure on prices, thus companies need to be aware of their costs.

Product cost is defined as the cost caused by a product that would not occur if the product was not manufactured (Curran et al., 2004), including direct and indirect costs. Generally, about 75% of the total product costs is determined in the early design phase. This means that when the early design phase is completed, most of the opportunities to make changes have passed and therefore the possibility to reduce costs (Weustink et al., 2000). Decisions made during the early design phase are requirements for the design such as dimensions and tolerances, and also what materials and which manufacturing processes to use. That in turn, affects the manufacturing time, the product quality, performance and cost. To change these decisions after the design phase will lead to delays and additional costs. This means that the largest impact on product cost can be done in the early design phase and the ability to select between different design options thus relies on the ability to estimate the accurate product cost. This highlights the importance of using an appropriate and accurate cost estimation technique early in the design phase (Niazi et al., 2006).

The aerospace industry is characterized by complex products with high costs which are highly customized and produced in small batches (Curran et al., 2004). The manufacturing time is long and the manufacturing processes very advanced, which increases the risks that something might go wrong. Many different companies may also be involved in the product and the development process, which increases the complexity (Hongzhuan et al., 2013). This makes cost estimation very important because of heavy capital investments, long lead times and high risks (Curran et al., 2004). Wrong decisions can lead to expensive consequences that jeopardizes the continuation of the business. For this industry, the design phase is extra crucial and requires a solid basis to estimate the product cost to make cost efficient decisions.

Up until the 1980s, the main driver was technology when manufacturing a product within the aerospace industry and cost was not highly prioritized. The focus was on the product and its performance, quality, reliability and durability. This started to change as the industry became more commercialized, due to increased competition and pressure from customers to reduce costs. Today, costs are acknowledged as a vital part of the design and are highly prioritized. (Curran et al., 2004)

It is difficult to estimate the product cost for a complex product during the early design phase, since product information is not yet available in detail (Curran et al., 2004). It includes many uncertainties such as cost for manufacturing, which are affected by manufacturing time, manufacturing deviations, labor costs, machine costs, tools cost and tolerances. Another uncertainty is material cost, which is affected by the supplier base and raw material prices.

How to estimate the product cost is a subject with many different views and opinions of what the best approach is (Cooper and Kaplan, 1988). One difficulty that is identified within cost estimation is lack of knowledge. The cost estimator is required to have sufficient knowledge of the product design, manufacturing process and the cost incurred therein. Another issue is that there is no structured mapping of the relationships between the design features and what contributes to their cost i.e. cost drivers. (Jiao and Tseng, 1999).

To decrease uncertainties within cost estimation, one strategy is to be able to capture and get use of experts´ knowledge (Rush and Roy, 2001). Experts possess a great deal of knowledge within their area of expertise, which can reduce uncertainties if considered in the design phase. The expert knowledge contains understanding of the cost drivers, manufacturing times, material characteristics and the design features. Their judgement are therefore very important to consider when estimating the product cost.

1.2 Problem discussion

Complex products within the aerospace industry are often very expensive to manufacture, which implies the importance of being able to estimate the cost for these products (Curran et al., 2004). When choosing between which design concept that should be selected, it is vital to know the estimated product cost in order to make a cost efficient choice without compromising on product quality or function. This requires an accurate cost estimate which is hard to conduct since the product information is limited in the design phase (Curran et al., 2004). The more detailed the cost estimate is, the more accurate will the estimated product cost most likely be. On the other hand, there is a balance between how much it cost to determine the exact product cost and the cost efficiency that can be done from determining the product cost. According to Howard's (1966) theory "The value of information" the cost for informing oneself should be less than the value of information given.

When estimating a product cost there are several uncertainties to consider as mentioned in the background, that all can lead to unexpected costs. The problem is then, how to identify and manage the most significant uncertainties. Gathering information in the early design phase and using different methods to obtain information for estimating product cost is crucial to reduce uncertainties. Two ways of gathering significant information are by using cost estimation techniques and to capture expert's knowledge. Experts can, based on their experience and knowledge, identify risks that otherwise would be undetected (Eris and Leifer, 2003).

Various cost estimation techniques exist today that capture different costs and estimate the product cost in different ways based on different information. Historical data are often used, sensitivity analysis and earlier experience are used to some extent, where databases, CAD programs and business systems are used to store information (Niazi et al., 2006). Layer et al. (2002) states that there are shortcomings in the established cost estimation techniques and that they do not deliver an accurate product cost as required. The costs are often determined in a lump-sum fashion where the cost-driving product characteristics not are identified (Layer et al., 2002). This occur because the more detailed the estimate is, the more time consuming and expensive will it be to conduct. It is also hard to obtain required data to conduct the estimate. However, product cost is very company specific, since every company has different conditions, which is why a customized model is required (Layer et al., 2002). Curran et al. (2004) highlights the importance of understanding the cause and effect relations, and the importance of looking at the holistic cost structure when estimating the product cost.

Considering this, the aim of this study is to investigate how to explore and manage uncertainties when estimating product cost in the early design phase when choosing between different design concepts. The focus will be on how expert knowledge can be integrated into the cost estimate and thereby get use of their judgement to reduce uncertainties.

1.3 Company description

GKN Aerospace is a supplier of high-performance and complex engine products for aircrafts and rockets. GKN Aerospace is one of three division within the British group GKN plc, where the others are GKN Driveline and GKN Powder metallurgy. GKN is active in more than 30 countries and employs over 56,000. About 12,000 work at GKN Aerospace and 2,000 are stationed at GKN Aerospace´s head office in Trollhättan, Sweden. (GKN, 2017)

GKN Aerospace Sweden (GAS) represents three fields; space, military and commercial. They are the European Center of Excellence for space turbines, which means that they are world leading in design and manufacturing of space turbines. Their components are used in 90% of the commercial aircrafts that take off every day. The site in Trollhättan is characterized by a complex and advanced manufacturing environment. The product studied in this work is produced in small batches, customized and highly advanced with hard tolerances. (GKN, 2017)

Today GAS manufactures two types of turbines providing power to two turbo pumps, one for liquid hydrogen (LH2) and one for liquid oxygen (LOX), The turbines are intended for the Vulcain rocket engine in the European space program and their rocket, the Ariane 5. The turbines are produced through serial production and the company manufacture about 10-12 products of each sort every year. The turbines should be able to withstand high loadings from temperature, pressure and rotational speed. The turbines are only used once during their lifetime, which means that there is no aftermarket. The future turbines that are under development are called Vinci LOX and Vinci LH2. (GKN, 2017)

1.4 Objectives

The main objective is to explore how expert knowledge can be integrated within cost estimation. This to reduce uncertainties regarding product cost when making design choices in the early design phase.

1.5 Delimitations

The research problem has been studied at one specific company. The new cost estimation model (NCEM) developed is created to fit a specific product at the case company. The estimated product cost in the NCEM refers to the expected product cost during series production and does not include development cost. The estimated product cost in the NCEM affects the design choices that are done in the early design phase. Furthermore, the design choices will affect the outcome of the expected product cost.

2 THEORETICAL FRAMEWORK

The purpose of this chapter is to give the reader an understanding of relevant theories used in the study. This chapter describes the theory behind product cost, product development process, design phase and manufacturing environment. Thereafter, established cost estimation techniques and their shortcomings are explained. Lastly the subjects within uncertainties and expert knowledge are clarified.

2.1 Product cost

Product cost is the cost for manufacturing a product. It can be defined as the cost caused by a product that would not occur if the product was not manufactured. The product cost can be calculated differently depending on the purpose and product type. Within absorption costing, the product is carrying all costs associated by its manufacturing. The cost elements included are usually; direct material, direct salaries, direct manufacturing cost, direct sales cost, material overheads, manufacturing overheads and selling and administrative expense. (Aniander et al., 1998)

Costs can generally be divided into direct and indirect costs, where overhead costs are the same as indirect cost. Direct costs can be linked to a specific product, e.g. the cost for material or number of machine hours. Indirect costs include costs that are common for multiple products and are often difficult to distribute fairly across the products. Overhead costs are usually distributed with an allocation formula based on production volume, machine hours, the products profitability or turnover. The chosen allocation formula depends on the company's production strategy or the financial control method. (Aniander et al., 1998)

An overhead cost that is hard to distribute is the method support, which includes design support and manufacturing support from different disciplines at the company. Kaplan and Cooper (1988) describes a scenario where method support is distributed according to production volume. The need for method support increases for complex low volume products, which increases the total support for the company. If the method support cost is distributed according to production volume, the simple high volume products will carry the rising method support cost, which actually is due to the low volume product. The simpler high volume product seems to have higher costs and compared to the low volume product it seems less profitable, but in fact that is not the case. This example shows how important it is to use a correct allocation formula. (Kaplan and Cooper, 1988)

Important to remember is that product cost is calculated differently and that the calculation method must be adapted to the conditions of the company and how the value is used. Concluding this, depending on the purpose with the product cost calculation, different cost elements will be included. (Kaplan and Cooper, 1988)

Another cost classification is fixed and variable costs. Variable costs vary with the number of units manufactured or sold and are usually considered to be proportional to the production volume. Fixed costs are, in principle, independent of the volume manufactured or sold, but refers to costs for production equipment, facilities and fixtures. Although, the classification of the costs depends on the time perspective. (Johannesson et al., 2013)

A cost driver is referred to any factor which causes a change in the total cost of an activity. It describes the root cause of why a cost occurs and identifies a linkage between the cost and the factors. Identifying cost drivers leads to new insights about how the costs can be reduced. (Govindarajan, 1993)

2.2 Product development process

Project forms with representatives from different departments are the most common way to conduct product development for industrial companies. Industrial companies are often divided by functionality such as manufacturing, sales, design and testing, and it is therefore suitable to gather these disciplines in a project. (Aniander et al., 2004)

Johannesson et al. (2013) divides the product development process in five phases, which can be seen in Figure 2.1. The figure also shows how the product cost increases during the project time.

