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COST ENGINEERING: WHY, WHAT AND HOW?

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Abstract

Cost has become a major business driver in many industries. It is observed that there is a lack of understanding about the process to estimate, manage and control costs across the lifecycle of a product. This report presents a business case to understand the principles of 'Cost Engineering' within the manufacturing industries. The main focus of the report is in the techniques and tools used in cost estimating – one of the major activities in cost engineering. Five different methods of cost estimating are discussed in the report along with cost management issues including risk analysis. The report also presents research findings on 'industry practice' in hardware and software development cost estimating. The study shows the lack of research in hardware cost estimating and highlights the lack of communication within different groups of people involved in cost engineering. The report then focuses on the research trends in cost engineering and presents two case studies from recent research projects at Cranfield University. The case studies clearly show the progress in formalising the cost engineering process and the improvements in the current understanding about the domain. Two major areas of research as identified in the report are: i) integrating the cost engineering capability with the ERP (enterprise resource planning) environment so that data can be shared effectively, and ii) capture and reuse of human expertise in cost engineering for performance improvement. Finally, the report also identifies the need for simpler and cheaper cost engineering software for Small and Medium scale Enterprises (SMEs).

Keywords: *Cost engineering, Cost estimating, Cost management, Cost modelling*

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1. Introduction

Cost is perhaps the most influential factor in the outcome of a product or service within many of today's industries. More often than not, reducing cost is essential for survival. To compete and qualify, companies are increasingly required to improve their quality, flexibility, product variety, and novelty while consistently reducing their costs. In short, customers expect higher quality at an ever-decreasing cost. Not surprisingly, cost reduction initiatives are essential within today's highly competitive market place. Since cost has become such an important factor of success, project development needs to be carefully considered and planned. Recent research demonstrates that companies unable to provide detailed, meaningful cost estimates, at the early development phases, have a significant higher percentage of programs behind schedule with higher development costs, than those that can provide completed cost estimates [Hoult et al. 1996]. Therefore, it is essential that the cost of a new project development be understood before it actually begins. It could mean the difference between success and failure.

Cost engineering is concerned with cost estimation, cost control, business planning and management science, including problems of project management, planning, scheduling, profitability analysis of engineering projects and processes. The cost engineer is a qualified professional dedicated to total cost management over the life cycle of a project, facility or manufacturing operation. They need to stay abreast of technology and legislative changes so as to understand the cost implications.

This report introduces cost engineering concepts, techniques, current status and issues for manufacturing engineers. The intention is to encourage engineers to think about and appreciate cost engineering. This report starts with a discussion on the need for cost engineering and then briefly introduces different cost estimating methods. The next section of the report presents state-of-the-art practices in hardware and software cost estimating. Along with the industrial practice, research in cost engineering is presented with two case studies from Cranfield University. The research results are limited to aerospace, automotive and defence industries, and reflect mostly an European view on the issues.

2. The Need For Cost Engineering

Cost engineering helps companies with decision-making, cost management and budgeting with respect to product development. It is a methodology used for predicting/forecasting/estimating the cost of a work activity or output [Stewart et al. 1995]. Cost estimates during the early stages of product development are crucial. They influence the go or no-go decision concerning a new development. If an estimate is too high it could mean the loss of business to a competitor. If the estimate is too low it could mean the company is unable to produce the product and make a reasonable profit. In this ever-increasing competitive market, cost engineering is becoming a necessity for survival and not a 'nice to do'.

Many authors agree that 70-80% of a product cost is committed during the concept phase [Stewart et al. 1995; NASA 2002a; Taylor 1997; Mileham et al. 1993]. Making a wrong decision at this stage is extremely costly further down the development process (Figure 1). Product modifications and process alterations are more expensive the later they occur in the development cycle. Thus, cost estimators need to approximate the true cost of producing a product, based on empirical data, with the purpose of satisfying both the customer and company.

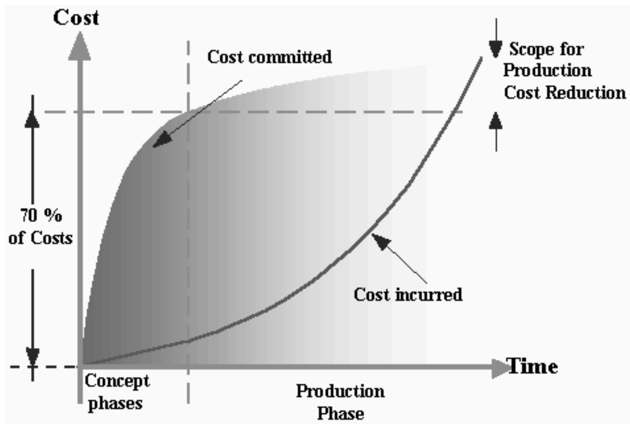

Figure 1: Cost commitment curve

The difficulties of estimating at the conceptual design phase are well recognised [Pugh 1992; Buxton et al. 1994; Meisl 1988; Rush and Roy 2000]. The major obstacles estimators need to address are:

- Working with a limited amount of available data concerning the new development.
- Accounting for step changes within technology over the life span of a product development (a more pronounced problem within the aerospace industry).
- The requirements to show how cost estimates were derived including the assumptions and risks.
- Cost of outsourcing a part to a supplier.
- The estimates need to be accurate.

Therefore estimators/engineers need company-wide co-operation and support, to assist them with their decision-making. Concurrent engineering is an excellent approach to assist this process; however, it does present a new set of challenges as outlined in the next section.

The ongoing value migration from hardware to software and continued pressure on profit margins, resulting from global competition, stresses the need for organisations to implement estimating practices for the software cost estimating domain as well. Consequently, the effects of poor estimating are growing ever more severe. The importance of software to businesses has also dramatically increased in recent decades. The business benefits and potential rewards of powerful software have become so huge that many organisations have been able to justify the large amount of investment in its development. Today, 80% of total expenditure on information technology is spent on software, compared to 20% in the 1950s, mirroring the continuous migration of value from hardware to software [Roy et al. 2000]. This report also presents the status of software cost estimating practice in Europe.

3. Cost Engineering Within A Concurrent Engineering Environment

An optimised concurrent engineering environment provides an opportunity to substantially reduce the total cost of a project. This is because integrated product teams (IPTs), containing members of various skilled disciplines, enable a simultaneous contribution to an early product development and definition. Therefore, within a fully integrated product development (IPD) cycle, multidisciplinary teams working together increase the likelihood of a reduced lifecycle cost by avoiding costly alterations later in the design process. With this view in mind, concurrent engineering is a great step forward when compared to an 'over the wall mentality' where each department works in 'isolation'. However, a concurrent engineering environment presents many new challenges to cost estimators whom, it could be argued, are more used to predicting the cost of an 'over the wall' environment. The impacts from adopting a concurrent engineering philosophy are substantial and often require significant changes to long-standing working practices. The whole culture begins to change. Existing costing methods and systems soon become outdated and require updating to reflect the new environment. Thus, cost engineers find it extremely difficult to predict cost within this new environment with their existing tools [Rush and Roy 2000]. This is not all bad because it offers an opportunity to introduce new approaches to old and possibly outdated working practices. This could cause difficulty for some, since advances in technology and techniques have grown rapidly over the last decade. The period of change could be a daunting prospect unless practitioners have had the opportunity to follow recent trends and developments.

4. Cost Estimating Methods

4.1. Traditional Cost Estimating

In traditional costing there are two main estimates: a 'first sight' estimate, which is done early in the cost stage, and a detailed estimate, done to calculate costs precisely. The former of these cost-estimating methods is largely based around the experience of the estimator. For example, it is not uncommon for a 'first sight' project estimate to be based upon a past similar project or purely on experience in costing. However, to attain this level of experience takes years of apprenticeship and considerable oversight from senior estimators. Although useful for a rough order of magnitude estimate, this type of estimating is too subjective in today's cost conscious culture and more quantified and justified estimates are required [Roy et al. 1999a, 1999b].

For detailed estimates, cost is based upon the number of operations, time per operation, labour cost, material cost and overhead costs in case of hardware cost estimating. Much of the information in a detailed estimate is based upon the internal synthetics (times or costs based upon expected rates of work for any particular task) of the company. To generate these estimates, it is necessary to have an understanding of the product, the methods of manufacture/process and relationships between processes. Detailed estimating goes through several iterations, since feedback from the relevant departments enables the estimates to be reviewed and improved. Thus, detailed estimating can be achieved only when a product is well defined and understood.

Activity based costing (ABC) is a process for measuring the cost of the activities of an organisation [Dean 2003; Cokins 1998]. It is a quantitative technique used to measure the cost and performance of activities e.g. inspection, production processes and administration. Each activity within an organisation is first identified and then an average cost is associated. Once this is achieved, it is then possible to estimate the amount of activity a product is likely to need and then associate the relative costs. This makes ABC appealing since it combines estimates with hard data. This method follows similar processes to detailed estimating and also requires a detailed understanding of the product definition. Thus, both detailed and ABC techniques are not useful during the conceptual phase of project development. In order to estimate a project during this stage other approaches are required. These are now discussed.

4.2. Parametric Estimating

A widely used method for estimating product cost at the early stages of development is known as parametric estimating (PE). To illustrate this concept more clearly consider this hypothetical example: typically for aircraft development mass relates to the cost of production. That is, as the weight of the aircraft increases, so does the cost of producing it. This particular relationship is often described as linear as illustrated in Figure 2 where the points of the graph represent the relationship of cost to mass for different aircraft. The line traversing the points represents a linear relationship, i.e. as the mass increases so does the cost. Using relatively simple algebra it is possible to derive a formula to determine a mathematical relationship for cost to mass, i.e. the equation $y = ax + b$ is used to describe the line of best fit between the points. With the relationship described, it is then possible to use the formula to predict the cost of a future aircraft based on its weight alone. Within the field of cost estimating this relationship is known as a cost estimating relationship (CER).

This is a rather simplistic illustration describing the main principals of parametric estimating. Nonetheless, variations of this approach are a widely used method within industry to predict the cost of a product under development and throughout the lifecycle. As CERs become more complex involving several variables, more complex mathematical equations are used to describe the relationships. When CERs become too complex for mathematical equations to solve, cost algorithms are developed [NASA 2002a]. Similarly, for software cost estimating often a linear relationship between number of source lines of code (SLOC) and cost is established.

