Cost Engineering: Current Trends and Future Research

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Abstract

This paper aims to review the current practice in cost engineering, identify the scientific research challengesand suggest future direction of this area research. It has been developed based on both the outputs from the academic forum of cost engineering at Cranfield University in the UK and the state of art on cost engineering research. The promising future research subjects in Cost Engineering have been identified and discussed in detail such as understanding the factors impacting design rework; cost estimation using CAPP information; estimating the uncertainties through life cycle; and developing uncertainty modelling methods.

Keywords: Cost Engineering, Whole Life Cost, Risk and Uncertainty, Affordability Engineering, Design Cost, Manufacturing Cost, Operation Cost, Service Cost

1. Introduction

Cost is crucial for successful production and delivery of functional needs, especially within today's highly competitive market place. 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. Companies that are unable to provide detailed and meaningful cost estimates at the early development phases have a significantly higher percentage of programs behind schedule and with higher development costs than those that can provide completed cost estimates (Hollmann, 2006).

Cost Engineering is defined by the Association for the Advancement of Cost Engineering (AACE) as “the area of engineering practice where engineering judgment and experience are used in the application of scientific principles and techniques to problems of cost estimating, cost control, business planning and management science, profitability analysis, project management, and planning and scheduling” (Hollmann, 2006). It is a methodology used for predicting/forecasting/estimating the cost of a work activity or output (Stewart et al., 1995).

Cost Engineering is widely practised in various industry sectors, especially in aerospace and defence, where a number of approaches have been developed and applied. However for the academia, although they are heavily involved in industry projects now, the key issues are: what are the scientific challenges for Cost Engineering; what are supposed to be the research focuses, how academia can make a more valuable scientific contribution to Cost Engineering. In other words, the scientific challenges need to be better understood.

Some researchers have reviewed the practice of Cost Engineering, e.g. Curran et al (2004) reviewed the cost modelling techniques for aerospace industry, and stated that there is no consolidating theoretical approach for Cost Engineering, the paper consequently proposed the genetic causal approach for cost modelling (Curran et al., 2004). Roy (2003) reviewed the cost engineering techniques, and the state of art of hardware and software costing. Roy (2008) presented the research formalizing the cost engineering reasoning process, and full service supplier cost modelling. He also pointed out the need of matching the data available in ERP systems against the data requirement for cost engineering (Roy, 2008). Niazi et al. (2006) reviewed cost estimation techniques and classified them in a hierarchy. However, the scientific challenges in Cost Engineering have not been well discussed in literatures.

Having recognized the importance of understanding the scientific challenges of Cost Engineering, the Academic Forum of Cost Engineering UK was held at Cranfield University in Dec. 2008. Major researchers from different universities in UK (also Europe) attended this event and discussed some important topics. Based on that, this paper aims to bring together the current Cost Engineering research and identify the scientific challenges in Cost Engineering. In Section 2, the methodologies applied to this paper are explained. Section 3 highlights the background and subsequently in Section 4 the current research in the key topics of Cost Engineering, including Design and Manufacturing Costing, Operational and Disposal Costing, Whole Life Costing, Risk and Uncertainty, Affordability Engineering, and Value Engineering is explained. Thereafter identification and discussion on promising future research in each topic of Cost Engineering are presented in Section 5.

2. Methodology

This paper was written based on the outcome of the Academic Forum of Cost Engineering held at Cranfield University, UK in Dec. 2008. Researchers from University of Bath, Southampton University, Loughborough University, Durham University, and Cranfield University in the United Kingdom and Jönköping University in Sweden presented their research on Cost of Design, Production Costing, Operation Costing, Disposal Costing, Whole Life Cycle Costing, Risk and Uncertainty, and Affordability Assessment. For the literature review, the content analysis method was adopted where specific words or concepts used in searching literature materials. Figure 1 illustrates the key topics that have been considered in this paper.

Insert Figure 1

The materials consulted included books, essays, theses, conference papers, industry reports, journal articles, and unpublished or published working papers. In order to capture current practice, the Delphi method (Turoff and Linstone, 2002) was applied for some sessions in this paper. This is because some of the information required were embedded in individual experts and they needed to be captured in an iterative way to obtain reliable consensus of expert opinion.

In each selected area, the current research is reviewed by integrating the literature review results and the presented research on the Academic Forum of Cost Engineering. On the Forum, a discussion session was run to brainstorm the scientific challenges of Cost Engineering. The discussion, supplemented by further inputs from each author after the Forum, formed a basis to identify the future research of Cost Engineering. The methodology adopted for this paper can be seen in Figure 2.

Insert Figure 2

3. Background

There are researches in different topics on Cost Engineering, and each research topic has their particular context, i.e. the research contents, importance and status. This section will look at those research topics, and understand their importance and why these topics are included in this paper.