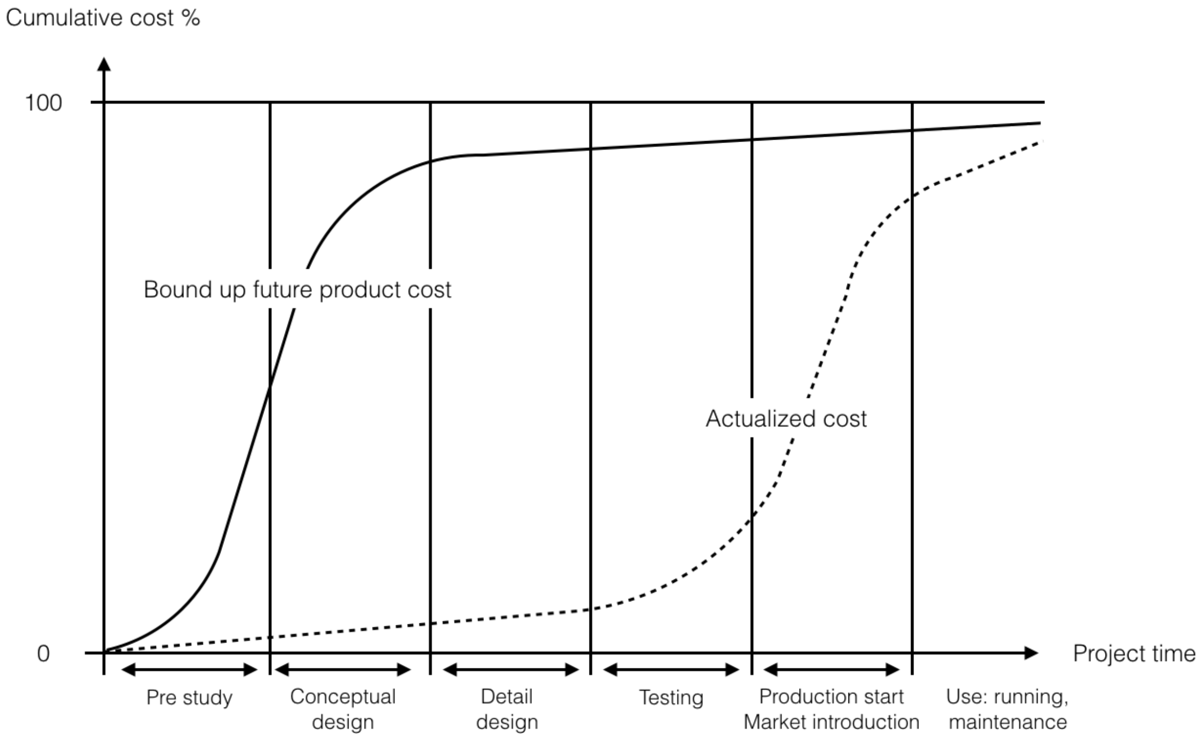

Figure 2.1, Example of different phases within the product development process. (Johannesson et al., 2013)

2.3 Design phase

During the design phase, major decisions must be taken about what technologies that provide the products desired functions. There will often be a variety of design alternatives for the product development team to consider. Decisions that are made during the early design phase are material choices, choices of manufacturing processes, geometries and tolerances. Making the right decisions during the early design phase when choosing which product concept to develop further, is a challenge concerning a lot of uncertainties. In order to choose the right product concept, information regarding the final product´s functionality and cost must be available to make the selection easier. Limited information and knowledge create uncertainties, which make the choice harder. Decisions taken at the early design phase are therefore a fine balance of opportunities and risks (Georgiou et al., 2016). According to the theory "The Value of Information", the key is to make sure that the cost for information is less than the value of it (Howard, 1966). The cost for collecting knowledge from experts about product costs, should thereby not exceed the value of the gained information.

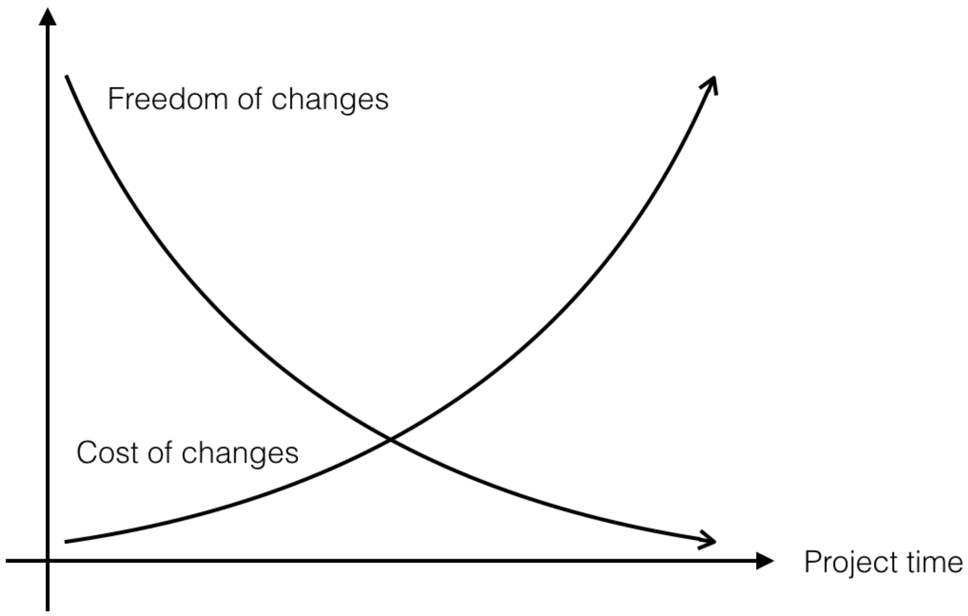

Figure 2.2, This diagram show how the degrees of freedom decreases and cost of changes increases as project time goes by. (Johannesson et al., 2013)

According to Curran et al. (2004) about 75 % of a products cost is fixed in the design phase because of all the decisions being made during that phase, this is supported by several other authors (Jiao and Tseng, 1999; Weustink et al., 2000). As seen in Figure 2.2, the costs for making changes to the product design gets higher as time goes by (Rush and Roy, 2001). This implies the importance of making major changes earlier on in the development process when modifications are not as costly to implement (Georgiou et al., 2016; Johannesson et al., 2013, 136). Johannesson (2013) therefor suggest to spend many hours in the beginning of a project to decrease the number of expensive mistakes later in the project. This also means that when the design phase is completed, most of the opportunities to make changes have passed and therefore also the possibility to reduce the costs (Weustink et al., 2000).

2.4 Manufacturing

Customer oriented production and stock oriented production are two different types of manufacturing. The customer oriented production is controlled by orders from the customers, which means that the production do not start until an order has been received. Stock oriented production is determined by the stock and for this type it is a predetermined stock volume that controls the production rate. The predetermined stock volume is determined through demand prognosis of the market. (Aniander et al., 1998)

For most manufacturing companies today, it is common with a combination of both production types. In these cases, the product is manufactured to a certain stock level and is then kept in stock until a customer order has been received and thereby the manufacturing continues. (Jonsson and Mattsson, 2011).

Production system involves different classical ways to conduct manufacturing. The most common are; process production, line production, functional production and design team. In process production, the manufacturing flows and the product are closely linked to the manufacturing process. This type is common in the paper industry. Line production is characterized by the products being transported forward at the speed in which they are manufactured and the operations are placed in the order they are performed on the product. This production system is commonly used for consumer products when they are put together, for instance in the automotive industry or within television manufacturing. (Aniander et al., 1998)

In a functional production, machines with similar functions are grouped together and the product is moved between the different machine groups when manufactured. This type of production allow a great flexibility, but can lead to long lead times and an increased capital tied up. It is commonly used in specialized companies and subcontractors. Lastly, within construction teams the work is performed on a stationary product and the workers and machines are moved to the product. This production is commonly used when manufacturing airplanes or building houses. (Aniander et al., 1998)

2.5 Cost estimation techniques

A cost estimate is a prediction about the future. To estimate product cost, different cost estimation techniques exist which will be described in this chapter. Overall, cost estimations techniques can be classified as:

- Intuitive – the cost estimates are mainly based on past experience.
- Analogic – the cost estimates are based on comparisons and relationships with other designs.
- Parametric – characteristics as weight, dimensions and materials are used to describe a mathematical relationship for the cost.

- Analytical – summarizes the values of parameters within the manufacturing processes, which require detailed information about the operation list. (Niazi et al., 2006)

Niazi et al. (2006) categorizes the existing cost estimation techniques into qualitative and quantitative techniques. According to the classification described above, qualitative techniques include intuitive and analogic techniques, while quantitative techniques include parametric and analytical techniques. The difference between the techniques is their level of detailed information considered and the accuracy in the result. In the next chapters the techniques will be described more in detail.

2.5.1 Qualitative techniques

Generally, qualitative techniques are based on a comparison between the new product and a similar previously manufactured product, to use historical data. These methods are favorable to use early in the design phase, since they require little information and are easy to apply. Unfortunately, they often lack in accuracy. (Niazi et al., 2006)

- Intuitive techniques are based on experience where a domain expert´s knowledge is used to estimate the cost (Niazi et al., 2006). Within the Case-Based Methodology, the estimator adapt a past design from a database that matches the attributes of the new design, and identifies the changes to calculate the cost (Rehman et al., 1998). Decision support system is often used in order to assist the estimator in making better decisions and judgements, based on stored knowledge of experts in the field. Methods included are Rule-Based Systems, Fuzzy-Logic Approach (Shehab et al., 2002) and Expert Systems, which all make use of knowledge stored in a database (Niazi et al., 2006).

- Analogical techniques are based on historical data, where similarities between historical and new parts are used to estimate the costs (Niazi et al., 2006). The Regression Analysis Model establishes a linear relationship between the product costs for the past design cases and the values of certain selected variables, that are used to forecast the cost of the new product (Niazi et al., 2006). The Back-Propagation Neural-Network Model uses a neural-network that can store knowledge and be trained to infer the answers to questions it may not have seen before (Cavalieri et al., 2004).

2.5.2 Quantitative techniques

Quantitative techniques are more detailed and based on an analysis of the product design, the features and corresponding manufacturing processes (Lin et al., 2011). These techniques provide more accurate results, but their use is normally restricted to the final design phases, due to the requirements of detailed information about the product design (Niazi et al., 2006).

- Parametric techniques estimate the costs by expressing it as a function of its cost drivers and is done on a per unit basis (Niazi et al., 2006). Linear regression is used to establish a relationship between one or more parameters that are observed to change as cost changes (Curran et al., 2004).

- Analytical techniques will often be found in business systems and break down the product and the manufacturing processes into elementary units, activities and operations that represent various resources consumed during production. The cost is then expressed as a summation of all these components (Niazi et al., 2006). These methods can also be referred to as bottom-up, which are very detailed estimates (Curran et al., 2004). The Operation-based technique estimate manufacturing cost as a summation of the costs associated with the time for performing manufacturing operations, nonproductive time and setup time. The breakdown approach estimates the total product cost by summing up all the costs incurred **during** the production cycle, including material cost and overheads. Tolerance-Based techniques estimates the product cost considering design tolerances of a product as a function of the product cost. Feature-Based techniques are often used in CAD programs and identify cost related features in order to determine the associated costs. The features may be design related such as type of material or specific geometric details, or process oriented, i.e. particular processes needed. Lastly, Activity-Based Costing System (ABC) calculates the costs incurred on performing the activities to manufacture the product (Niazi et al., 2006).

2.5.3 Shortcomings in established cost estimation techniques

Cost estimating can be defined as "the art of approximating the probable worth or cost of an activity based on information available at the time" (Stewart, 1991). This means that the estimated cost, compared with an actual cost, only consider the most important factors based on available information (Ou-Yang and Lin, 1997).