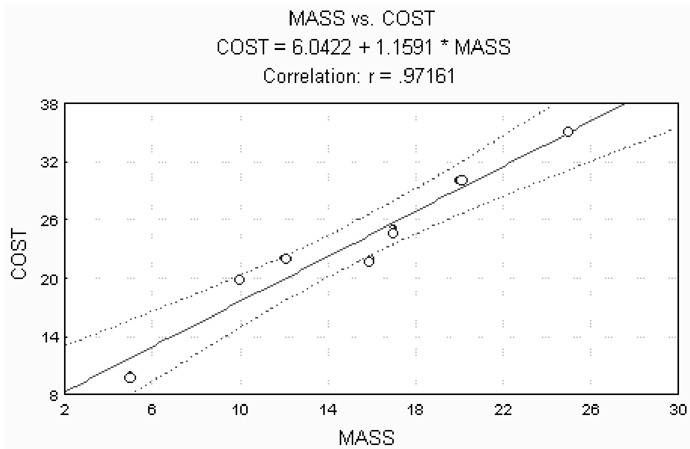

Figure 2: Example of a parametric equation

4.2.1. Using Parametric Estimating

Parametric estimating can be used throughout the product lifecycle. However, it is mainly used during the early stages of development and for trade studies, e.g. within design to cost (DTC) analyses (Section 5.2.). Both industry and Government accept the techniques, and many authors commend its usefulness [Stewart et al. 1995; NASA 2002a; Mileham et al. 1993; Pugh 1992]. However, PE does have its downsides, for example, CERs are sometimes too simplistic to forecast costs. Furthermore, PE is primarily based on statistical assumptions concerning the cost driver relationships to cost, and estimators should not completely rely upon statistical analysis techniques. Hypotheses, common sense and engineering knowledge should come first and then the relationship should be tested with statistical analysis. Most CER literature describes the process for estimating quantitative issues but not qualitative/judgmental issues. Cranfield University is currently researching this area and early work demonstrates the validity of this innovative approach [Roy et al. 1999a, 1999b]. In summary parametric estimating is an excellent predictor of cost when procedures are followed, data is meaningful and accurate, and assumptions are clearly identified and carefully documented. A relatively new form of PE is that of feature based costing. This has become popular due to the rise and sophistication of CAD tools.

4.3. Feature Based Costing

The growth of CADCAM technology, especially that of 3D modelling tools, have largely influenced the development of feature based costing (FBC). Researchers are investigating the integration of design, process planning and manufacturing for cost engineering purposes using a feature based modelling approach [Wierda 1991; Bronsvoort and Jansen 1994; Catania 1991; Ou-Yang and Lin 1997]. FBC has not yet been fully established or developed with respect to cost engineering. Nonetheless, there are several good reasons for examining the use of features as a basis for costing during the design phase. Products can essentially be described as a number of associated features i.e. holes, flat faces, edges, folds etc (Figure 3). It follows that each product feature has cost implications during production, since the more features a product has the more manufacturing and planning it will require [Brimson 1998]. Therefore, choices regarding the inclusion or omission of a feature impact the downstream costs of a part, and eventually the lifecycle costs of the product [Kekre et al. 1999].

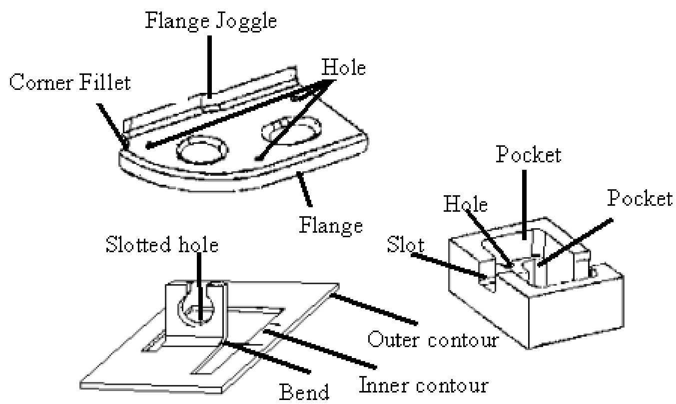

Figure 3: Examples of different views on features [Rush and Roy 2000]

Other reasons for using FBC are that the same features appear in many different parts and products; therefore, the basic cost information prepared for a class of features can be used comparatively often. Furthermore, manufacturers will have numerous past geometric data that can be related to features. Another reason developers explore whether costs should be assigned to individual design features is that it would provide designers with a tool to visualise the relation between costs and aspects of the design that they can influence in real time as the product is developed. Furthermore, engineering intent can be encapsulated within features such as product functionality, performance, manufacturing processes, and behaviour characteristics. Cranfield University is currently performing research to develop a methodology for 'cost of function'.

4.3.1. Feature Based Costing Issues

Although feature based costing is gaining popularity, there are limitations for using it for the costing process. There is no widely accepted consensus on what a feature is across the disciplines of an organisation. This problem is magnified when viewed across companies and industries. With respect to this problem, companies are faced with producing their own feature definitions. Table 1 shows an example of how one cost engineering group categorised features for the purpose of costing [Taylor 1997]. This illustrates one level of feature definition; however, there are several levels of features definitions. For example, a feature of an aircraft could be a wing, yet this wing contains many parts, each of which consists of many lower level features. Therefore companies are also left to decide how to cope with the changing product definition and applying an appropriate feature based CER. Thus, the feature based costing approach is not yet fully established and the implications are not yet completely understood. Nonetheless, companies find the concept appealing.

Table 1: Examples of features

Feature type	Examples
Geometric	Length, Width, Depth, Perimeter, Volume, Area.
Attribute	Tolerance, Finish, Density, Mass, Material, composition.
Physical	Hole, Pocket, Skin, Core, PC Board, Cable, Spar, Wing.
Process	Drill, Lay, Weld, Machine, Form, Chemi-mill, SPF.
Assembly	Interconnect, Insert, Align, Engage, Attach.
Activity	Design Engineering, Structural Analysis, Quality assurance.

4.4. Neural Network Based Cost Estimation

Other recent developments within the cost estimating community concern the use of artificial intelligence [Rush and Roy 2000]. Neural networks (NNs) and fuzzy logic present the next generation in computerising the human thought processes [Villarreal et al. 1992]. Many researchers and practitioners are fast developing and investigating the use of artificial intelligence (AI) systems and applying them to cost estimating situations [Bode 1998; Smith and Mason 1997; Hornik et al. 1989]. For cost estimating purposes, the basic idea of using NNs is to make a computer program learn the effect of product-related attributes to cost. That is, to provide data to a computer so that it can learn which product attributes mostly influence the final cost. This is achieved by training the system with data from past case examples. The NN then approximates the functional relationship between the attribute values and the cost during the training. Once trained, the attribute values of a product under development are supplied to the network, which applies the approximated function obtained from the training data and computes a prospective cost. Recent work has demonstrated that neural networks produce better-cost predictions than conventional regression costing methods if a number of conditions are adhered to [Bode 1998]. However, in cases where an appropriate CER can be identified, regression models have significant advantages in terms of accuracy, variability, model creation and model examination [Smith and Mason 1997].

4.4.1. Uses Of Neural Networks

The neural network does not decrease any of the difficulties associated with preliminary activities when using statistical parametric methods, nor does it create any new ones. The analyst is still left with a choice of cost drivers and must make a commitment to collecting specific cost data before analysis can begin. Models can be developed and used for estimating all stages of a product life cycle provided the data is available for training. A great advantage that a neural network has compared to parametric costing is that it is able to detect hidden relationships among data. Therefore, the estimator does not need to provide or discern the assumptions of a product to cost relationship, which simplifies the process of developing the final equation [Hornik et al. 1989].

4.4.2. Issues Related To Neural Networks

Neural networks require a large case base in order to be effective, which would not suit industries that produce limited product ranges. In addition, the case base needs to be comprised of similar products, and new products need to be of a similar nature, in order for the cost estimate to be effective. Thus, neural networks cannot cope easily with novelty or innovation. With regression analysis one can argue logically and audit trail the development of the cost estimate. This is because the analyst creates a CER equation that is based on data, common sense and logic. When considering neural networks, the resultant equation does not appear logical even if one were to extract it by examining the weights, architecture and nodal transfer functions that were associated with the final trained model. The artificial neural network truly becomes a 'black box' CER. This is no good if customers require a detailed list of the reasons and assumptions behind the cost estimate. The black box CER also limits the use of risk analysis tools.

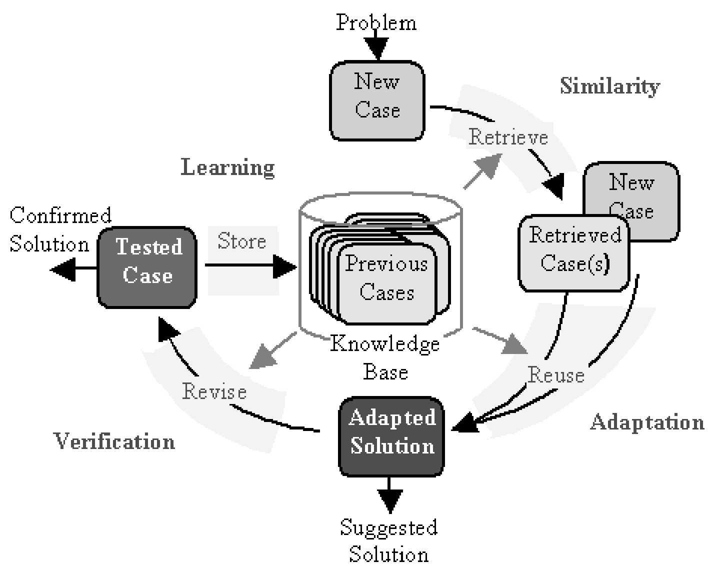

Figure 4: Case based reasoning process [Aamodt and Plaza 1994]

4.5. Case Based Reasoning

A final estimating technique to discuss is the analogous method or more particularly that of case based reasoning. Analogy makes use of the similarity of products. The implicit assumption is that similar products have similar costs. By comparing products and adjusting for differences it is possible to achieve a valid and useable estimate. The method requires the means of both identifying the similarity and differences of items. This can be through the use of experience or databases of historical products. A more modern approach to the analogy method is case-based reasoning. Case-Based Reasoning (CBR) can also be classed as a form of artificial intelligence since it can be used to model, store, and re-use historical data, and capture knowledge for problem-solving tasks. An important feature of CBR is the ability to learn from past cases/situations. A CBR system stores and organises past situations, then chooses situations similar to the problem at hand and adapts a solution based on the previous cases. An overview of the CBR process is illustrated in Figure 4. As with FBC, CBR relies on a feature description base. As previously explained, this is not a straightforward task. Furthermore, CBR requires a number of past cases in order to be effective. In a highly innovative company past cases may not be available and hence reduce the effectiveness of the CBR system. Companies that use analogy estimates regularly may find CBR a robust, useful method.

4.6. Cost Estimating Techniques And Product Life Cycle

Table 2 summarises where and when each of the techniques and processes discussed are best used throughout a product lifecycle. The matrix shows that as a product moves from development to production the estimating process needs to change. The table suggests hard breaks between where one technique should be used against another. However, it should be borne in mind that PE, NNs and CBR could be used during later project phases, whereas detailed cost estimating cannot be used during the earlier product phases. NNs are not deemed suitable in the concept phase of innovative products since the estimates they produce are of a ‘black box’ nature. That is, they do not provide a facility to demonstrate the assumptions and reasoning behind the final estimate. An important note is that Expert judgement is used throughout the product lifecycle and with all techniques [Roy et al. 2002a; Rush and Roy 2001a].