3.1 Design Cost

Cost of design is accounted as a non-recurring cost which includes the cost from defining requirement until design drawing release for manufacturing stage (Basir, 2000). The cost of design is basically considered as the human effort required to finish a design (Putnam and Myers, 1997). There are two parts in cost of design: the planned cost and unplanned cost (Cho and Eppinger, 2005). The unplanned cost is stochastic in nature and is recognized as "a design rework cost", and is more difficult to predict. The design rework is defined as unnecessary repetition of design effort due to influences from other design tasks (Arundachawat et al., 2009a) and is considered as negative iteration in product design and development (Ballard, 2000). This unnecessary iteration is a result of design error or design failure due to neglecting something previously known, and moreover the lack of knowledge. The design rework does not cover the design changes due to requirement changes, which is considered as non-monotonic (Krishnan et al., 1997). So predicting design rework is important to better understand initial effort required for a project.

3.2 Manufacturing Cost

A large number of methods for cost estimation have been developed to enable the calculation of manufacturing cost based on the amount and type of information available. The methods can be classified as intuitive methods, parametric techniques, variant-based models and generative cost estimating (Shebab and Abdalla, 2001). The main approaches for manufacturing cost estimation (Weustink et al, 2000) are variant based costing using the similarities with previously manufactured products, and generative cost estimating where the manufacturing operations are determined. Intuitive methods (e.g. the method of successive calculus by Lichtenberg, 2000) are subjective in their nature and rely on the experience of the estimators. Parametric methods map characterising product parameters to product cost using relations defined by statistical methods. Examples of parametric methods for different manufacturing and assembly processes are given in Boothroyd et al (2002).

3.3 Operating Cost

Operating costs constitute a major part of the life cycle including the service (e.g. maintenance, product modification) and operation content (e.g. fuel usage, electricity consumption) (Curran et al, 2004). While its importance had traditionally been partially ignored due to the heavy focus on initial capital costs, and also the growth in life cycle based contracts which promoted the need for robust cost estimates (NASA, 2004). A major source of challenge affecting the prediction of operating costs is associated with the limited level of available information (Asiedu and Gu, 1998). This has caused low reliability of estimates and low uptake for practitioners. Furthermore, the life cycle view of equipment has created additional challenges by means of risks and uncertainties (Erkoyuncu et al, 2009; Gruneberg et al. 2007).

3.4 Whole Life Cost

Life cycle cost is the total cost over a product's life cycle span (Dhillon, 1981, Xu Y. et al., 2008a). The alternative terminology for LCC is WLC (Whole Life Cost) and TLC (Through-Life Cost). Nowadays, companies are more concerned to prepare lifecycle cost estimates of a product from its conception until the end of its life. This is emphasised by the shift in industrial business processes which have moved from delivering spares and parts to total care packages through the whole lifetime of the product (Roy et al., 2009), and it is included in the paper.

In effect, products such as aircraft are now being leased and the customers pay per hour of flying time, often referred to as "Power by the Hour" or Performance-Based Logistics (PBL) (Kim, 2007). For example, in aerospace engines, 55% (£4.265billion) of Rolls Royce's sales were from aftermarket service in 2007 (Rolls-Royce, 2007). By 2028 they predict a civil after sales market opportunity of US$550 billion and for military engines of US$300 billion. Hence, modelling through-life costs and making a decision at the concept design stage to save 1% on in-service costs would save taxpayers US$3 billion - just on military engines. The in-service costs for the Defence Equipment and Support arm of the MOD was £10b in 2007-08 excluding new equipment. Achieving cradle to cradle cost modelling will enable Original Equipment Manufacturers, policy makers and governments to make decisions based on the Through Life Costing of a product.

3.5 Disposal Cost

In terms of industrial application, there is still much room to bring the disposal segment into the design process of solutions. Furthermore, as interest has grown in this area, various routes to take at this stage have been proposed. For instance, recycling, remanufacturing, reuse and disposal, broadly, are four strategies that can be applied (Asiedu and Gu, 1998). Currently, the major focus tends to maximise recycled resources in the disposal phase. Whatever, it is important to select the appropriate strategy at the design stage so that the most efficient manner is incorporated into operations.

3.6 Uncertainty

Uncertainty can be considered as any deviation from the unachievable ideal of complete deterministic knowledge of the relevant system (Walker et al, 2003). In the context of modelling, uncertainty can be defined as a potential deficiency in any phase of activity of the modelling process that is due to lack of knowledge which causes the model-based predictions to differ from reality (AIAA 1998; DeLaurentis 1998). The term contains fuzziness and randomness, while creating doubtfulness and lack of confidence. There is a significant amount of literature concerning the definition and modelling of uncertainty in a wide range of fields. However, it is worth recognising that definitions have been driven by "purposes" and "scientific disciplines" (Refsgaard et al., 2007) therefore numerous and varied typologies can be found (Heijungs and Huijbregts 2004; Lloyd and Ries 2007). One important characterisation of uncertainty is whether it is epistemic or aleatory in nature because this distinction allows them to be treated effectively. Aleatory uncertainty, being inherent in the system and cannot be reduced without changing the system, requires the availability of statistical data to fully describe its characteristics. The challenge within its cost estimating is to improve the availability of useful data, particularly from in-service phase where most of the costs are encountered within the life cycle. The cost drivers such as repair time and down time can be characterised as random variables. The epistemic uncertainty caused by lack of knowledge is arguably more difficult to quantify and will require fundamentally different strategies (Erkoyuncu et al., 2010a). For instance, uncertainty associated with the future which is unknown including costs associated with future scenarios such as technology obsolescence or changes in legislation.