Layer et al. describes important required features for a generic cost estimation technique. The result must be accurate even though the product is complex. The cost structure should be transparent to expose cost drivers and support the designers. The method should also be flexible, be able to consider changes in available resources and manufacturing operations and enable acquisition of knowledge (Layer et al., 2002).

The established cost estimation techniques described above show shortcomings in several aspects. This is also the reason for Layer et al. (2002) to state that none of the techniques has found widespread application within the industry. There is often a lack in accuracy, especially when dealing with complex parts. The models do not consider enough information to deliver a reliable estimate. Statistical and analogous models often determine the costs in a lump-sum fashion, which means that they are not able to identify the cost-driving product characteristics. These models also depend on historical data and can thereby not calculate estimates for innovative technologies or new resources. The knowledge and experience provided by experts do not carry enough weight in rule-based systems. At last, most of the methods do not consider that manufacturing technology is company specific. Concluding this, none of the methods are as effective or efficient as needed, where conceptual design is not sufficiently supported. (Layer et al., 2002)

2.6 Expert knowledge

Experts are individuals that possess a great deal of knowledge within an area. They often say that their judgements are based on gut feel, when in fact it is simply years of experience (Rush and Roy, 2001). Expert knowledge can be found within core competences. The concept of core competences is defined as “the collective learning in the organization, especially how to coordinate diverse production skills and integrate multiple streams of technologies” (Prahalad and Hamel, 1990). More concretely expressed, a core competence contributes to the customer benefit of a product, is competitively unique and possibly provides access to new markets.

Expert knowledge is a necessity when developing complex products, but can also bring some difficulties known as “over the wall engineering”. The major difficulty is to get experts to collaborate from different areas in an efficient way. This makes it difficult to develop a product with low product cost that is easy to manufacture. If experts become too specialized in their own area, collaboration with other experts will be complicated, since they have lack of knowledge of other experts areas of expertise. There might be a revelatory and lack of social contacts between the departments, which can be illustrated as walls that needs to be crossed, shown in Figure 2.3. (Aniander et al., 2004)

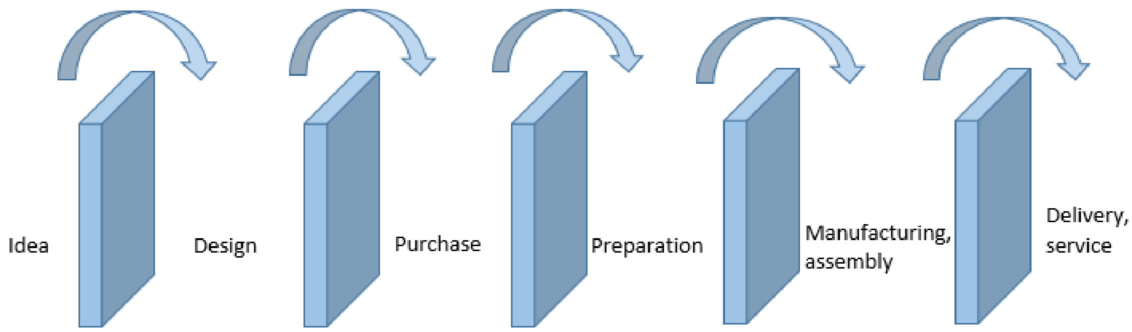

Figure 2.3, Illustrates "Over the wall engineering". (Aniander et al., 2004)

When experts generate cost estimates, they are done through a combination of skills, experience, common sense, logic and judgement. Rush and Roy (2001) states that experts judgement are unavoidable and continually used throughout the cost estimation process, whether a cost estimation technique are used or not. When product cost estimates are generated based on expert knowledge, it is difficult but very important to understand how the final estimate derived. It is also important to understand the reasons and logic behind it, to make it more apparent and reusable. It is vital to show the assumptions that have been done and to capture the knowledge and rationale behind the estimate. Advantages from doing this are that the process of using expert knowledge becomes more structured and the tacit knowledge of experts are captured, which means that others can learn from the motives behind the estimate. (Rush and Roy, 2001) Tacit knowledge is referred as subjective, context-specific and personal and is also difficult to describe, examine and use. Also, letting the experts describe their knowledge helps them to clarify their thinking and specify their knowledge better (Ford and Sterman, 1998).

Eris and Leifer (2003) states that experts also can be seen as linkers that mediates their expert knowledge between themselves and the product development team in the design phase. Experts can be used to recognize risks and fill out gaps with their knowledge.

2.7 Uncertainty

Uncertainty derives from the incomplete knowledge that is necessary to forecast future events, but also from the inability to act and control the result. To reduce the lack of knowledge involves learning processes and the ability to reduce uncertainty by framing the choices. (Dosi and Egidi, 1991)

The most known typology within uncertainty is Knight's (1921) distinction between certainty, risk and uncertainty. When something is certain, the true outcome is known. On the other hand, uncertainty refers to the lack of certainty, which is a state with limited knowledge and where it is impossible to describe the exactly future outcome. In other words, uncertainty is an immeasurable risk that is not possible to calculate, which usually is called Knightian uncertainty. However, a risk is referred to as a measurable uncertainty where it is possible to assign probabilities to a specific outcome, which usually is called Knightian risk. Probabilities is the measure of the likelihood that an event will occur. Concluding this, risk can be quantified while uncertainties cannot. Risks can thereby be a way to manage uncertainties. (Knight, 1921)

Uncertainty can also be classified in endogenous and exogenous, depending on whether they derive from within or outside the supply chain (Trkman and McCormack, 2009). Endogenous uncertainty describes factors that are of control within the firm, while exogenous uncertainty describes facts outside the control of the firm. Furthermore, Dosi and Egidi (1991) describes two concepts of substantive and procedural uncertainty. Substantive uncertainty is when there is a lack of information about environmental events to make decisions with a certain outcome. On the other hand, procedural uncertainty is when agents are unable to recognize and understand relevant information, even when available, due to lack of competence. Hence, uncertainty can thereby be related to the knowledge level of the decision maker (Vilko et al., 2014).

Cost estimation techniques act as a tool to reduce uncertainties regarding product cost. When estimating product cost based on limited amount of historical data, the risk becomes higher. Risk models can thereby be used to quantify uncertainties when estimating costs. Involving risk analysis within cost estimation provides understanding and helps to guide when making decisions. (Curran et al., 2004)

3 METHOD

The following chapter discuss different methodological approaches. Furthermore, the methods used in this study are explained and why they were suitable to use.

3.1 Research process

Ghauri and Grønhaug (2010) presents a suggested research process which represents the stages that a research goes through, see Figure 3.1. However, within this study the process has gone back and forth between the different stages and some stages have been performed at the same time.

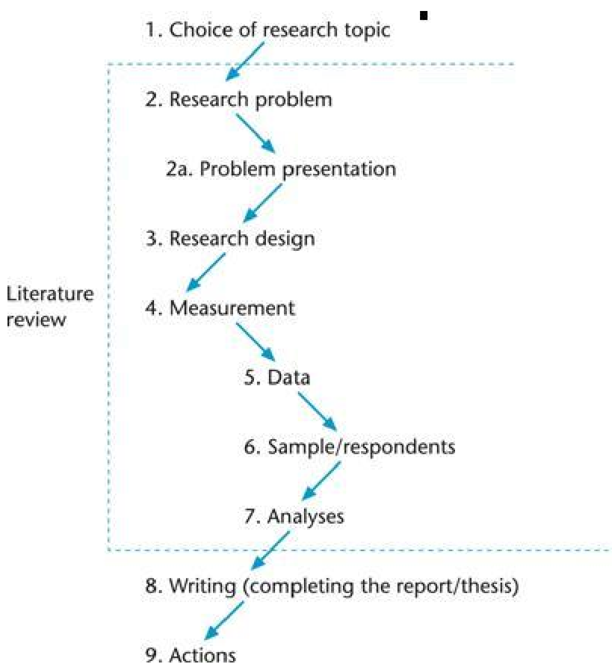

Figure 3.1 A setup of a research process and the including stages. (Ghauri and Grønhaug, 2010)

The first step was the choice of research topic, which was limited to product cost estimations. Once that was established, the research problem was defined and specified. A way to define the research problem is to conduct a literature review which also was done in this study. The purpose with a literature review is to create a knowledgebase and build a theoretical framework that helps the researcher to identify what theories, concepts, facts and methods that exists (Björklund and Paulsson, 2012).

In Figure 3.2 below, an overview of the research process in this study is illustrated and will be described more in detail in the following chapters.

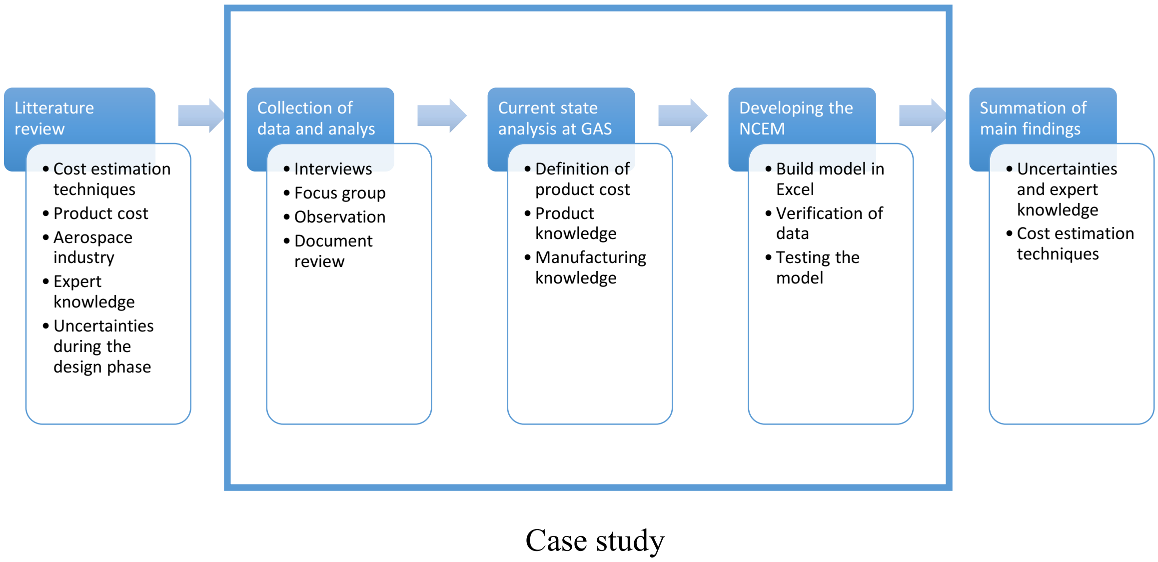

Figure 3.2, Description of the work process during the study.