Table 2: Cost estimating techniques and product lifecycle [Rush and Roy 2000]

Cost Estimating Techniques USED WHEN:	PE	NN	CBR	FBC	Detailed Cost Estimation
Concept design phase (innovation)	✓	✗	✓	✓	✗
Concept design (similar products)	✓	✓	✓	✓	✗
Feasibility Studies	✓	✓	✓	✓	✗
Project definition	✓	✓	✓	✓	✗
Full Scale development	✗	✗	✗	✓	✓
Production	✗	✗	✗	✓	✓

5. Cost Management And Cost Reduction

5.1. Value Analysis And Value Engineering

Value analysis and value engineering, although similar to each other, serve different purposes. Value analysis (VA) is concerned with the analysis of a product with respect to reducing product/process costs. Typically, VA is a technique used on existing items/products in light of new processes, materials or assembly methods being available. Value engineering (VE) on the other hand is an approach that rigorously examines the relationship between a product function and cost and can be used during the concept stage of a product development. VE identifies the functions that are beneficial to the customer so that the value of a product is not just perceived as a low cost product but rather one that satisfies the customer. This technique was used widely within the aerospace industry up until the 1970’s [Rush and Roy 2000]. However, with the introduction of tighter defence budgets, a more stringent technique was required for ensuring cost targets were achieved and design to cost was introduced.

5.2. Design To Cost

The objective with design to cost (DTC) is to make the design converge to an acceptable cost rather than to let the cost converge to design. DTC activities, during the conceptual and early design stages, are one of determining the trade-offs between cost and performance for each of the concept alternatives. DTC can produce massive savings on product cost before production begins. The general approach is to set a cost goal, then allocate the goal to the elements of the product. Designers must then confine their approaches to that set of alternatives that satisfy the cost constraint [Michael and Wood 1989]. However, this is only possible once cost engineers have developed a tool set that designers can use to determine the impact of their decisions as they make them. Figure 5 illustrates an example of the types of input required for producing a DTC tool.

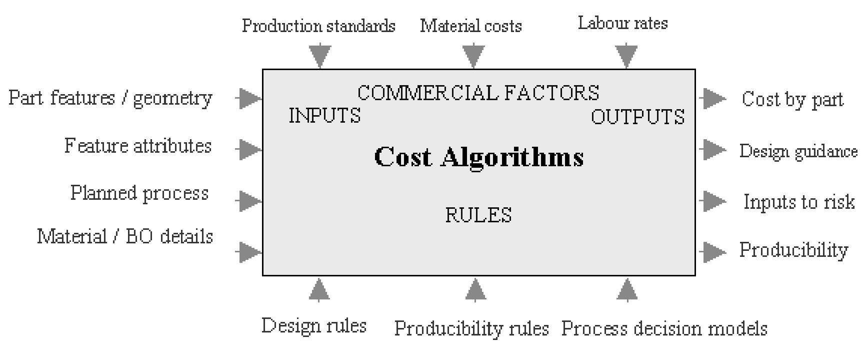

Figure 5: A design to cost model

It is the cost engineers who are responsible for bringing back, to the early stages of product development, enough information on cost that will enable the designer to use it for decision-making. They develop algorithms that designers can use to monitor the impact of their decisions as they proceed with their design [Taylor 1997]. In addition, they are responsible for updating and maintaining the validity of any algorithms used [Sivaloganathan et al. 1994]. The tools to assist the designer in meeting and verifying cost goals are in most cases developed within the context of a specific industry or company [Sivaloganathan et al. 1994]. A few European aerospace manufacturers use commercial computer based tools. However, it should be stated, the results produced from using such a tool are only as valid as the data that has been collated, normalised and input. Both VA/VE and DTC help to manage the risk of failing to meet the required cost targets; however, they are not focused on risk as a main project objective. Therefore, the next section discusses risk management and its role within today's estimating community.

5.3. Risk Analysis And Management

The objective of a cost risk analysis is to predict the amount of uncertainties involved in the cost estimate of future projects. There will always be uncertainties, i.e. risks, involved in a project. If these uncertainties can be identified and quantified, effort can be made to successfully deal with the impact of them occurring. Risk management is a very broad term, meaning the management of any situation, which is controlled in one way or another by uncertainty. The aim of risk management is to minimise the negative impact of risk in a project and reduce uncertainties. In the context of cost, risk management uses cost risk analysis as a tool to identify risks and then mitigate the risks.

By looking at the uncertain variables within a situation, a risk analysis can show which those that have the most effect on the solution and pinpoint where most effort should be targeted. The risk analysis makes sure that uncertainty within the variable can be accounted for before committing the project. Therefore, the outcome of the analysis can be used as a decision tool for the designer. That is, if the designer understands the risks involved with certain cost drivers, he can choose a different approach to lower the risk. Thus, using risk assessment and risk analysis ensures that the consequences of risks to a programme cost and schedule are understood and taken into account for the commercial bid on programme price and duration. Since estimating is based on assumptions concerning the likely cost of an, as yet, unknown product outcome there is an increasing trend to combine the statistical techniques of parametric cost analysis with statistical risk analysis methods. Parametric estimating, because of its statistical approach, offers the cost analyst the advantage of being able to quantify the risk of an estimate.

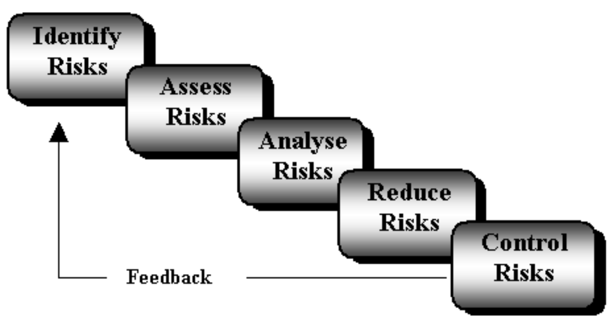

Figure 6: Risk management process

Risk management ensures that the goals of the producer and consumer materialise and that they both benefit. It provides confidence concerning final costs and identifies actions needed to keep cost and schedule on target. There are five key steps to follow in the risk management process [Heinmuller and Dilts 1997]. Figure 6 illustrates this process more clearly. One of the most important benefits of using risk assessment is to generate a distribution/range of costs, i.e. to move away from single point estimating, since a range of costs are much easier to estimate than a single cost [Forsberg et al. 2002]. Furthermore, once a risk analysis has been conducted the analyst can consider ways to reduce the risk, e.g. by avoidance, deflection or contingency, and then plan accordingly to control the reduction process. Risk management along with VA/VE and

DTC can be better utilised by combining them into a state-of-the-art cost management framework known as target costing.

5.4. Target Costing

Target costing (TC) is a cost management concept that is well suited for use within a manufacturing environment. It has mostly been used within the automotive industry as a means of strategically managing cost [Rush and Roy 2000]. TC provides a framework that places cost management issues into the forefront from the early phases of product development and can be used throughout all phases of a product lifecycle. However, it is mostly practised during the design and development stages where most of the decisions that impact lifecycle cost are made [Herner 1997]. TC is a framework in which estimating becomes an integrated element. It combines the concepts from existing cost management and cost estimating/engineering tools e.g. VA/VE, DTC, risk management, and bases its philosophy on the logic and benefits of activity based costing.

5.4.1. Unresolved Target Cost Issues

TC is not suited for all industries. It is best used on new products, which characterise small incremental development changes from past similar products. The concept falls down when addressing the cost estimation of innovative products. Chiefly because the process requires a breakdown of how the components of a product will effect the functionality of an, as yet, undefined product, and furthermore, what the cost of each product feature or component will cost in relation to whole product. This is not possible unless some sort of system has been developed that has the capability of producing a detailed product definition/breakdown during these early stages. Therefore, it is not as yet, widely used for companies that develop highly innovative products.

6. State-Of-The-Art-Practices: Hardware Cost Estimating

6.1. Tools And Techniques

Seven high technology manufacturing companies were interviewed as part of a research carried out by Cranfield University [Roy et al. 1999b]. The analysis was conducted within three main areas: the use of CERs, general costing, and the types of computing tools adopted. Only a few of the companies had developed CERs for the manufacturing processes. These were either developed using computer tools or using the experience of highly skilled cost engineers. There seemed to be a lack of formal validation procedures for the CER's and no formal documentation seemed to be in place. There was generally no structured approach for costing the conceptual or detail design stage. Companies that did attempt these estimates seemed to rely mostly on expert knowledge with regards to past data, which is fraught with subjectivity. None of the companies had CERs to predict cost of their design activities.

For general costing analysis there was a tendency for companies to use a computer-based tool at the detailed manufacturing cost estimation level. The results produced from these analyses were reasonably accurate. Most companies could validate this through feedback from production. In most of the cases it was found that cost benefit analysis was not conducted. However, the companies did review their costing processes regularly, although there were no costing standards used as guidelines for this process. A variety of costing software was used for both high level and detailed costing, and there was a mix of the level of integration with other business systems. Examples of the tools used included KAPES, PRICE (H), TIMSET and specifically developed in-house systems.

6.1.1. The Challenges Faced By The European Manufacturing Industry

The snapshot view highlighted that the application of CERs within industry was not widely practised. Companies could greatly enhance CER effectiveness and use by examining their procedures and methodologies for creating them. The application of CER's for the design process was not even considered by the companies. This was one of the underlying reasons that Cranfield University devised a methodology to take account of both quantitative and qualitative issues of design, and developed a CER methodology for cost estimating the design effort [Roy et al. 2000; Hamaker 1994]. The use of features, artificial intelligence and case based reasoning techniques were not used within any of the companies visited. And few of them had adjusted their cost estimating practices after the adoption of IPT or concurrent engineering practices. In summary, there appeared to be a general lack of planning and order to the estimating process. In view of cost becoming an ever-increasing concern cost estimating and management needs a better focus. Companies considering the adoption of a concurrent engineering philosophy should use the opportunity to re-examine current practises and evaluate the possibility of adopting some of the more recent developments within the field of cost engineering. Benchmarking the leaders can also assist this process.

6.1.2. Benchmark The Leaders

In cost engineering, USA leads the way in both practice and development [NASA 2002a; Herner 1997]. In Europe, the European Space Agency (ESA) actively promotes the sharing of estimating best practices [Novara and Wnuk 1997]. One leading European aerospace manufacturer is currently examining the feasibility of developing a seamless cost-estimating environment. Their early development plans and intentions are to adopt a feature based costing approach [Taylor 1997]. The company embraced the philosophy of an Integrated Product Development (IPD) approach and has demonstrated a strong commitment towards concurrent engineering. They have invested extensively into digital product assembly methods and information management systems, which are used to discharge information in line with their concurrent engineering process development. The emergence of the new IPD processes rendered their existing parametric estimating algorithms out of date, particularly for the design process. They seized this opportunity to embrace and integrate new estimating processes.

They recognised the potential of providing non-specialist cost estimators (design engineers) with a computer tool to inform them about the costs incurred with particular design approaches in real time. This capability would empower non-cost specialists to make decisions related to cost improvements as they design the product. This potential was realised due to the advent of 3D CAD modelling systems, which stores information related to features throughout the product hierarchy. The idea of the process is to capture features from the CAD modelling tools which can then be integrated to a design for manufacture (DFM) expert system that can price the cost of a design in real time. The DFM software could accept part geometry directly from feature based modelling tools such as Pro-E and Unigraphics. The tool can be populated with design and manufacturing knowledge in the form of producibility algorithms so that it can evaluate a design based on the features, materials, and manufacturability. This then empowers the designer to make decisions related to cost during the design process.

Figure 7 illustrates a high level concept of the companies intent to integrate their cost modelling capabilities using a feature based approach throughout the concurrent engineering phases. Companies wishing to use this approach would need a complete set of computerised tools that interface with each other. An obvious drawback for companies that may want to follow such an approach is the requirement for a comprehensive suit of expensive computerised tools. However, as computing power increases these tools become available and accessible for other industries to use. This development work may provide future estimators with an almost seamless system that can be used throughout the product lifecycle.

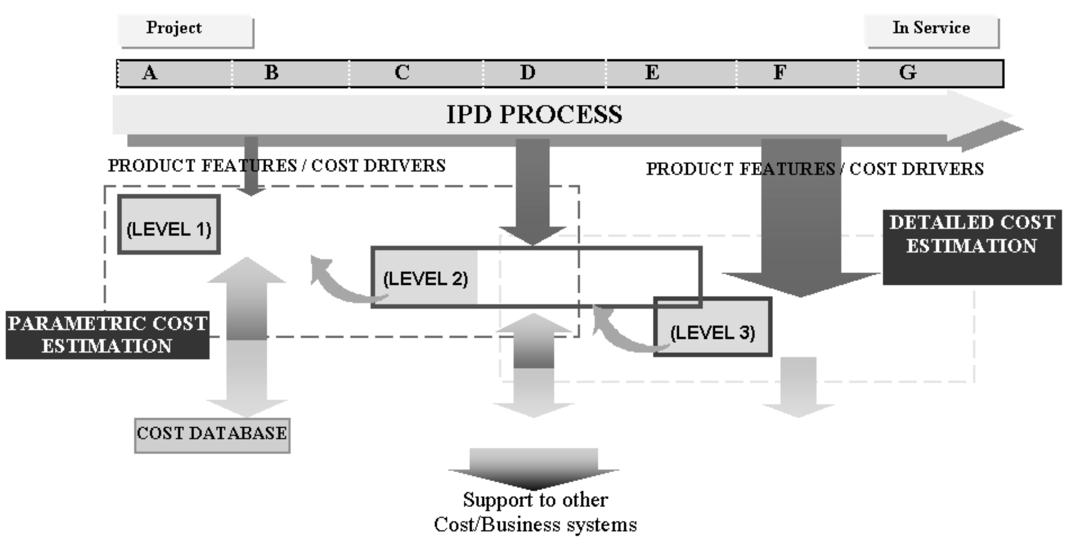

Figure 7: Integrated cost modelling [Rush and Roy 2000]

6.2. Internal Practice

Another recent study at Cranfield focused on identifying the internal cost estimating practice within aerospace, automotive and defence organisation [Roy et al. 2001]. The objective of this research was to identify the costing practice interface between the commercial and engineering activities within cost estimating. In total 14 companies were visited and cost estimating experts were interviewed with a semi structured questionnaire. Manufacturing industry performs cost estimating throughout the lifecycle of a product. The disciplines involved in costing a product are from both commercial and engineering areas of expertise. The purpose of commercial activities within cost estimating is to provide key business information for decision making in a top-down fashion [Pugh 1992]. This costing discipline attempts to evaluate and optimise a combination of requirements with potential or selected solution(s), across a wide range of business processes, with cost as the common denominator. The commercial activities in cost estimating are also required to consider such influences as standard costing and accounting methods, and government legislative regulations; as well as an overview of the production process, from the conceptual design stages onwards. Alternatively, the engineering activities within cost estimating tries to model the design to manufacturing cost in a bottom-up approach, for establishing relative costs for different solutions and methods. The process and organisations covered by commercial cost estimating include: engineering, testing, tooling, manufacturing, procurement, logistic support, and management. Similarly, the engineering activities in cost estimating are required to have detailed knowledge about the product, the manufacturing process and manufacturing capability of the organisation. But, unlike the commercial activities, the engineering activities are focused on design, manufacturing and tooling tasks only. The commercial cost estimators also have to follow standard costing and accounting methods, e.g. questionnaire on the method of allocation of costs (QMAC), depending on customer requirements, and comply to post contract work management and control methods like EVMS (Earned Value Management Systems). They also need to be fully aware of customer government legislative regulations which govern justification and access to data used in the estimating process. Due to this mismatch in focus and differences in terminology and level of detail, there is a gap between the two disciplines; this leads to inconsistencies in costing practices [Roy et al. 2001]. There is also a lack of knowledge about each other’s activities. Both commercial and engineering activities within cost estimating are essential during the conceptual product development stage for design evaluation, and thus optimisation. If these activities are properly aligned, they will provide better quality cost estimates at the very early stages of product lifecycle, and thus help during conceptual design evaluation. The community requires lateral transfer of cost estimating knowledge and information to bridge the gap [Mishra et al. 2002a, 2002b]. Some of the conclusions from the research are:

- The communication within organisations, in general, is very primitive; informal methods of interaction and communication are still employed).
- Commercial activities within cost estimating can generally be seen to concentrate on the final price of product.
- Whilst engineering activities within cost estimating are more involved with product cost.
- There are no standards for industrial terminology within commercial and engineering activities in cost estimating.
- Fear cultures within companies cause the workforce to act directly against the commercial interests of the company; integrated working practices between the costing activities would improve/eliminate this detrimental practice.
- There is also lack of training and education for the cost engineering community.

7. State-Of-The-Art-Practices: Software Cost Estimating

A short-term research project on Software Cost Estimating (SCE) in the European Defence and Aerospace Industry [Roy et al. 2000] identified the current practices. The research has highlighted some major weaknesses in the industry resulting in serious challenges for the implementation of rigorous cost estimating processes for software development. The Cranfield study involved extensive literature research, face-to-face interviews and email questionnaires with software cost estimators from eight different companies. These included organisations from defence and related industries and some SCE consultants. The research highlighted that the USA is also well ahead in the research and practice of SCE within the defence and aerospace industry.

There appears to be an acceptance that due to the highly complex nature of software development, the collection of historic data is a key factor in offering customers the accuracy and consistency they require. Other key findings include a marked shift towards implementing more formal and defined processes. What appears to be needed is a more pragmatic application of parametric models, a unified and more studied approach to software metrics and further integration of software cost estimating into the project management discipline itself. Significant investment is necessary in the process, the people and the technology to improve the state of SCE within the industry in Europe.

The most commonly used SCE techniques are estimation by analogy, estimation by expert judgement, top-down and bottom-up approach, and parametric estimating. It is observed that there is a large gap between academic research worldwide and actual practices within the industry. Most of the research effort is going to develop cost models for manufacturing processes or services. Development of realistic cost models is dependent on the quality of data available within an organisation. And this is a major bottleneck in many businesses. It has to be mentioned that, although every researcher identifies historic data collection as a major bottleneck for the industry, there is no consolidated effort to improve the data collection process. With the implementation of ERP (Enterprise Resource Planning) systems within the industry, it would now be possible to use ERP databases as a central repository for cost information and so improve the process. Further research is also needed into parametric models and their role in the future of SCE. In the same vein, research needs to be undertaken into efficient data collection methods for Cost Estimating Relationship (CER) development within the software domain and the proper calibration of the models. Increasingly, the tacit knowledge of software experts will need to be captured and understood, using knowledge capture tools and techniques. Models must be properly calibrated with extensive historic data, via a formal metrics program. Additional research is also necessary into how to accurately account for the qualitative issues in estimating, such as complexity measures, quality measures and employee capability. Finally, further work incorporating software project management and SCE is required, particularly the CMM (Capability Maturity Model) and its effect on the estimating capability.

7.1. Software Classification Techniques And Complexity

Organisations classified software by domain, including Aerospace, Commercial, Mission Critical, Safety Critical, Real Time, etc. Organisations also agreed that safety critical, real time and embedded systems were the most complex types of software. However, the organisations questioned could not give a clear definition of complexity.

7.2. Cost Estimating Relationships And Parametric Costing Techniques

It was noted that few organisations took a comprehensive approach to identifying and analysing cost drivers within their SCE process. Therefore many do not build them into their estimation equation, but prefer to rely on experience and tacit knowledge. The cost drivers that were cited included:

- Labour rate to estimate effort.
- Size lines of code (LOC), by analogy, % of code re-use.
- Language LOC/day rate.
- Risk % per activity in life cycle.
- Complexity.
- Skills base.

The study identified a real opportunity to carry out further academic/industrial research within the area of CERs within the software environment.

7.3. SCE In General

What information is required for successful SCE?

- Understand customer culture to assess likelihood of change.
- Well defined set of requirement, understand the implications to the organisations, make a business case, i.e. risk.
- Previous project data.

As a guide it was highlighted that organisations need to ensure a direct link between estimating and the measurement process.

What are the main causes of inaccurate estimates?

- Misunderstanding the level of complexity involved.
- Optimism, lack of time, resources or knowledge regarding software cost estimating process.
- Lack of historical data, forgetting lessons learned.
- Poorly defined or regularly changing requirements.
- Costing to win or political decisions which take no account of estimated cost.
- A belief that the latest tools and techniques will completely improve the process.

What advice would you give to a company regarding SCE?

- Plan, knowing that you need to collect historical data – you need good data to support the process.
- Employ metrics.
- Formalise the process, make it multidisciplinary.

- Use a combination of methods in conjunction with expert knowledge.
- Spend as much time as possible analysing the requirements and associated risks.
- Do not view measurement and estimation separately they are tightly coupled.
- Develop benchmarks.
- Emphasis post mortems in the process as a means to collect lessons learned and reliable cost data.

What are the key success factors of SCE?