3.1.1 Literature review

Within this study, the literature review and a theoretical framework was built up by mainly peer reviewed articles and books. The framework considers topics within cost estimation under uncertainty, product cost, concept selection during the design phase and expert knowledge. From that, the scope of the study was defined and limitations were set, which later resulted in the research problem. The work with the literature review was structured into a matrix, which can be seen in Table 3.1. The articles were listed to create an organized way of working. Different categories were mapped and explained, such as the purpose, discussed theories, methods used, the result of the studies and lastly identified gaps and proposed further research.

Table 3.1, Literature review matrix.

Title	Purpose	Theory	Method	Result	Identified gaps and continued research

3.2 Research design

According to Ghauri and Grønhaug (2010) the research design generates an overall plan for how to collect data and analyze it in a way that is relevant to the research problem. It is the way of relating the research problem to practicable empirical research and further down it is described how this is done within this study. The research design is greatly connected to the purpose of the study and dependent of how well it is stated. (Ghauri and Grønhaug, 2010)

There are three main types of research designs, e.g. exploratory, descriptive and causal (Ghauri and Grønhaug, 2010). In this study, it was chosen to conduct an exploratory study since that is preferable when the problem is unstructured or badly understood. A key is flexibility since new information that can change the course of action may be provided along the way.

3.2.1 Case study

The chosen research design within this study was to conduct a case study at the company GKN Aerospace Sweden (GAS). This was done to get in depth information about the company and thereby gaining deeper understanding of the research problem. Case studies are often used within exploratory research and are especially suitable when the problem needs to be studied in its natural context and when it is problematic to measure or calculate the concepts (Ghauri and Grønhaug, 2010). Only one company was studied due to gain in-depth information and understanding, which is harder to get if many companies would be studied.

To explore how uncertainties can be managed when estimating product cost, the problem was studied in its natural context by creating a new cost estimation model (NCEM) for a specific product, a space rocket turbine. The company GAS has a complex manufacturing environment that produces highly advanced products with extreme characteristics. The employees possess a wide range of expert knowledge within material, design, manufacturing and product cost. This made the study suitable and interesting to perform at GAS.

The purpose with the NCEM is to use it in the early design phase when selecting between different design concepts. The model should deliver an estimated product cost to compare with the cost for other design concepts. To manage uncertainties regarding product cost, the model is built up by knowledge from experts within different fields of manufacturing, material and support. This was done to explore how expert knowledge can be integrated within cost estimation and thereby reduce uncertainties.

An overview of the work process during the case study can be seen in Figure 3.2. When performing a case study the unique characteristics of the case is important to understand. Therefore, the research started by exploring the current state within product cost, how cost estimation was conducted and which techniques that were used at GAS today. At the same time, the product and its characteristics were studied.

The further work consisted of the creation of the NCEM. The first thing was to define product cost at GAS and identify cost elements and cost drivers. This work was done through data collection with several interviews, document reviews and observations, which will be described in the following chapters. From that, a NCEM was developed. The manufacturing processes and their costs were mapped with all the operations included and the cost for each operation was calculated. The tool "Walter" (Walter Machining Calculator, 2017) was used to calculate different removal rates for turning, milling and drilling. Lastly, one test of the NCEM was conducted. The cost for method support was estimated and then compared to a real outcome or prognosis.

3.3 Data collection

Data has mainly been collected through qualitative methods such as interviews, focus groups, observations and document reviews, which were most suitable for this study. The purpose of using many data collection methods is to confirm and complete the data. Both primary and secondary data have been collected. Secondary data is the base for the literature review and theoretical framework. Source criticism has always been in mind when collecting this data. Primary data was mainly collected through observations and interviews with employees from different departments at the case company. The interviewees can be referred to as experts within different fields that possess valuable experience and knowledge. A focus group was also put together in a workshop. Numerical data was collected from GAS business system. Important to remember when collecting and processing data from these systems is that they may not always be complete (Ekengren and Hinnfors, 2006). The numbers taken from the business system were therefore verified by an expert before they were used.

3.3.1 Document review

Documents have been studied at GAS in terms of operation lists and structure trees of the turbines. This was done to get deeper knowledge of the product and manufacturing processes and thereby be able to construct better interviews.

3.3.2 Interviews

During this study, many interviews were conducted which can be seen in Table 3.2, and all interviews lasted approximately one hour. Finding the right persons for the interviews was sometimes a challenge and in some cases the process went back and forth between different people before the right person was found. The interviewees were thoughtfully chosen considering their expertise and experience, and covered all areas/cost elements related to the product cost.

All interviews were conducted personally where the researchers sat down with the interviewees and was later followed up with questions by e-mail when the information was incomplete or data was missing. In some cases, a second interview was held to follow up or collect more data. The interviews were of an unstructured type and considered a specific topic where pre-set questions were used as a guide, but new questions were also allowed which gave the interviewee more freedom in how to answer and explicate the answers (Björklund and Paulsson, 2012). The unstructured type of interviews provides the advantage of more in-depth discussions as the researcher is letting the interviewee to elaborate the subject if needed.

Before the interview, the interviewees were informed about the purpose of the interview and introduced to the subject. By preparing the interviewee, the opportunity was given to get acquainted with the subject and to be able to update themselves with facts they thought would be interesting to share. This also led to more in-depth interviews since the start-up became shorter.

Initially the interviews focused on the current state at GAS, how they work with product cost management today, what affects the product cost and to clarify what drives the costs. Then, the main purpose of the interviews was to develop the NCEM and capture expert knowledge and integrate to the NCEM, but also to collect and verify numerical underlying data. During the interviews, the researchers tried to influence the result as little as possible, to achieve a fair and objective result (Björklund and Paulsson, 2012). This meant not asking questions with directions, but leaving the objectification of the question open to the interviewee.

Except these interviews, several meetings have been organized together with three supervisors at GAS (one product cost management engineer, one process verification engineer and one engineer in charge) with the purpose to develop the NCEM further.

Table 3.2, The table show the interviews, focus group and observation conducted in this study.

Interviews		
Interviewee	**Purpose**	**Date**
Product Cost Management Engineer	Current state at GKN within product cost, development of NCEM: method support.	**2017-01-25, 2017-03-24, 2017-04-03**
Manufacturing Process Verification Engineer	Current state at GKN: Earlier work within product cost Vinci turbine.	**2017-01-31**
Engineer in Charge	Current state at GKN: Information about product characteristics and cost drivers.	**2017-02-15**
Chief Manufacturing Engineer	Current state at GKN: Information about the manufacturing, product characteristics and cost drivers. Development of NCEM.	**2017-02-15, 2017-03-17, 2017-04-04**
Purchasing Analyst	Current state: Information about material cost, cost drivers, material prognosis and quote calculations.	**2017-02-03**
Strategy Manager	Current state: Information about material cost, material prognosis and quote calculations.	**2017-02-03**
2 Operations Controller	Current state at GKN: Product cost within accountancy.	**2017-03-07**
Systems and Support Engineer	Current state at GKN: Product cost estimations.	**2017-03-23**
2 Product Engineer	Current state at GKN: Product cost estimations. Development of NCEM: Guidance about tool cost	**2017-03-23, 2017-03-27 2017-04-18**
2 Materials and Process Engineer	Development of NCEM: Information about cutting machining.	**2017-03-20**

Materials and Process Engineer	Development of NCEM: Information about manufacturing processes.	**2017-03-23**
Material Planner	Development of NCEM: Information about manufacturing processes.	**2017-03-23**
3 Program Managers	Development of NCEM: Information and testing of method support.	**2017-03-24, 2017-04-03, 2017-04-12, 2017-04-20**
Product Engineer	Development of NCEM: Information about grinding.	**2017-03-27**
Manufacturing Process Verification Engineer	Development of NCEM: Information about Non-destructive-testing processes.	**2017-03-28**
Materials and Process Engineer	Development of NCEM: Information about SPRT-process.	**2017-03-28**
CAM consultant	Development of NCEM: Calculation of removal rate for turning, milling and drilling.	**2017-04-04**
Process Engineer and Senior Buyer	Development of NCEM: Information about material cost and value add.	**2017-04-04**
Product engineer	Development of NCEM: Information about welding.	**2017-04-10**
Engineering Management and Support	Development of NCEM: Information about splines.	**2017-04-27**
	Focus group	
Solid mechanics, Purchasing analyst, Product cost management engineer, Product engineer, Chief manufacturing engineer, Engineer in charge and Manufacturing process verification engineer	Workshop	**2017-03-21**
	Observation	
Chief Manufacturing Engineer	Shop tour in the production. Information about the manufacturing processes.	**2017-03-08**

3.3.3 Focus groups

During this study, a focus group was put together with experts from different areas that could contribute to the development of the NCEM. According to Ghauri and Grønhaug (2010) using focus groups is a good method when collecting data in qualitative research. Seven persons with different experience and expertise, the roles can be seen in Table 3.2, were invited to join a workshop. Some days before the workshop was planned the focus group were prepared with information about the content and topics of the discussion. The workshop started by doing a quick run-through of the concept with the NCEM and a scenario where it is supposed to be used was explained.

The reason to conduct the workshop was to start a discussion between the experts to inform each other about their area of expertise and to get pass some holdbacks. The expected outcome from the workshop was information within product knowledge, manufacturing processes, purchasing and design. A benefit from conducting focus groups compared to single person interviews is that the attendees can interact with each other and to encourage discussions. Thoughts and ideas of value might be detected during these kind of discussions, that otherwise would have remained unexplored (Ghauri and Grønhaug, 2010). During the workshop, the participants gave their opinion on how to improve the layout of the NCEM.

3.3.4 Direct observations

Observations were used to collect new data, but also to confirm data received from the interviews and document review. Conducting observations required listening, watching and interpreting the environment at GAS. Visits to the manufacturing were conducted to learn about the different manufacturing processes at GAS and the product characteristics. This was also done to gain more knowledge and thereby create better interviews. The work with this study has mainly been performed at GAS office in Trollhättan and can also be a kind of observation since several contacts with the employees have been established.

3.4 Data analysis

During a qualitative research the collection of data and the analysis of the data are performed at the same time. The collected data raises new questions, which in turn initiate further data collection and so on. (Ghauri and Grønhaug, 2010)

According to Ghauri and Grønhaug (2010) the purpose of the analysis is to gain understanding and insights from the collected data, which also have been the purpose for this study.

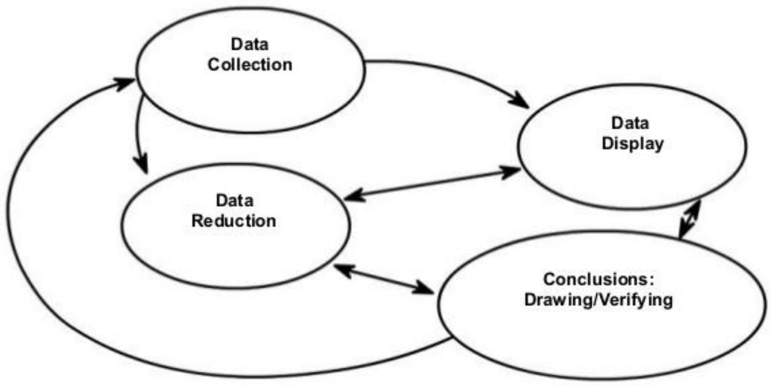

Figure 3.3, A generic model of the data analysis process described by Miles and Huberman (1994). (Ghauri and Grønhaug, 2010)

Miles and Huberman (1994), describes an interactive data analysis model, as can be seen in Figure 3.3. It shows different stages in the data analysis process and how they interact with each other. During the data reduction, data from field notes or transcriptions are selected, simplified, abstracted and transformed to be manageable. Categories are generated and themes and patterns identified, and the data becomes gradually clearer. During the data display, the data is sorted and conclusions can be drawn.