- The knowledge, skills and experience of the people carrying out the estimate.
- Collect historical data – accurate recording of previous project cost/time scales.
- Senior management commitment and buy in at all levels - provide incentives for good estimating practices.
- Models employed need to be robust and calibrated.
- SCE must be viewed as a strong and vibrant part of the organisation.
- Clear understanding of the requirements and well agreed definitions.

The organisations interviewed recognised that they have, in the past, been weak with their software cost estimating methods. However, there now appears to be a marked shift towards implementing more formal and defined processes for software cost estimating. At the time of the research project, the Cranfield team could not find a documented formal process in most of the organisations participating in the research. All the organisations involved relied heavily on ‘expert judgement’. In fact, most of the organisations did not use CERs at all, with even awareness being very limited. In some cases companies did compare their estimates, based on analogy or expert opinion, with a commercially available SCE model. However, the tendency was for this to simply be done as a ‘sanity check’. The commercial tools provide an estimate of cost but often can not implement the required formal process for the estimation, starting from good quality data collection etc. Industrially available commercial software cost estimating models include COCOMO, COCOMO II, Price-S, KnowledgePlan, SoftCost, and SLIM. It is also observed that the commercial tools are not used as a regular business tool within the organisations.

There is a pressing need to understand the SCE process in the context of the software development process and try to formalise the ‘black art’ of the estimating process. It is strongly recommended to benchmark the companies for the process improvement. It is also necessary to improve employee awareness of the need of the process and achieve their co-operation in proper data collection. Communication between the commercial estimators and software developers is a key issue for the co-operation, a common language is necessary. Finally, European Defence and Aerospace Industries are behind in the SCE research and practice compared that of the US, but with the changing awareness within the industry there is a significant opportunity to improve the estimating process, and that requires urgent action and finally more investment for the process improvement.

8. Research In Cost Engineering

Research in hardware and software cost engineering is not very wide spread. Software cost estimating research community is much more active than the hardware side. USA and Europe are equally active in the research. The main areas of software cost estimating research are developing advanced cost estimating metrics and models for complex software development within object oriented environment, using Rational Unified Process (RUP) and Unified Modelling Language (UML) use cases, and for commercial off the shelf software (COTS). Experimental studies to understand the impact of cost estimator background and skill on the accuracy of software cost estimates produced are also performed in Europe [Jorgensen 1997]. Research groups in academia and consulting organisations are active in cost engineering research in the US and in Europe. Commercial software vendors, mostly for their product development also carry out research, and therefore it is mostly confidential. It is observed that in spite of some research in the area of cost engineering; there is a big gap in transferring the results to industry. The NASA cost engineering website [NASA 2002b] is a leading site in promoting the 'Best Practice' within the manufacturing industry. This section briefly presents results from two recent research projects at Cranfield University. The case studies show the general trend in hardware cost engineering research.

8.1. Formalising The Cost Engineering Reasoning Process

Expert Judgement (EJ) is used extensively during the generation of cost estimates [Rush 2002]. Cost estimators have to make numerous assumptions and judgements about what they think a new product will cost. However, the use of EJ is often frowned upon, not well accepted or understood by non-cost estimators. This is mainly due to the subjective nature of the judgement. Computerised cost models, in many ways, have reduced the need for EJ but by no means have they, or can they, replace it. The cost estimates produced from both algorithmic and non-algorithmic cost models can be widely inaccurate (due to poor quality base data) and, as this section highlights, require extensive use of judgement in order to produce a meaningful result. Very little research tackles the issues of capturing and integrating EJ and rationale into the cost estimating process. The research is carried out as part of a three year long project, please refer to Curran et al. (2002) and Rush and Roy (2001b) for other results from the project. In this case study the reasoning processes of EJ are identified and an inference structure has been developed, which represents an abstraction of the reasoning steps used by an expert as they generate an estimate. This model has been validated [Rush 2002] through both literature and interviews with cost estimating experts across various industry sectors.

Subjectivity is an issue that surrounds the compilation of all cost estimates and the use of EJ is unavoidable whether complex cost models are used or simple spreadsheets [Rush and Roy 2001b; Beltramo 1988; Stensrud and Myrtveit 1998]. By nature, an estimate is a prediction of what experts think something should cost. EJ, although not a cost estimating technique, is widely used and acknowledged as necessary for generating estimates [Hughes 1996; Shepperd and Schofield 1997]. To be successful, the expert needs to have many years of experience and the cost estimating is considered as a 'black art'. This method is obviously prone to bias; the limitations can be summarised as:

- Subjective.
- Risky and prone to error.
- Experts with the same starting information will provide different cost estimates.
- Use of expert judgement is not consistent and an unstructured process.
- Prone to bias: personal experience, political aims, resources, time pressure, memory recall.
- The reasoning is known only to the owner of the estimate.
- Estimate reuse and modification is difficult.
- Difficult to negotiate effectively with customers.
- Difficult to quantify and validate the estimates.
- Estimate depends on level of experience.
- Experts leave the company – knowledge loss.
- Difficult to provide an audit trail.
- Estimates are black box in nature.

However, there are advantages to using EJ such as:

- Quick to produce.
- Requires little resource in terms of time and cost.
- Can be as accurate as other more expensive methods.

One of the formal and rigorous methods for capturing EJ is the Delphi technique [Dalkey and Helmer 1962]. This method attempts to capture expert opinion through a group of experts. The major drawbacks are related to its practicality. The first is related to the time needed to obtain the group opinion and the second is related to the number of experts required to produce worthwhile results. Estimators make many qualitative judgements as they generate estimates and are often under time constraints and working with limited amounts of information. Furthermore, the Delphi technique does not attempt to capture the reasoning process of how an expert made their judgement, which is a main aim of this research. This formalisation will remove the notion of 'black art' in cost estimating.

The research started by modelling the cost estimating process followed in industry that lead to the identification of most knowledge intensive tasks in cost estimating. With this knowledge and with published literature [Rush 2002], an initial model of the reasoning process was developed (inference model). The model was further developed and validated [Rush 2002] through interviews with 11 (eight for the development and three for final validation) cost estimating practitioners from aerospace, automotive and defence industries. Their years of experience ranged from 5 to 32. The projects ranged from cost estimating new air-system concepts to the disposal of nuclear waste plants. The questionnaire is presented as follows:

Part 1: The Context

- What type of product was the estimate for? (mechanical, systems, etc.)
- What was the stage of product development? (development, manufacturing)
- What estimating techniques were you using? (e.g. parametric, detailed analysis)

- When was the estimate made?
- What was the purpose of the estimate? (e.g. ROM, Budget, detailed, fixed price etc.)
- How would you rate the difficulty of this task? (on a scale of 1 to 5, 1 being very easy and 5 being very difficult)
- How many years of cost estimating experience with respect to generating estimates had you? (at the time of estimate)
- How often were you producing estimates? (at the time of estimate)

Part 2: The Process

- Where does the work request come from?
- What are the basic data you require, and the main things you look for? And why?
- What sort of constraints do you often face (example: time, etc. etc.)?
- At what point could you say that you understand the new product and the cost estimating requirements? Please give an example from your case study.
- What tells you that you have all the requirements you need, whom would you talk to for any advice? How often do you consult others?
- What do you do to identify and prioritise requirements?
- What do you have to do to organise the new product data for preparing the estimate?
- At what point do you begin searching for source or reference data?
- What difficulties do you encounter when searching for source data?
- What do you look for in the source data? Please give examples from your chosen case study.
- What tells you that you have identified a suitable candidate to use as a comparison?
- What do you do to when comparing the source data and the new product data? Can you provide examples? (What criteria do you use? And why?)
- What assumptions do you make when comparing the products? Could you please give examples?
- How would you use the costs from the source data?
- What do you do when you make adjustments to account for the differences between the source data and the new product data?
- What sort of assumptions do you use when adjusting the costs? Could you please give examples?
- Do you record and explain the rationale for the adjustments made? If yes, can you say how?
- How often would you review any assumptions made?
- Do you understand the cost impact of a change in any of the assumptions used?
- What are the potential areas where your estimate may differ from another person's estimate?
- Could you please explain the thinking process you go through when making a comparison, as you understand it.

Part 3: Inference model analysis

- In your opinion, how do the inferences match your reasoning process?
- Is there anything you would change?
- What inferences are most assumption intensive?

Part 1 of the questionnaire was designed to gather information concerning the case study and the context in which the estimate was made. Part 2 was designed to assess what the expert did as they carried out their tasks. The questions in both Parts 1 and 2 were asked without showing the initial inference model to the interviewees. After the second set of questions had been answered, the inference model was presented. Part 3 of the questionnaire was designed to understand how the initial inference model differed from the expert's view of their reasoning process (during development). Any discrepancies were highlighted and then later assessed through the respondents' answers to the questions posed in Part 2 of the questionnaire. All the interviews were recorded and later transcribed in order to assess that their answers matched the inference model. General perception of people is that cost engineering is a 'black art', but the research proved that the thinking process could be modelled as an inference structure.

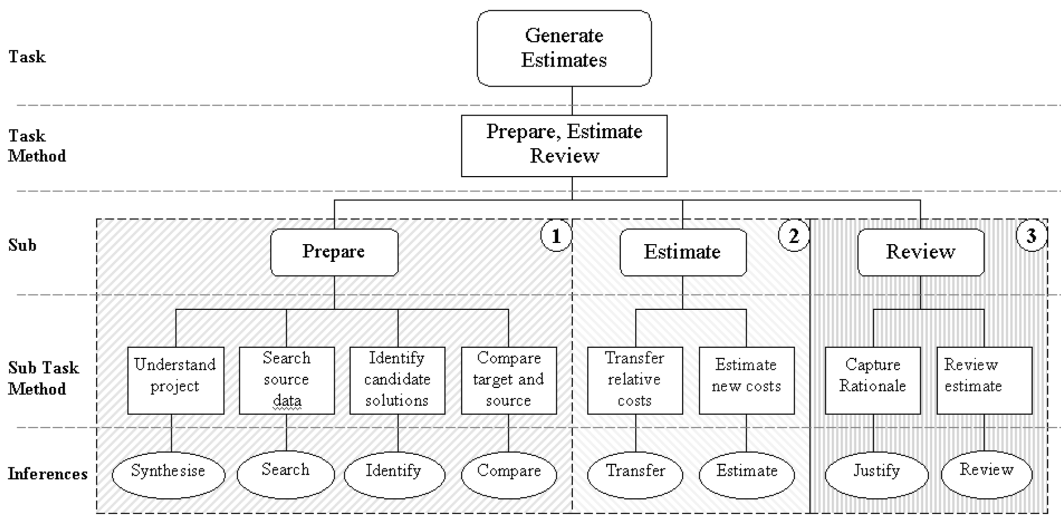

Figure 8: Task and inference decomposition for analogy based cost estimating [Rush and Roy 2001a]

8.1.1. Identifying The Task: Generating An Estimate

Before one can capture the reasoning processes of an expert, the task they perform needs to be defined. This enables one to understand and formalise how the expert is reasoning. In this case, the task is related to what an expert does when generating an estimate, based on reference to historical projects or experience. As mentioned previously this is often referred to as analogy. The task in this case, is a complex reasoning process and needs to be decomposed in order that it can be more clearly understood (Figure 8).

In Figure 8, the main task of generating an estimate is hierarchically decomposed into smaller tasks, this in turn is divided into even smaller tasks. The tasks in the diagram describe what the expert does. The task methods describe how an estimator completes the task. In order to understand what the expert does, the task method needs to be further decomposed into subtasks, i.e. Prepare (1), Estimate (2) and Review (3). Each of these subtasks has a number of associated lower level subtask methods that describe how the cost estimator completes each subtask. For each subtask method, the corresponding inferences used by the estimators are shown. Descriptions of inferences are provided in the next sub-section.

The main tasks prepare, estimate, and review describe the order of how the estimate is generated. For example, before estimating, the data needs to be prepared (1) so that the expert can estimate (2). Then the estimate needs to be reviewed (3). However, the task decomposition does not illustrate how the expert reasons during the task, it simply demonstrates the 'what' and 'how' of the cost estimator as they complete their tasks, and illustrates the inferences used. The shaded areas in Figure 8 are numbered and correspond to the shading and numbering shown in Figure 9. This helps the reader visualise how the task of 'generating estimates' translates into the experts' reasoning process.

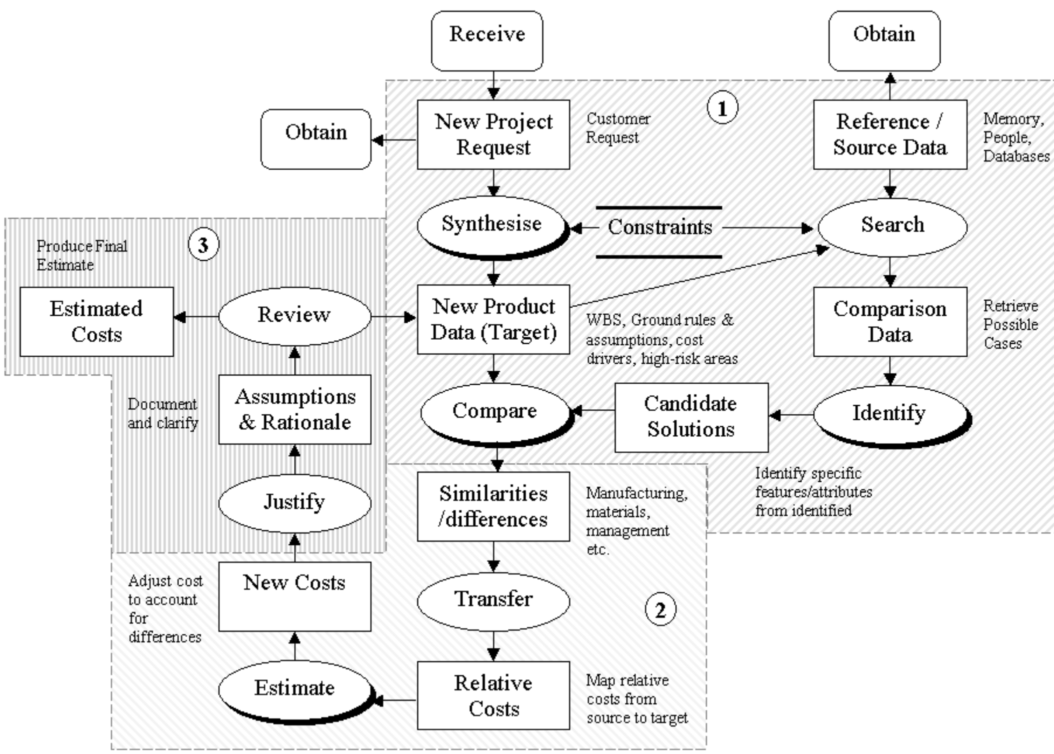

Figure 9: The reasoning process behind analogy based cost estimating – Formalisation through an inference structure [Rush and Roy 2001a]

8.1.2. The Inference Structure

The inference structure, illustrated in Figure 9, is an abstract representation of the possible reasoning steps an estimator uses as they refer to a similar product to generate an estimate. Together, these inferences form the building block of the expert reasoning process. They define the basic inference actions that the expert can perform whilst executing their tasks. The combined set of inferences represent the experts inference structure.

Knowledge roles, transfer functions and inferences
The research uses CommonKADS notations for the model description [Schreiber et al. 2000]:

- The rectangular boxes within the model are known as Knowledge Roles (KR). The KR's describe at an abstract level, the kind of data that the estimator will infer or reason with.
- The ovals represent the Inferences (I) or the reasoning processes that the expert uses. The arrows are used to indicate input-output dependencies between the KR's and inferences.
- The rounded boxes represent Transfer Functions (TF). The TF's relate to the estimator interacting with other agents e.g. suppliers, customers, IPT members, and collaborating companies.

Inference structure description
The following information provides a walk through of the inference structure illustrated in Figure 9.

<u>Prepare (1):</u>
The estimators first receive information about the new project in various forms. They receive a request to do the work, and data such as 3-D models, drawings and documents. From this information, the estimator deepens their understanding of what it is that needs to be cost by synthesising all the data and information. During the synthesis of data, the expert may need to obtain more data to deepen his/her understanding of the project. The estimator needs to analyse the requirements, and classify the type of product and the type of estimate they are required to produce. They also need to understand the constraints in terms of time and resources. Once they understand what is required, they establish and document any ground rules and assumptions and identify the main cost drivers of the project. A Work Breakdown Structure (WBS) is produced and used as the framework to cost the new product.

In addition, during the synthesis of data and information the estimator normally begins searching for more data and identifying projects that can be used for comparison. For example, the search can be from memory, other people or existing databases. The estimator needs to consider what elements of the source/reference data can be used as a basis for comparison. When ready the expert will begin to compare the similarities and differences of source and target projects and match them. The matching can be based on different levels of abstraction with respect to features, functionality, and project management and so on. The level of detail searched for will depend on the time constraints and the type of estimate required. The searching process will happen continuously throughout the synthesis process.

Estimate (2):
As the estimator compares the similarities and differences, the relative costs from the source product are transferred to the target product. The estimator will continuously assess the projects in order to understand what costs can be transferred and those that need to be adjusted or estimated for the new project. When estimating the estimator uses their experience and judgement to predict the cost of the new product. The new costs need to be justified through cataloguing any assumptions used. It is observed that the assumptions are not recorded during the estimating process in a systematic manner.

Review (3):
The final part of the expert reasoning is to justify and document the assumptions used. As mentioned previously, this rationale is not always captured. In addition, the estimator will continually review the estimate because of more information being received or obtained. Finally, the estimator may use various means to 'sanity check' the validity of their estimate. This can be through other people, or using other estimating techniques and tools.

Key inferences
The inference structure presented in Figure 9 is an abstract representation of the reasoning steps used by an estimator. In reality there are many more sub inferences used. However, the main aim of an inference structure is to get to a level of decomposition where the inferences used describe the reasoning processes to a sufficient level of detail to understand the domain. The shadowed ovals (inferences) are those identified by the experts where most of the assumptions are made during the process of generating an estimate. In future research, these inferences will be further decomposed in order to identify the knowledge intensive areas of a specific judgement. Due to the limitations of space, only generic descriptions of the assumption intensive inferences are presented below.

Synthesise

Operation:
The inputs for this inference are the cost-estimating request, and the available project data. Data can include drawings, process plans, work breakdown structures. The experts obtain more data as required in order to understand the estimating requirements. The constraints are recognised, as are the high cost drivers, and high-risk areas of the project. The output of this inference will be the new project data prepared for comparing with the source data, such as the WBS, assumptions and ground rules, and high cost drivers.

Example:
Here the expert analyses, clarifies, establishes, and assimilates all the information into a format ready for comparing and producing the estimate. Typical assumptions are related to envisage process improvements, and improved communication through using CE principles.

Knowledge:
The ability to identify those areas that will drive the cost, and establish the high-risk areas. This knowledge is dependent upon the project or product being estimated. In a specific domain, the cost drivers and risk areas may have common characteristics so can therefore be captured to guide a novice or an expert.

Identify

Operation:
The inputs are the source data and the details related to the retrieved project or product. The outputs are the identified features, attributes of a product, or project areas that can be used for comparison. This uses assumptions and exclusions.

Example:
Example assumptions would be related to the management structure, the experience of the teams, the quantity of production, the level of complexity, the functionality of the product and the manufacturing processes used.

Knowledge:
Knowledge of historical products and those areas that are commonly used as a basis for comparison would need to be identified. These would relate amongst many others to, specification, materials used, mass, type of system, manufacturing processes, assembly techniques, functionally, and productivity rates, whether VAT was used, economic conditions and exchange rates.

Compare

Operation:
The inputs for this inference are the source or reference data and the new product data (target). The output of this inference process will be a measure of both the similarities and differences identified by the estimator.

Example:
Examples of similarity measures include manufacturing methods of the source and target data. Assessing whether the technologies are the same, the same sorts of quantities being produced, the learning curves associated to volume, the processes required and so on.

Knowledge:
This relates to the types of comparisons that are often made. For example, manufacturing methods, project management, materials, mass, technology, system type etc. A full list would need to be identified and captured and related to the domain in which the comparisons are made.

Estimate

Operation:
The inputs are related to the differences identified between the source and target data. The outputs would result in an adjusted cost and new costs based on the assumptions used by the estimator.

Example:
The estimator may assume that the manufacturing processes used to produce the historical product are not representative of the manufacturing processes for the new product. And may therefore assume a saving of, for example, 40%. It is here that the rationale would need to be captured in order to validate the estimate.

Knowledge:
The knowledge required here would be related to the expected changes in manufacturing processes and productivity. The knowledge also includes the impact of any changes to the cost.

8.1.3. Inference Structure To CERC Tool Development

The formal inference structure provided the basis for the development of a Cost Estimating Rationale Capture (CERC) framework. This framework can be used to capture cost estimating assumptions, judgement and rationale to inform non-cost estimators, and other cost experts, how an estimate was derived. Thereby providing understanding regarding the decisions and choices made during the build up of the cost estimate [Rush and Roy 2001a]. After the inference structure was developed, the sponsoring company requirements for the CERC framework were captured during a brainstorming session. Figure 10 illustrates the CERC framework, which was developed from both the requirements captured and the authors understanding about the limitations of the current practices. The three shaded areas of the CERC framework are illustrated to show how the task and inference structure relates. The terminology in the flow chart differs from the inference structure for two reasons 1) the inference structure was developed from a theoretical viewpoint of analogical reasoning, and 2) the CERC flow chart illustrates a conceptual system of a software model.