3.5 Validity and Reliability

Validity refers to the extent to which something really measure what is intended to be measured (Björklund and Paulsson, 2012). In other words, the measuring should capture what is supposed to be captured. It is about measuring and investigating the correct type of data. Reliability refers to the stability of the measure and the degree of reliability in the measuring instrument. It means to what extent you get the same value if you repeat the survey again (Björklund and Paulsson, 2012). The measurement should be conducted in the right way and data should be managed correctly. Concluding this, a valid measure is also reliable, but a reliable measure does not need to be valid. (Ghauri and Grønhaug, 2010)

A result with good validity, means that the result is consistent with its true value. Reliability is more about how well the measurement is conducted in a correct way. Reliability is measuring how well repeated measurements give the same results. If the same study deliver the same result in repeated measurements the reliability is high. (Ghauri and Grønhaug, 2010)

The terms of validity and reliability differs somewhat between qualitative and quantitative studies. Controlling the validity and reliability in qualitative studies is often more difficult than in quantitative studies. The quality depends on the researchers interpretations of the empirical data, and the researchers are in turn affected by personal values, attitudes and beliefs. Qualitative studies thereby require researchers with high self-awareness. (Ghauri and Grønhaug, 2010)

Although, Yin (2009) describes ways of judging a qualitative research by construct validity, internal validity, external validity and reliability. Constructed validity can be done using multiple sources of evidence, having key informants for draft reviews and establish chains of evidence (Yin, 2009). Within this study, drafts of raw data and analyses have been shared with supervisors. Data from interviews were also shared to come extent with the interviewees once more. Numerical data extracted from the business system were also shared with experts to verify the validity. The costs extracted from the NCEM were also verified in several tests where the outcome was compered to real outcomes.

Within internal validity, triangulation is a method that uses different sources to gain better understanding and to find out if conclusions from different sources converge (Miles and Huberman, 1994). External validity shows whether the research findings can be generalized to other settings, for instance if the explanation is true for other companies or industries as well (Miles and Huberman, 1994). Since this study was conducted at a specific company, some parts may not be generalized into other companies. However, the descriptive parts where general insights and challenges are described may be relevant for other business. Another part that is important to remember is that the interviewees represent the perspectives at a specific company.

Finally, reliability represent if the study is reasonably stable over time and across methods and researchers. This study has been conducted by two researchers, which can increase the reliability somewhat. According to Wästerfors and Sjöberg (2008) reliability is otherwise harder to check in qualitative studies, since the term originally originate from quantitative studies. Instead they use terms as methodological awareness where the methodological problems and qualifications of the own study are explained in detail.

4 RESULT

This chapter presents the result from the case study at GAS. Data are based on interviews, observations and document reviews. First, a current state description of GAS is presented including a description of GAS product development process, production system and current way of estimating product cost. Further, a new developed cost estimate model (NCEM) will be presented and the results from testing the NCEM. Advantages and disadvantaged with the NCEM is presented and compared to the current way of estimating product cost at GAS. Lastly, the results from integrating expert knowledge into product cost estimation is presented.

4.1 Current state description at GAS

4.1.1 Product development process at GAS

The product development process at GAS is complex and consist of twelve phases, which can be seen in Figure 4.1. The NCEM is developed for usage in the conceptual design phase. During the conceptual design phase the preliminary product design is determined and the product requirements are set.

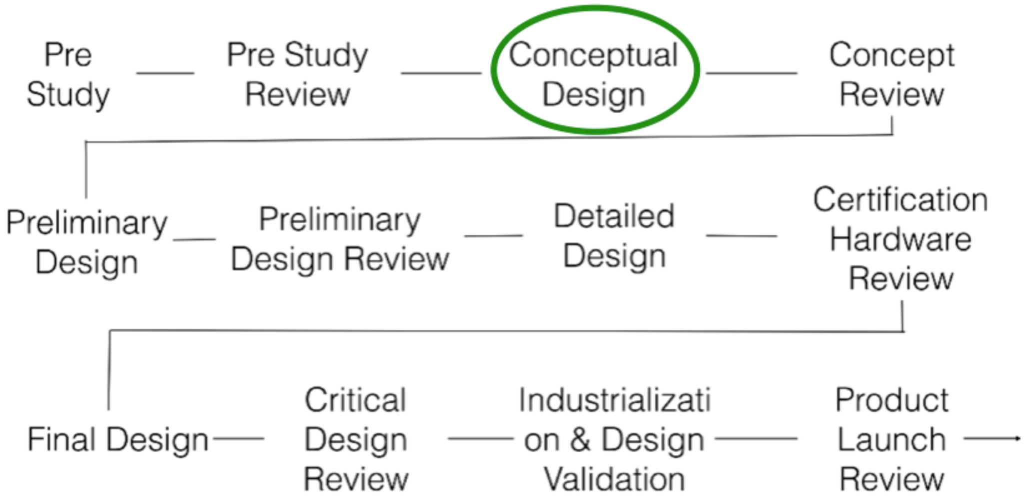

Figure 4.1, Current development process at GAS. The green circle highlights the phase where the NCEM will be used.

4.1.2 Production system at GAS

The manufacturing at GAS is characterized by manufacturing in expensive machines with long processing times. They have a functional layout which results in cost such as internal storage and transportation. Multiple types of products are often manufactured in the same machine and the products are moved between different machines, departments and workshops.

4.1.3 Definition of product cost and identified cost drivers at GAS

Derived from interviews, ten cost elements are identified within product cost at GAS, shown in Table 4.1. Several cost drivers are also identified, which can be seen in the same table.

Table 4.1, Definition of identified cost elements and cost drivers.

Product Cost at GAS			
Cost elements	**Definition**	**Cost drivers**	**Data source**
Material cost	The price payed to suppliers when purchasing raw material.	Weight, alloy, dimensions, requirements, supplier base, ordering volume	Interview with product cost management engineer, purchasing analyst, strategy manager, process engineer and senior buyer
Purchased parts cost	The price payed to suppliers when purchasing a finished part.	Weight, alloy, dimensions, requirements, supplier base, ordering volume	Interview with product cost management engineer, purchasing analyst and strategy manager
Material surcharge cost	An overhead cost for ordering material, internal and external logistics cost and storage.	Material complexity	Interview with product cost management engineer and 2 operations controller
Manufacturing cost	The cost for all manufacturing operations.	Tolerances, product complexity, requirements, specific operations, number of processes, number of parts, extra inspections, material alloy	Product cost management engineer and chief manufacturing engineer
Manufacturing surcharge cost	An overhead cost for non-planned extra	Tolerances, product complexity,	Product cost management

	operations and non-conformances in manufacturing.	requirements, specific operations, number of processes, number of parts, extra inspections, material alloy	engineer, process verification engineer and chief manufacturing engineer
Outsourced operations cost	The price payed to suppliers when purchasing a manufacturing operation.	Part complexity, requirements, supplier base, ordering volume	Product cost management engineer, process verification engineer and chief manufacturing engineer
Method support cost	The personnel cost for all disciplines needed to support a product.	Product complexity, number of operations, number of processes, severity of processes, number of deviations in manufacturing, number and size of design changes	Product cost management engineer, process verification engineer and 3 program managers
Delivery cost	The cost for delivering the product to the customer.	Weight, requirements	Product cost management engineer and process verification engineer
Warranty cost	An overhead cost covering eventual warranty cost.	Risks of non-conformances	Product cost management engineer and process verification engineer
Scrap cost	An overhead cost covering eventual discarding cost.	Risks of non-conformances	Product cost management engineer and process verification engineer

4.1.3.1 Material cost

Material cost is the price GAS pay their suppliers when purchasing raw material. The three most common raw materials within turbines are forgings, castings and sheet metal in titanium based alloys or nickel based alloys.

The cost drivers within material cost are weight, dimensions and type of alloy. Complexity and specification of requirements also affect the cost, for instance if certain test methods are required in the fabrication. Furthermore, the order volume affects the cost but also the supplier base, which determines the competitiveness in the market. To have a broad supplier base is very important since it is significant to have a competitive situation with multiple suppliers to get good raw material prices. Therefore, GAS has a close collaboration between involved parties to increase the possibilities to control the material flow.

Buy-to-fly ratio is an indicator that refers to how much material that is removed within manufacturing before the product is finished. The strive is to remove as little material as possible, due to lower the manufacturing cost. Although, net shaped raw materials are more expensive, which means that there must be a balance between the purchase price and manufacturing cost.

4.1.3.2 Purchased parts cost

The cost for purchased parts are finished components that GAS buys from a supplier that goes directly into the assembly, for example standard parts such as screws, nuts and washers. GAS does not change anything on the parts and it does not go through any manufacturing processes at GAS. The cost drivers can be seen in Table 4.1.

4.1.3.3 Material surcharge cost

Material surcharge is an overhead cost that include the cost for ordering the material, i.e. personnel costs at the purchasing department and supplier quality engineers. Other included costs are logistics cost such as transportation costs to GAS's site in Trollhättan with freight charge, insurance and customs, but also internal transportation-, logistics- and storage costs. The main cost driver is the complexity of the material.

4.1.3.4 Manufacturing cost

The manufacturing cost is the cost for all manufacturing operations, including machining cost, tool cost, consumable cost and personnel cost for the operator. Every product has an operation list that describes the manufacturing flow and the included operations. All manufacturing operations for turbines can be seen in Appendix B.

There are many cost drivers within manufacturing. Generally, number of parts, number of processes and specific difficult operations affect the manufacturing cost. Another main cost driver are tolerances, where narrow tolerances want to be avoided if possible. By designing toward as wide tolerances as possible, costs can be reduced, since a wider range of manufacturing possibilities will be available and difficult and unnecessary processes can be avoided. Although, there must be a balance between how wide or narrow the tolerances are.

Alloy characteristics is a cost driver that affects the processing speed, which in turn affect the manufacturing time, and tool cost since the tools only stands for a certain amount of usage. The alloy type also affect the manufacturing risk since certain materials are more difficult to process. Generally, within cutting machining, nickel based alloys are more difficult, time consuming and expensive to manufacture than titanium.