A prototype system was developed using Microsoft Access, Excel and VBA to demonstrate the practicality of a CERC tool. The initial prototype is specific to the aerospace industry. The basic idea of the CERC framework is to capture assumptions and relate their impact to the PBS (Product Breakdown Structure), the POBS (Process Oriented Breakdown Structure), and RBS (Resource Breakdown Structure). Each assumption can impact on many parts of the breakdown structures or be specific to one part of a breakdown structure. As a user works within Excel (most common tool in cost estimating), the CERC database can be called and the assumption detail captured. Each assumption will have rationale associated, and a risk level of low, medium and high, along with a probability of occurrence. If an assumption requires updating a new version can be added so that an audit trail of can be kept throughout the life cycle. Also, the user will be able to query what assumptions affect certain elements of the breakdown structures and vice versa. The CERC tool is being validated across other industries and further developed to make it more generic.

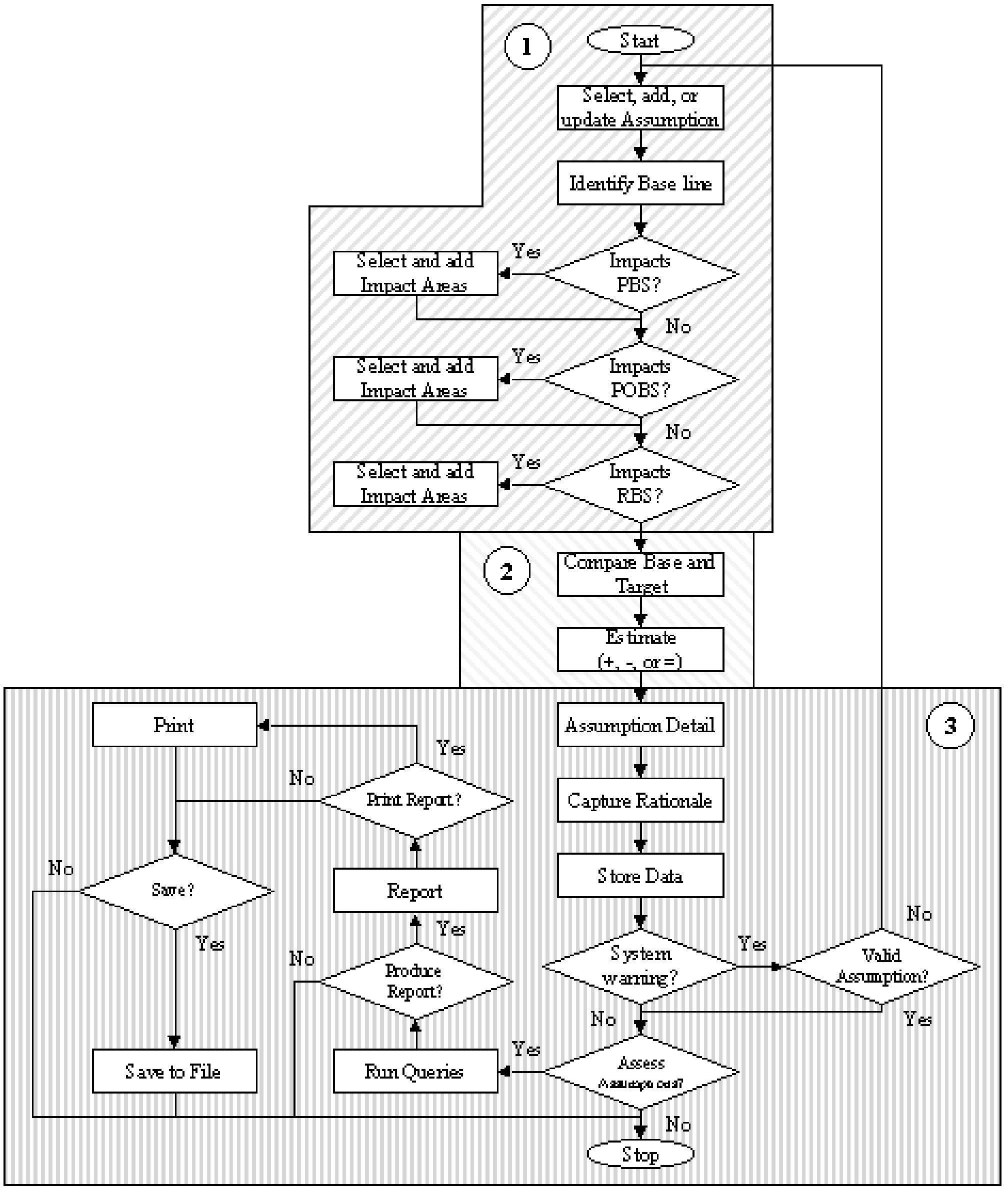

Figure 10: The CERC framework [Rush and Roy 2001a]

8.2. Full Service Supplier Cost Modelling

Major automotive manufactures are developing Full Service Suppliers (FSS), creating strategic relationships, which fully utilise supplier expertise in product development and Research and Development (R&D). With this partnership the cost base is shifting towards the FSS, who recover this cost from their customers through prices of components supplied. FSS cost is becoming an increasing proportion of component pricing in the automotive industry; therefore a significant competitive advantage can be gained for the company that has this cost under control. This study identifies the cost drivers or FSS cost, and presents a model for FSS cost estimating [Roy et al. 2002b]. This approach differs from the current practice of labour intensive cost simulation of every activity in the development process.

8.2.1. Cost Estimating For R&D Effort

R&D is one of the major costs for FSS. The focus of this section is to review different approaches to estimate R&D expenditure for a project. There are several factors which need to be considered when allocating funds to R&D:

- Expenditure by competitors.
- Company's long-term growth objective.
- The need for stability.
- Distortion introduced by large companies.

While R&D expenditure varies greatly between industries, there is some similarity. It is possible to establish reasonably accurately competitors' R&D expenditure, and the number of research personnel employed etc. By analysing the expenditure of its competitors, a business is able to establish an appropriate figure for its own research effort [Dumbleton 1986; Kroonenberg 1989; Liker et al. 1996]. R&D expenditure can be based on a constant percentage. Turnover usually provides a reasonably stable figure that grows in line with the company. As an example of this method, a company has decided to spend 25% of its annual turnover on R&D. If its turnover were GBP £10^7 then its annual R&D expenditure would be GBP £$2.5\text{x}10^6$. A criticism of this method is that it uses past figures for future investment. Fixing R&D expenditure to profits is highly undesirable. It implies that R&D is a luxury, which can only be afforded when the company generates profits. This method completely ignores the role of R&D as an investment and the likely future benefits, which will follow. Often, in fact, poor profits can be turned around with new products.

Automotive companies depend heavily on R&D with ever reducing model lives and shorter development time. Bringing completely new vehicles to market every four years and 'freshenings' in between. R&D expenditure has to be at least on parity with competitors. It does not always follow that a company will pursue a new innovation to the point of mass production. There are many areas to be considered, does the company have the expertise and capability of efficient cost effective manufacture? Are there better-suited companies that may take up the manufacture to better effect, which may render investment in this area redundant in a short space of time? Does this innovation fit within the corporate image and strategy? A potential source for development budgets of companies can be obtained from their annual accounts.

As the cost of R&D becomes increasingly expensive, it makes sense to consider options to share the bill. This may be affected in many ways:

- Group Concept – where a company, typically a large multinational, buys companies making similar components, then combines and optimises the R&D function. For example, Ford has developed the Trustmark companies, including Volvo, Jaguar, Land Rover, Aston Martin, Mazda and Lincoln. New developments can be used in multiple product lines, thereby sharing the R&D cost recovery over a larger volume base. Suppliers adopt a similar strategy.

- Strategic Alliances – an agreement between two or more partners to share knowledge and resources, which could be beneficial to all parties involved through Joint Venture, Collaboration and R&D Consortia [Parkhe 1993; Nordwall 1991].
- Joint Ventures – where a company combines resources with a competitor on a specific project for their mutual benefit, for example Ford and Volkswagen (VW) with the Galaxy/Sharon people carrier, developed by VW and manufactured by Ford. Ford and PSA, diesel engine development.

Examples of Strategic Alliances in the Auto Industry between automotive manufacturers include General Motors/Lotus, Ford/VW and between automotive manufacturers/automotive suppliers include Ford/Cosworth Engines, Ford/PSA Diesel Engines [Baker 2002].

8.2.2. FSS Cost Estimating Model Development

The general methodology employed was to first collect high-level data from suppliers to the sponsoring automotive company, draw conclusions from and model this data. Then progress is made through an initial validation and improves the early cost model with detailed specific case studies using an iterative improvement procedure. And finally, a second phase of validation utilising a review with experts in the field was also performed. The data collection was facilitated through questionnaires and interviews. The model should be flexible enough to allow progressive development, changing basic concept, adding further sensitivity and fine-tuning for greater accuracy of result [Baker 2002].

In total, 12 suppliers were visited all across Europe during the course of this research and questioned informally using a questionnaire for guidance; many of their comments influence the generation of the cost tables used in this research. Two of the key questions asked of the suppliers and subsequently used in the cost model were: What, in regard to a component description, do you believe generates cost for a FSS? Of the work that you do as an FSS, where are the most significant cost incurred? The responses to the questions were grouped and summarised to provide the origins of the cost drivers used in the cost model, which are: Design innovation, Engineering changes, Design complexity and Manufacturing complexity. Elements of cost breakdown, as identified also, are: Design, Engineering, CAD work, Prototypes, Testing, Project management, Expenses – Travel and Expenses – Accommodation.

The weighting for the cost drivers were initially performed considering the responses from the questionnaires, and fine tuned iteratively using three case studies: seat, fuel rail and hard trim. The procedure adopted was to focus on the most significant cost driver initially and progress down to the least significant until all case studies gave a result within tolerance of +/- 5%. Finally, the model is validated with three experienced cost estimators.

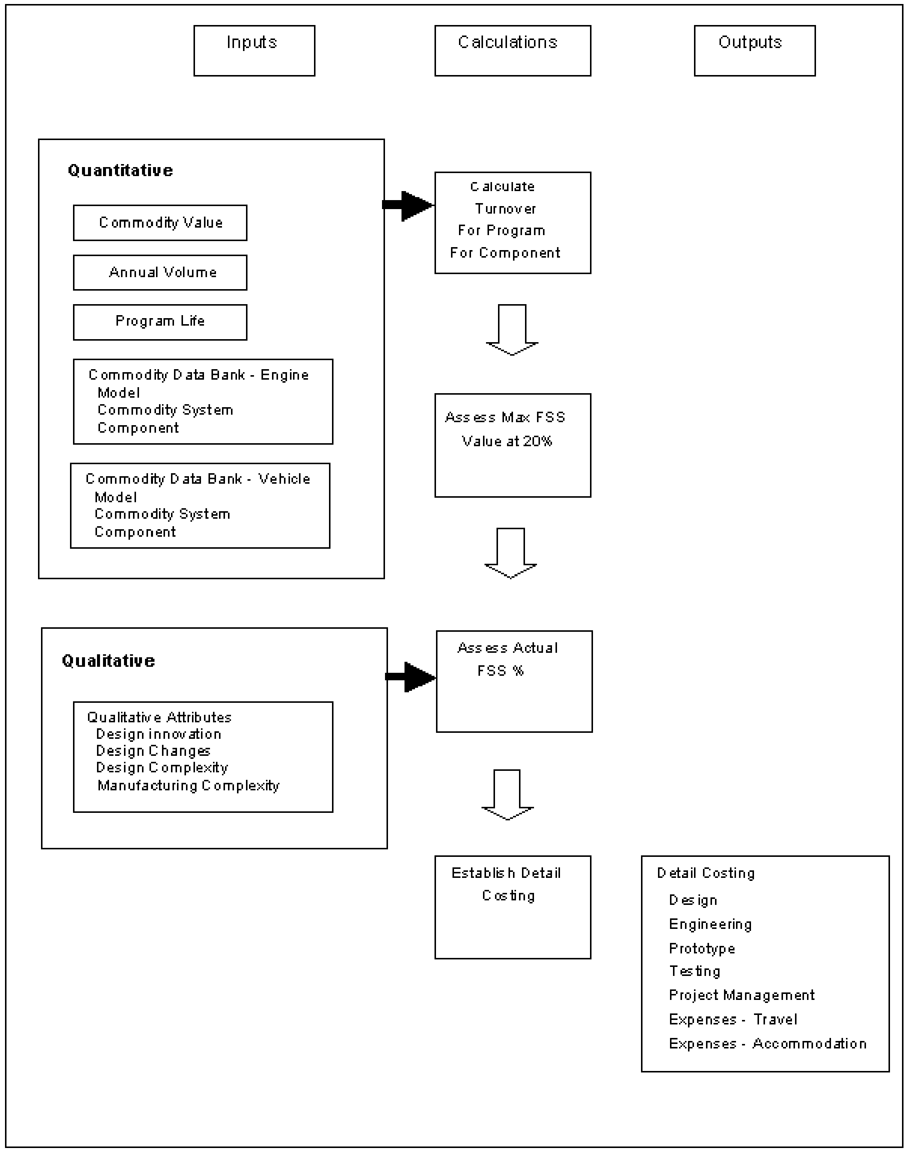

Figure 11: FSS cost model flow diagram [Baker 2002]

8.2.3. Description Of The FSS Cost Estimating Model

The cost model starts by focusing on the quantitative portion of the costing, generating a base line value of the total FSS cost for a Vehicle/Engine Program. This total is then sub-divided, by applying percentages from a well-established system structure. Following this allocation of cost from a vehicle/engine program total, through cascading levels of commodity system groups, through finally, to the commodity component, a preset baseline output or work activity forecast is applied as illustrated in Figure 11.

Quantitative Cost Generation – Total baseline FSS cost is established for an engine/vehicle line through a cascading commodity percentage split and on to a baseline output.

Qualitative Cost Generation – Cost driver modifiers are applied to a baseline including level of design innovation, level of engineering changes, level of design complexity and level of manufacturing innovation.

For each of the 'influences on cost outputs', there is an association with a particular aspect of a components design. So what is it about a component design that generates cost? It is necessary to establish a meaningful way of describing the component and its environment. The cost drivers as identified are design innovation, engineering changes - proximity to job one, design complexity and manufacturing complexity. Having decided on the cost drivers it is necessary to decide how each one effects the cost and to what degree, or the significance, as shown in Table 3.

Table 3: Cost driver significance

Cost Driver or Qualitative Attribute	**Significance/ Weighting**
Design Innovation	60%
Engineering Changes	20%
Design Complexity	15%
Manufacturing Complexity	5%

The attributes and values in this table were established through analysing the results in the supplier survey responses received during the course of this research, and were also used to generate an FSS value of between 0 and 20% as shown in Figure 12.

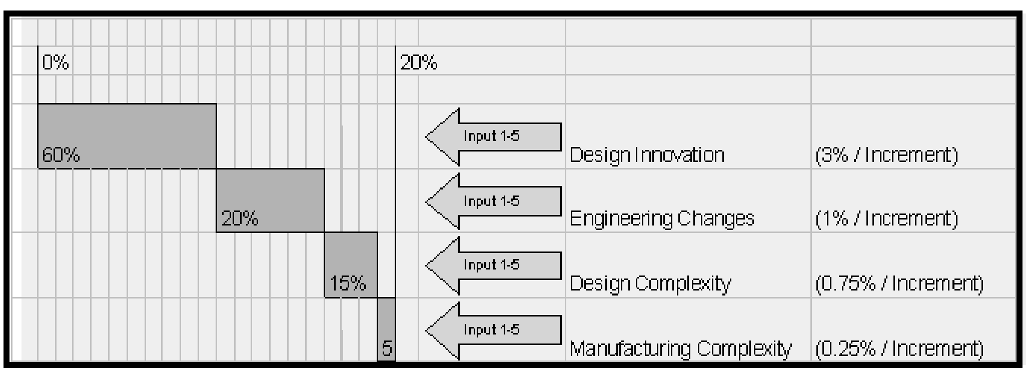

Figure 12: FSS % allocation

The cost driver significance table was also used to modify the output baseline allocation table (Table 4) to produce the final cost breakdown. The modified 'output baseline allocation table' was applied to the total FSS value together with specific hourly rates for each of the work activities to produce a split of hours for each work activity, which can subsequently be used for detailed cost discussion with the supplier. Sample results from a case study are presented in Figure 13. The current model needs further development by incorporating more case studies from different groups of commodities. This will make the model more generic within the automotive environment.

Outputs

Calculated

Design	$564,901	24.4%
Engineering	$1,069,888	46.2%
CAD Work	$96,290	4.2%
Prototypes	$11,501	0.5%
Testing	$43,865	1.9%
Project Management	$235,910	10.2%
Expenses – Travel	$134,806	5.8%
Expenses – Accommodation	$157,274	6.8%
	$2,314,435	100.0%

Actual

Design	$580,739	23.9%
Engineering	$1,175,481	48.4%
CAD Work	$91,508	3.8%
Prototypes	$7,779	0.3%
Testing	$47,024	1.9%
Project Management	$234,046	9.6%
Expenses – Travel	$131,202	5.4%
Expenses – Accommodation	$162,366	6.7%
	$2,430,145	100.0%

Variance (Calc'd (Over)/Under Actual

		CS#1
		Seats
Design	-$15,838	-0.5%
Engineering	-$105,593	2.1%
CAD Work	$(4,782)	-0.4%
Prototypes	$(3,722)	-0.2%
Testing	-$3,158	0.0%
Project Management	$(1,865)	-0.6%
Expenses – Travel	$(3,604)	-0.4%
Expenses – Accommodation	-$5,092	-0.1%
	-$115,710	-0.4%

Figure 13: Case study (Seats)

Table 4: Output baseline allocation table

Cost Category	**Allocation %**
Design	20.0
Engineering	50.0
Cad Work	4.0
Prototypes	0.5
Testing	2.0
Project management	10.5
Expenses – Travel	6.0
Expenses – Accommodation	7.0
Total	**100**

9. Cost Engineering: The Future

Cost engineering is enjoying a renewed interest in industry. Commercial cost engineering software vendors are busy developing specialist cost models for modern hardware and software development techniques. This trend will continue in the future. In USA and Europe there is also an increasing trend of developing integrated cost engineering systems that can share data for cost estimating between different stages of a product development. It is observed that the process is adhoc and in many cases fails to share data with other enterprise integration software such as Enterprise Resource Planning (ERP) tools. Industries have heavily invested in ERP software, and it is logical that cost engineering software should utilise data stored in the ERP data warehouses. Such integration requires further research in terms of matching the level of data available in ERP systems Vs data requirement for cost engineering.

Industries also require developing better data collection process outside ERP systems to provide additional better quality data for the cost engineering. Another area of future growth and research in cost engineering is to capture and reuse human expertise or knowledge used during the development of a cost estimate. This will help to analyse an old estimate better before it is reused. Current commercial software needs to go a long way to develop this capability in an intelligent manner, so that the additional workload on the cost estimators is reduced. It is observed that larger companies mostly practise systematic cost engineering. With increasing competition, larger companies are expecting transparent cost estimating from their suppliers. There is a need to develop low cost engineering software for Small and Medium scale Enterprises (SMEs). This is particularly relevant for European SMEs, where there is a distinct lack of commercial software for this sector.

10. Concluding Remarks

This report describes how cost is an increasingly important factor of success within industry. And how cost estimating and cost management is essential to the survival of leading companies. Several state-of-the-art-techniques and processes, used to facilitate cost estimating, have been discussed with particular reference to their applicability within a concurrent engineering environment. This provided a broad overview of the strengths and weaknesses of each method. Research results from industrial surveys were presented identifying the current practice in hardware and software cost engineering. These studies identified a lack of formal processes, common terminology and best practice in the cost engineering discipline. Internal communication within the cost engineering community in a company is very weak, especially between commercial people and engineers. There is a general lack of recognition of the discipline, leading to under investment. There is no formal education or effective training available for cost engineering.

In practice, many people thinks cost engineering is still a 'black art', but research has shown that the reasoning processes behind analogy based cost estimating in different industries are actually similar and can be modelled. It is also possible to elicit expert judgment used in cost engineering and reuse it for future estimates. Commercial software for cost engineering is more data centric rather than 'expert knowledge' based. The inference structure presented represents the same reasoning process for cost estimating at different levels of product definition and detail. The same reasoning process is used whether in the conceptual stages of design or whether in the disposal life cycle phase of a project. The process or method by which an expert uses judgement does not change. Only the level of abstraction changes. In the conceptual stages of project development, the comparisons are made at a much higher level of project definition, and as the project moves into the later stages of development, the comparisons become increasingly detailed.

Another area of research, presented in this report, highlighted the importance of developing cost models for commodities involving strategic suppliers. Manufacturing companies are developing strategic partnerships to share risks in a very competitive world. Strategic suppliers in the automotive industry play a major role in the product development. It is observed that estimating R&D effort for such strategic development is a most difficult challenge. It is almost impossible to estimate the effort quantitatively therefore the research presents a qualitative cost estimating framework to estimate the R&D costs. The framework uses a scale of 1 to 10 to capture people's opinion on this subjective issue. There is a need to train cost estimators in using this qualitative tool so that there is less subjectivity. In general it is also observed that there is a lack of motivation to capture necessary data for cost model developments. This is mainly because of the resource pressure. There is a need to develop methodologies to capture good quality data from people and also from other computer systems.

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