4.1.3.5 Manufacturing surcharge cost

The manufacturing surcharge is an overhead cost, including the costs when something does not go according to the manufacturing plan i.e. non-conformances and extra operations. A non-conformance occurs when the product does not meet the set requirements and are often discovered in inspections. Non-conformances are classified in four categories;

- Q1 – Escapes, a non-conformance occurred at GKN but discovered by the customer.
- Q2 – A non-conformance occurred at the suppliers, but discovered by GKN.
- Q3 – A non-conformance that is internally discovered and occurred at GKN's manufacturing
- Q4 – Remaining, for instance non-conformances handled by specific processes and where the customer needs to be contacted to decide on what action to take on.

4.1.3.6 Outsourced operations cost

An outsourced operation, lejdoperation, is a manufacturing operation conducted at a supplier. For instance, when an unusual manufacturing process is required that does not exist at GAS, they hire another company. It can also be in cases of capacity reasons, where there is no available capacity in the own manufacturing.

4.1.3.7 Method support cost

Method support are the cost for all personnel needed to support the product that is not included in the other cost elements. It is built out of many disciplines involved in the product, for example project management, welding engineer, quality inspection and design engineer. All involved disciplines can be seen in Appendix A.

The identified cost drivers within method support are the complexity of the product, number of operations, number of processes and their severity, number of parts, tolerances set for the product, number of deviations within manufacturing and lastly number and size of design changes. The manufacturing volume also affects the method support cost for each product. If the production volume is higher, the cost is spread over a larger number of units, which lower the cost for each unit.

4.1.3.8 Delivery cost

Delivery cost represents the total cost for shipping the finished product to GAS's customers.

4.1.3.9 Warranty cost

Warranty is an overhead cost covering eventual warranty cost. The amount is saved internally for later use if needed.

4.1.3.10 Scrap cost

Scrap is an overhead cost covering eventual discarding costs.

4.1.4 Product cost estimation at GAS

The following information is based on interviews with several employees at GAS, which can be seen more precise in Table 4.1, but also from reviewing internal documents at GAS. Product cost management is not new at GAS, but prioritizing product cost in the early design phase is new within the space department. In the past product cost was not classified as important when selecting between design concepts, but is today highly prioritized. GAS do not have a clear procedure of estimating product cost adapted to the early design phase at the space department.

The present estimation methods that are used at GAS in the later design phase are very detailed and the product cost is broken down into elementary units, similar as analytical cost estimation techniques, which requires much information. The process is time consuming since much input data are needed and many disciplines must be involved since the required knowledge is spread. The models are developed during a long time in order to fit the manufacturing at GAS, and it is only a few persons that know how to use them correctly. Because the models are so detailed, the result may be very misleading if the models are filled in the wrong way. Experts must validate the maturity of the data, to get an output with high quality.

In the following chapters, it is explained for each cost element how product cost is estimated today at GAS.

4.1.4.1 Material cost

Material cost can be divided in two parts; "Raw material" and "Value add". The first part, raw material, is the actual price for the raw material at the market. The second part, value add, is the extra cost added by the supplier in order to fabricate the material and their profit.

$$\text{Total material cost} = \text{Raw material} + \text{Value add} \tag{4.1}$$

When estimating the material cost today several experts from the purchasing department and engineers are involved. The estimates are very detailed and accurate and often based on an offer from a supplier. These estimates are either calculated by one of GAS material experts or can be from a scaling of similar products.

4.1.4.2 Purchased part cost

Estimating the cost for purchased parts is done by experts at the purchasing department, by looking at quotes from suppliers or historical data.

4.1.4.3 Material surcharge cost

Material surcharge is calculated by a percentage of the material cost. The percentage is based on previous outcomes and updated once a year. The material surcharge is product specific and differs between various types of products.

4.1.4.4 Manufacturing cost

The manufacturing cost are estimated by the time for each operation and measured by the work center (WC) cost ($/h). A WC is a specific machine that has its own hourly cost, which includes the cost for machining, operators, electricity, standard equipment, maintenance, repairs and depreciation. It is calculated by dividing all costs in the WC with the budgeted processing hours and is updated once a year based on historical data from the business system.

$$\text{WC cost} = \text{all costs in WC} / \text{processing hours} \tag{4.2}$$

The manufacturing cost for an operation are divided into cost for set-up time, cost for machining time and cost for tools and consumables. The set-up time includes bringing the product to the machine, preparation and installation of the machine, change tools, cleaning and taking down the product afterwards. Machining time refers to the time when the product is processed. The cost for the set-up time and machining time is calculated by the hourly cost for the specific WC. Then, the cost for tools and consumables are added, to calculate the total manufacturing cost.

$$\text{Total manufacturing cost} = (\text{Setup time} + \text{machining time}) * \text{WC cost} + \text{tools cost} + \text{consumables cost} \tag{4.3}$$

When estimating the manufacturing cost today, the set-up time and operation time is estimated by experts. Estimating whether there is an extra tool cost is done by other experts. The process requires many involved experts, since it must be a detailed process.

4.1.4.5 Manufacturing surcharge cost

Manufacturing surcharge is calculated by a percentage of the manufacturing cost. The percentage is product specific and differs between various types of products. It is based on previous outcomes and updated once a year.

4.1.4.6 Outsourced operations cost

The cost for outsourced operations is fully dependent of what kind of work that is performed. When calculating the cost today, it is seen as purchased material and a material surcharge is added to the cost to cover the cost for buying the operation. The cost is estimated based on the cost for earlier outsourced operations or a quote from a supplier.

4.1.4.7 Method support cost

The cost for method support is calculated by estimating the hours required from each discipline to support the product in ongoing production. Every discipline belongs to a specific department which has its own hourly cost (cost/hour) that is based on the personnel costs. The method support is then calculated by multiply the hourly cost with the number of hours required from each discipline. Although, this can be difficult to follow up because it is problematic to find the number of hours required directly, since the business system is not built up so that every discipline can log their hours at a specific product.

$$\text{Method support cost} = \text{Number of hours} * \text{hourly cost} \tag{4.4}$$

4.1.4.8 Delivery cost

Delivery cost is estimated by looking at the cost for previous delivery to the same customer or by a quote from a supplier.

4.1.4.9 Warranty cost

Warranty is calculated from a fixed percent decided at GAS of the total product cost. The percentage is based on the risk of eventual unexpected events.

4.1.4.10 Scrap cost

Scrap cost is estimated by a percentage of the total product cost. The percentage is based on previous outcomes.

4.2 The new cost estimation model (NCEM)

GAS has a way of estimating product cost when an accurate product cost for complex products is needed, described in chapter 4.1.4. Although, when these models are used, a lot of information about the product is known, compared to the early design phase where no detailed information is available. Any common model to make rough estimates do not exist within the space department at GAS today, since it is hard to do these estimates sufficiently accurate. Together with experts from GAS and based on findings in the literature review, a new cost estimation model (NCEM) has been developed, which is a combination of various established techniques. Data was collected from interviews with many experts, which can be seen in Table 3.2, with the purpose to integrate their expert knowledge into the NCEM.

The NCEM developed in this study is a cost estimation procedure that is supposed to be used in the early design phase when estimating product cost. The NCEM is developed in Excel, but the functions are described in the following chapters. Product cost is broken down and includes the same cost elements as identified in chapter 4.1.3, which can be seen in Table 4.2. Furthermore, the way to estimate the costs has changed for some of the cost elements, which are described in the following chapters and a summary can be seen in Table 4.2. The model aims to be user-friendly and easy to apply. To use the NCEM, information is needed about what the product looks like, dimensions, material alloy and an idea of how the product should be manufactured.

Table 4.2, Definition of cost elements in NCEM.

Product cost in NCEM	
Cost elements	**Way of estimation**
Raw material cost	Estimated based on similarity in design and historical material alloy prices.
Purchased parts cost	No change
Material surcharge cost	No change
Manufacturing cost	Estimated based on a breakdown of the manufacturing operations. Depending on operation type, the cost is estimated based on removal rate, machining speed or standard times.
Manufacturing surcharge cost	Estimated per part based on the manufacturing overhead percentage which is scaled depending on product complexity.
Outsourced operations cost	No change
Method support cost	Estimated based on a prognosis for a specific product, which is scaled depending on product complexity.
Delivery cost	No change
Warranty cost	No change

Scrap cost	Estimated per part based on the scrap overhead percentage which is scaled depending on product complexity.

4.2.1 Material cost

The material cost is estimated based on historical data. A material list with 13 previous purchased alloys, whereof 8 nickel based forgings, 2 nickel based castings, 1 titanium based forging, 1 aluminum based plate and 1 stainless steel based forging have been created, including the price and price/kg. The estimation procedure will then be as follows; Identify a similar shape, alloy type, forging, casting or sheet metal, and if possible from the same supplier that is supposed to be used. Then, calculate the material cost by multiplying the weight with price/kg for the similar shape.

In the material list, it was shown that for nickel forgings the size of value add varies from 0-25% for the different parts. For nickel castings and the titanium forging, value add represent the major part of the total cost.

4.2.2 Purchased parts cost

The cost for purchased parts is estimated the same way as today at GAS, described in chapter 4.1.3.2.

4.2.3 Material surcharge cost

The cost for material surcharge is estimated the same way as described in chapter 4.1.4.3.

4.2.4 Manufacturing cost

The estimation of manufacturing cost is based on a breakdown of the manufacturing operations, which are then summed up. Depending on the type of manufacturing operation, the manufacturing cost can be calculated in three options, as seen below.

Option 1

Total manufacturing cost = (Setup time + standard time) * WC cost + tools cost + consumables cost

(4.5)

Option 2

Total manufacturing cost = (Setup time * WC cost) + machining cost + (extra machining time * WC cost) + tools cost + consumables cost

(4.6)

Option 3

Total manufacturing cost = (Setup time + machining time) * WC cost + tools cost + consumables cost

(4.7)

Option 1 is calculated by standard times. Based on interviews with manufacturing experts and reviews of operation lists for turbines, operations that usually take about the same amount of time has been identified, e.g. cleaning usually takes about X hours. The identified standard times have been integrated to the NCEM.

Option 2 is calculated by the machining cost. For turning, milling and drilling this is done by the cost for removed material. The cutting speed (cm^3/min) for the operations was identified together with a CAM consultant and Chief Manufacturing Engineer (2017-04-04), through a tool called Walter (Walter Machining Calculator, 2017). Different speeds were identified for a nickel based alloy and a titanium based alloy.

$$\frac{\$}{min} \Big/ \frac{cm^3}{min} = \frac{\$}{cm^3} \tag{4.8}$$

For welding and splines, the machining cost is calculated by the speed. The speeds (mm/min) were identified by one welding expert (Product engineer, 2017-04-10) and one splines expert (Engineering Management and Support, 2017-04-27). The welding speed varies for different types of welding, different thickness of the material and also for a nickel based alloy and a titanium based alloy. The speed for splines also varies for a nickel based alloy and a titanium based alloy.

$$\frac{\frac{\$}{min}}{\frac{mm}{min}} = \frac{\$}{mm} \tag{4.9}$$

Although, it was found out that the machining time includes much more time than the actual cutting time, for instance moving the component or changing tools. Thereby, an extra machining time must be added. The amount of time depend a lot of the product complexity and type of operation.

Option 3 is calculated the same way as today at GAS, described in chapter 4.1.4.4. This way is kept because it is the most suitable way of estimating cost for some operations.

Operation number	Operation Name	Enter number of units	Unit	Cost/Unit		Operation Cost	Factor	Manual Operation Cost	Setup time (h)	Setup time cost	Tools	Tool cost	Total Cost ($)	Risk	Guidance
Manufacturing inhouse															
100	START		h	-	-	-	1		-	-	-		-		-
200	TURNING		cm3	-	-	-	1		-	-	-		-		-
300	MEASUREMENT		h	-	-	-	1		-	-	-		-		-
400	GRINDING		h	-	-	-	1		-	-	-		-		-
500	CLEANING		h	-	-	-	1		-	-	-		-		-
600	INSPECTION		h	-	-	-	1		-	-	-		-		-
Total inhouse manufacturing cost without surcharges													0		
Manufacturing Surcharge													0		
Total inhouse manufacturing cost													0	-	

Figure 4.2, Example of an operation list in NCEM.

Guidance regarding tool cost (Product engineer, 2017-04-18) and set-up times are integrated in the NCEM. Operations that often follow each other are merged into a package that deliver an overall cost, which was developed together with an expert (Chief manufacturing engineer, 2017-03-17), to simplify the process of creating an operation list. An example can be seen in Table 4.3.

Table 4.3, A package of the different operations in a welding process.

Package: Welding TIG
CLEANING
FLOURESCENT PENETRANT INSPECTION
TIG WELDING
CLEANING
FLOURESCENT PENETRANT INSPECTION
X-RAY
HEAT TREATMENT
FLOURESCENT PENETRANT INSPECTION
X-RAY

A risk assessment matrix is also integrated in the NCEM, as can be seen in Table 4.4. The user should state how confident they are on the maturity level of the data. The user should also write down the assumptions that are made and on which facts data are based on.

Table 4.4, A risk assessment matrix form the NCEM.

Risk assessment

1-3	4-6	7-9
Uncertain	**Somewhat certain**	**Certain**
Choose this option if the process or technique is new to the company and the cost therefore is uncertain.	Choose this option if the process is somewhat familiar to the company and has been used before.	Choose this option if it is an operation that is performed every day and the cost therefore is certain.

4.2.5 Manufacturing surcharge cost

The manufacturing surcharge is estimated based on the current overhead percentage at GAS. Although, it can be scaled per part depending on how complex the part is to manufacture.

4.2.6 Outsourced operation cost

The cost for outsourced operations is estimated the same way as today at GAS, described in chapter 4.1.3.6

4.2.7 Method support cost

The cost for method support is estimated based on a prognosis of a method support cost for the turbine Vinci LOX that includes number of hours required from each discipline, which is scaled depending on the complexity of the new product. The way of estimating the method support in the NCEM was developed together with three Program Managers and one Product cost management engineer at several meetings.

The method support is divided in one fixed and one variable part.

$$\text{Total method support cost} = (\text{Fixed part/product volume per year}) + (\text{Variable part} * \text{Factor}) \tag{4.10}$$

The fixed part consists of the minimum hours required to support the project during a year, i.e. X hours of project management is required to support the product during a year. The cost for the total number of hours in the fixed part is divided by the product volume for one year, to get the cost per product. The variable part consist of hours that may be required per product, depending on the product complexity. The variable part is scaled by a factor, determined by the cost drivers, as can be seen in Figure 4.3. Data from the turbine Vinci LOX work as the baseline and a comparison is done between Vinci LOX and the new product.

Method Support Estimation			
Fact-based cost drivers	**Quantity Vinci LOX (target time)**	**Quantity New Product**	**Calculation**
Number of operations	10	5	0,5
Number of processes	10	5	0,5
Number of parts	10	5	0,5
Estimated cost drivers	**Factor Vinci LOX (target time)**	**Factor New Product**	
Tolerances	1	0,5	0,5
Severity of processes Number of deviations in manufacturing Number and size of design changes	1	0,5	0,5
Average Factor:			0,5

Factor estimation
Easy = 0-0,999
Normal = 1 (Equal Vinci LOX target time)
Hard > 1,111

Figure 4.3, Example showing the calculation of the factor that are used to scale the method support cost.

4.2.8 Delivery cost

The delivery cost is estimated the same way as today at GAS, described in chapter 4.1.4.8.

4.2.9 Warranty cost

The warranty cost is estimated the same way as today at GAS, described in chapter 4.1.4.9.

4.2.10 Scrap cost

The scrap cost is estimated based on the current overhead percentage at GAS. Although, it can be scaled per part depending on how complex the part is to manufacture.

4.3 Testing the new cost estimation model (NCEM)

Due to lack of data, only one real test was done to validate the NCEM. The outcome of an estimation of the method support cost was compared with a prognosis of a method support cost for three different turbines. The results can be seen in Table 4.5.

Table 4.5, Results from testing the way of estimate the method support cost in NCEM.

Test of method support cost		
Turbine	**Cost from prognosis**	**Cost from test**
Vinci LH2	A	0,98A
Vulcain LH2	B	0,5B
Vulcain LOX	C	0,8C

4.4 Advantages and disadvantages with the new cost estimation model (NCEM)

This chapter examines the advantages and disadvantages with the NCEM, which derived from interviews at GKN.

4.4.1 Advantages

- A structured and common procedure of estimating product cost in the early design phase, which means that the estimated costs can be compared, since they are estimated in a similar way. Information about available manufacturing processes and historical cost data are gathered in one file.
- Cost break downs per part, per cost element and per manufacturing process visualizes the main cost drivers.
- The risk assessment and written assumptions makes the estimate more transparent.
- Integrated standard times and standard cost for tools enables easy and quick estimates.
- The material list makes previous prices available directly.

- The packages of manufacturing operations guide the user when creating the operation list.
- Less experts needs to be involved in the product cost estimation process.

4.4.2 Disadvantages

- The NCEM must be kept up to date, otherwise it will not be useful.
- The underlying data in NCEM needs to be validated further.
- It is difficult to estimate the number of extra machining hours required when estimating the manufacturing cost.
- A real outcome should be used instead of a prognosis when estimating the method support cost.

4.5 Expert knowledge and reduction of uncertainties

An expert is someone that has a lot of knowledge and experience within a specific area and also knowledge of the various cost drivers. GAS has many experts within different areas, for instance purchasing, manufacturing processes, design and materials. The experts are many due to the high requirements of the products that GAS manufactures. Many employees have worked within the same area for many years, which means that they have extensive knowledge and experience within their area.

The main insights about how to reduce uncertainties in the early design phases when estimating product cost is to have knowledge about the cost elements and cost drivers. Transparency is therefore very important. It is of high significance to show the assumptions that have been made during the way and what data the estimate relies on and thereby create greater awareness. The data needs to be traceable, so that others also can get access to it and get the same picture. It is vital that everyone get access to the same information. This is of importance to manage and eliminate the uncertainties, but also to be able to map out the risks.

Undoubtedly, experts are a prerequisite for getting data with good quality, since they have knowledge of what good quality is. To get a deeper understanding about the cost elements when estimating product cost, it is vital to break down the cost into smaller units.

5 DISCUSSION

The following chapter will discuss the result presented in this study and be put in context with the objective. The development of the NCEM will be discussed and the NCEM and cost elements will be evaluated and discussed in relation to theory.

The manufacturing characteristics at GAS contributes to the difficulties in estimating product cost. Firstly, the production volume does affect the knowledge about the exact manufacturing time. Saving one minute within manufacturing does not affect the costs in a low volume production, in comparison to a high volume production where manufacturing time is highly prioritized. At GAS, functionality and quality are instead highly prioritized because of the high requirements of the product. Secondly, the production system also affect the difficulties in estimating product cost. Since every product has a unique manufacturing flow in a functional production, there may not be detailed cost information about all flows.

5.1 Development of the new cost estimation model (NCEM)

One of the problems when dealing with complex products, is that there is much information and it can therefore be difficult to sort out what is most significant. The hardest part when creating the NCEM was to not get stuck in the details. Since the NCEM consists of many parts, it was vital to collect information about all cost elements to get the whole picture. In this case, this worked well because the developed model is not meant to calculate an exact cost, but rather to be used to compare the cost of different concept in the early design phase. In other words, the NCEM should represent the total product cost in a reasonable way. Although, a model will never manage to show the exact picture of the reality. Further, the advantages of using a common way to estimate product cost is that the costs for the different designs will be compared under the same conditions.

Another difficulty, was that sometimes experts was not willing to share all information during the interviews, since they were afraid that it was going to be used in a wrong way or be interpreted incorrectly. Another reason could also be that they wanted to keep their own knowledge to not be left outside any processes.

The NCEM is a combination of the intuitive, analogical and analytical cost estimation techniques that are described in the theoretical framework, chapter 2.5. This since both a break down approach, historical data and past experience are used. In the NCEM, the product cost is broken down into different cost elements and the cost for each element are determined, which can be referred to the detailed analytical cost estimation technique. According to the theory, analytical techniques are often used in the final design phase, since they require detailed information. Although, if an accurate result is needed, this is the best way to conduct the cost estimate. As described by Niazi et al. (2006) in chapter 2.5.2, when dealing with complex products detailed information is needed to deliver a reliable estimate.

According to Layer et al. (2002), see chapter 2.5.3, cost estimation models are often company specific or product specific and a mixture of various techniques, which also is the case for the NCEM developed in this study. This means that the NCEM is limited to be used for space turbines at GAS. Although, it is the underlying data that are company specific and limiting due to the unique characteristics at GAS, for instance cutting speed and tool costs. However, the way of determining the costs can be transferred to other companies and similar industries. For sure, others can get use of integrating expert knowledge into product cost estimation to reduce uncertainty.

Important is that the NCEM will need to be updated with the new hourly cost and currency every year at GAS. The standard times will also have to be looked over to see if there are changes. Furthermore, the model only contains the manufacturing processes that exist within space turbines at GAS today, which is a limitation. If other processes will be used, they will have to be integrated into the model.

5.2 Expert knowledge and reduction of uncertainties

In comparison to not using any common way to estimate product cost in the early design phase, this is a great step in the right direction. By using a common approach, costs can be compared in a similar way and uncertainties regarding product cost can be identified. As Layer et. al. (2002) stated in the theoretical framework, see chapter 2.5.3, this study also identifies that a break down approach is vital to capture all costs and gain understanding of the cost drivers. Cost break downs in pie charts visualizes the main cost contributors in the NCEM. Transparency is important to see what assumptions that have been made and to show the maturity and quality of the data used in the estimate.

Furthermore, there is a connection between the cost drivers and uncertainty. The cost drivers generate uncertainties and difficulties, thus by integrating expert knowledge to the cost estimation procedure will create greater awareness of the cost drivers, which in turn can reduce uncertainties regarding product cost. Integrating expert knowledge in the early design phase is also in line with the concept of core competences, see chapter 2.6, which captures and utilizes the firm´s uniqueness. It is a way of rising the knowledge level, which according to Dosi and Egidi (1991) is a reason why uncertainties arise.

However, the uncertainties associated with cost estimations are of both substantive and procedural kind, as described in chapter 2.7. Some uncertainties, such as raw material prices, are due to lack of information. On the other hand, uncertainties such as manufacturing cost, are due to lack of knowledge of the decision maker, since the knowledge are spread across many experts.

A critical factor when estimating product cost in the early design phase is time. This because there often are several design concepts that should be evaluated. According to Howards (1966) theory the value of information, the cost for conducting the estimates should not exceed the value of it, which is why time is a critical in this phase. However, by integrating expert knowledge in the NCEM, the process will be time saving and not as costly to perform since much information is gathered in one place.

The NCEM is a way of breaking the phenomena "over the wall engineering", as described in Figure 2.3. Previously, this wall has been high between the design department and the production department at GAS. This may be due to the high requirements of the product and the advanced manufacturing processes. Although, the disadvantage of having many experts that are described in "over the wall engineering" does not exist in a larger extent at GAS today. Instead they see the advantage of collaboration between experts. Undoubtedly, this study and the NCEM has led to new connections between the departments and experts which hopefully will be useful and lead to new and improved collaborations in the future.

To reduce uncertainties regarding manufacturing cost in the NCEM, the user of the NCEM needs to do a risk assessment for every operation in the operation list. This is consistent with Knight (1921) who states that risks are a way of managing uncertainties. The risk assessment in the NCEM works as an indicator which create more awareness but do not affect the cost. Showing what assumptions that are done when conducting an estimate is consistent with Rush and Roy (2006) who states that it is important to understand the reason behind the knowledge, for instance why and how a certain cost driver affect cost.

5.3 Cost elements

The following chapters discuss the different cost elements more in detail. The conclusion can be drawn that different cost estimation techniques are suitable for different cost elements. However, this is what differs from the techniques described in the theoretical framework, since more than one technique are used to estimate the product cost.

5.3.1 Material cost

The way the material cost is estimated in the NCEM can be linked to the analogical technique since it is based on historical data. The analogical technique identifies similarities between historical parts and the new part, and estimates the new cost from that. This is also the idea with the material list, where the user is supposed to find a similar purchased part and thereby estimate the cost.

The first idea when finding a way to estimate the material cost in the NCEM was to find a common percentage of the amount of value add of the total raw material price. But, since there was a limited amount of previous purchased parts to study and the developed material list only consisted of 13 parts, it was not possible to find a reliable percentage. However, if more parts are added to the list, there might be a chance to find a common percentage. In that case, it will be possible to determine the raw material price on the market by only knowing the material weight and alloy type. But, there might also be that there are no common percentage, because the material price depends too much on the complexity of the product and the supplier base. Although, this will need further investigation. For nickel based forgings, the size of value add varied between 0-25%, which can be used as a guideline, see chapter 4.2.1.

The developed material list described in chapter 4.2.1, only consists of purchased parts used in today's production, which is a limitation if new alloys wants to be used in the future. The model will only work if the new design is similar to one in the list, which makes it incomplete. Another uncertainty within material costs which also needs to be considered, is the changes in raw material prices at the market, which is an exogenous uncertainty described by Trkman and McCormack (2009), see chapter 2.7. Although, the company itself cannot have any influence on the price at the market, but it is important to keep the raw material price forecasts up to date.

5.3.2 Manufacturing cost

The estimation of the manufacturing cost in the NCEM can be linked to both the analytical, intuitive and analogical techniques. The analytical technique breaks down the product into smaller units, which also is done in the NCEM, where the cost for each manufacturing operation is determined.

The operations where the costs are calculated according to option 1, see chapter 4.2.4, are based on standard times. These times needs to be updated occasionally to assure that they are up to date. This option can be referred to the analogical cost estimation technique where historical data work as the base. The operations where the costs are calculated according to option 2, see chapter 4.2.4, are supposed to be easy to estimate since only the material volume or welding length are needed, which easily can be obtained from a CAD-model. Unfortunately, the underlying data has not been validated and will thereby need further investigation. Also, guidance regarding how much extra machining time that must be added needs further investigation by experts. The operations where the costs are calculated according to option 3, see chapter 4.2.4, needs expert knowledge to identify a reliable operation time. Estimating the time for each operation can be linked to the intuitive technique that are based on expert's knowledge and experience.

Estimating the manufacturing cost in the NCEM is based on the hourly cost, which is determined by the WC cost, which in turn is based on historical outcomes. This way of determining the manufacturing cost can in some cases be misleading. The hourly cost may not show the exact cost for the manufacturing operation, since it depends on how the hourly cost is calculated but also the quality of the underlying data. For instance, the operation time that is logged in the business system may not always be the exact real time or there might be a difference in costs between different machines, but they still have the same hourly cost. However, it is the best information available and improving these numbers is a continuously ongoing improvement work at GAS.

Certain packages with related manufacturing operations have been created. This was done to visualize which operations that are mandatory in some processes. It eliminates the risk that some processes may be forgotten when creating an operation list. This is the kind of information that experts possess much knowledge of. As mentioned earlier, the packages are based on the manufacturing that exist today, which may be changed in the future.

5.3.3 Manufacturing surcharge cost and scrap cost

The manufacturing surcharge cost and the scrap cost are supposed to be scaled depending on the product complexity. If the product is less complex, fewer deviations within manufacturing would probably occur, which makes these costs lower. However, estimating the overhead percentage should be done together by at least two experts to ensure the reliability. To estimate the overhead percentage requires experience and knowledge from previous manufactured products. In line with Aniander et al. (1998), see chapter 2.1, overhead costs are difficult to distribute fairly.

5.3.4 Method support cost

Estimating the method support cost in the NCEM can be linked to the analogical and intuitive techniques. Historical data work as the baseline where data from a prognosis is compared with the new design and scaled to fit the new product. Expert knowledge will be needed to estimate the factor, since certain experience and knowledge is required to perform that correctly. The suggestion is that the estimate is done together with at least one coworker to enable a discussion and thereby get a more reliable result. Because, if the estimate is conducted by only one person it will be very personal. For instance, one coworker might find the tolerances to be equal to Vinci LOX while another might find them wider. It is therefore beneficial if the involved are familiar with the tolerances on Vinci LOX, the requirements of new product and what affect tolerances have on manufacturing processes.

In the NCEM a prognosis work as the baseline, but it would have been even better if a real outcome was used. However, due to lack of data this could not be done. Although, showing the number of hours required from each discipline to support the product during manufacturing, gives a great knowledge of the amount of support needed. In the NCEM the method support was divided in one fixed and one variable part to be able to affect the size depending of the complexity of the product, but still keep the fixed part as a minimum support.

Just as Kaplan and Cooper (1988) states, see chapter 2.1, the method support cost is hard to estimate. The results from the test, shown in chapter 4.3, show variable results. Nevertheless, only 3 tests were conducted and to validate the model, more tests are required. The test of Vulcain LH2 which differed in 50% probably varies because all disciplines involved within that turbine was not represented. The user of the NCEM should therefore have that in mind when estimating the method support cost and add extra hours or cost if all disciplines are not represented.

6 CONCLUSION

The following chapter aims to answer the objective of this study and explain under which circumstances this is useful. Further, the limitations within the study are discussed.

The cost drivers generate uncertainties and difficulties in the early design phase, and there is a connection between the cost drivers and uncertainty. Integrating expert knowledge, brings greater awareness of the cost drivers, which in turn can reduce uncertainties regarding product cost. Knowledge about the cost drivers during the early design phase can also contribute to a reduced product cost by designing and selecting low-cost products.

This study identifies that different cost estimation techniques are suitable to use for different cost elements. When estimating product cost, it is always important to state what assumptions that have been made. The key to build a good product cost estimate is transparency where the cost can be broken down and the assumptions are clearly stated. This identifies risks and in turn reduces uncertainties. Transparency also provides an increased knowledge level for other estimators, which can lead to reduced uncertainties.

Within this study, a NCEM model is developed at GAS, which means that the model is limited to be used at GAS. The limiting part is mainly the underlying data, but the way of determining the costs can be transferred to other companies and in similar industries.

The data that has been studied is mainly within space turbines. This means that the NCEM is limited to be used within these kinds of products at GAS. Furthermore, the model only contains the manufacturing processes that exist within space turbines at GAS today, which is a limitation. If other processes will be used in the future, they will have to be implemented into the model.

7 RECOMMENDATIONS AND FUTURE WORK

This chapter proposes recommendations and future work within the research area.

Recommendations for future work within this area is to explore how to estimate the size of identified uncertainties. This knowledge would provide greater insights in the early design phase when estimating product cost.

Another suggestion is also to explore how much it costs to integrate expert knowledge when estimating product cost in the early design phase.

Future work is also to further develop the NCEM presented in this study and to validate the functionality. This can be done by create a real test of the NCEM and thereafter compare it to a real outcome. The NCEM can also be developed to become more general and to be applicable for other products as well.

At last, this study can also be performed at other companies and in other industries to explore the research area further.

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Appendix A: DISCIPLINES INCLUDED IN METHOD SUPPORT

Method support Fixed Part

Disciplines	**Percent Fixed (%)**	**Hours (h)**	**Hourly cost ($/h)**	**Total cost ($)**
Commercial				
Project Management				
Production technology serial support				
Method support various				
Instrumentation				
Compliance Verification Engineer (CVE) Product				
CVE Abrasion resistance and durability				
CVE Manufacturing and assembling				
Materials Application Engineer (MAE) and CVE Materials and Processes				
Quality Inspection				
Strength calculations				
Aero				
Engineering Method Specialist (EMS) Design				
EMS Method owners and Manufacturing processes				
Definition				
Construction Management				
Quality technology				
Material Technology				
Quality Assurance (QA)				
NC-Preparation				
CPT-Preparation				
Welding engineer support				
Total per year ($)				
Volume				
Total per hardware ($)				

Appendix B: MANUFACTURING OPERATIONS AT GAS

Machining

- Turning
- Milling
- Drilling
- Splines
- Grinding

Manual Processing

- Deburring
- Assembly
- Polishing

Inspections

- Start
- Inspections
- Labeling
- Balancing
- Control thermal spraying
- CMM
- Measuring

NDT

- Ultrasonic testing
- Fluorescent penetrant inspection
- Eddy current testing
- Pressure test
- Xray

Processes

- Vacuum brazing
- Pickling
- Etching
- Cleaning
- Shot peening
- Masking
- Blasting
- Plasma spraying
- Heat treatment
- Brazing
- Welding

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