Table summarised uncertainties in cost data and models typically found.

Insert Table 2

3.7 Affordability

Affordability analysis makes use of the outputs of a LCCA to apply investment strategies over the life cycle of equipment such as reserve strategies, and development cycles, it is of great importance. The word 'afford' is described as the ability to 'manage to bear without serious detriment' (Merriam-Webster Collegiate Dictionary). The concept of affordability is better understood and established in some industries than others.

Affordability is a social construct which needs to be conceptualised and operationalised. It is about aligning the customer budget with the WLCC. This means there are two possibilities:

1. The WLCC is higher than the customer budget, that is customer budget is lower than the WLCC

2. The WLCC is lower than the customer budget, that is customer budget is higher than the WLCC

Within the defence environment, the customer budget is usually set at the top (program) level, but there is a degree of flexibility within projects. This means that overall defence budget is fixed, but individual projects within the overall program could try to convince the top level that a particular project requires a higher budget in comparison to others. Generally there is a threshold which states the highest level of budget allocation. This means that in most cases the total WLCC is usually higher than the customer budget. From the customer side, it is important that the budget is set right the first time so that the budget is realistic to cover the cost of the project. From the manufacturer's side, the strategy is to reduce cost without decreasing Customers' Willingness To Pay (CWTP). This is important because if the manufacturer is able to reduce WLCC, there is the possibility for the customer to cut back on the budget since the WLCC is reducing. What would be beneficial for the manufacturer is to reduce WLCC but maintain the customer budget by maintaining or improving the CWTP. Economics researchers have identified possible methods of influencing CWTP such as Net Present Value (NPV), Conjoint Measurement, Auctions and Direct measures.

4. Current Research on Cost Engineering

4.1 Cost of Design

Research has been conducted to predict the design rework effort. The design rework efforts are developed by the fundamental understanding of product design and development, namely vertical planning and horizontal planning. The vertical planning is the planning to coordinate among functions, e.g. design function, prototyping, testing, manufacturing process design, while the horizontal planning is to achieve the integration among interactions of subsystems or components (Clark and Fujimoto, 1989). The interactions have been classified as independency, dependency, and interdependency design tasks (Yassine et al, 1999). Interactions among horizontal or vertical direction could cause design rework. If the product design follows a concurrent engineering approach, the preliminary information exchanged upstream and downstream becomes a key factor of design rework. Krishnan et al. (1997) and Terwiesch et al. (2002) studied the design rework caused by exchanging preliminary information. However, both of them simplified design tasks as two types of dependent tasks, i.e. downstream task depends on the change from upstream, while evolution of upstream changes and downstream sensitivity to the changes are the key criteria to model design rework. Some other literatures studied the design rework caused by more than two dependent design tasks (Roemer et al. 2000; Chakravarty 2001; and Browning & Eppinger, 2002). The design rework problem will be more complex, if it is in the context of multi design tasks interdependency (Arundachawat et al. 2009a).

The later development on design rework effort estimation is focused on simulation and optimisation; however, they are still relied on the fundamental stated above. Furthermore; the key criteria to estimate design rework are considered in more details by separation between probability of design rework occurrence and design rework efforts.

4.2 Manufacturing Cost

4.2.1 Engineering Design and Manufacturing Cost Estimation

For a single product the magnitude of its direct manufacturing cost is greatly affected by its design. The cost of material is commonly dominant for many manufactured products (Hendricks, 1989) and can be estimated when the final geometry is defined and the material specified. The cost for tooling, direct labour and machining presents more difficulties. To ensure a high level of accuracy in the cost estimation requires a final estimation based on the process planning accomplished by production engineers. The problem is the extensive work required to gather all relevant product and production data and to complete the process planning. A survey in ten Swedish manufacturing companies indicates that lack of information is a main problem in many manufacturing companies (Cederfeldt and Elgh, 2005), as shown in Figure 3.

Insert Figure 3

4.2.2 Cost Estimation Based on Computer-Aided Process Planning

For every operation defined in a process plan the processing time can be estimated based on the work rate for the resource used to accomplish the operation. When the processing time is known the operation cost can be estimated using the cost rate for the utilization of the resource. Computer-aided Process Planning (CAPP) systems are used for automating the task of process planning. By using CAPP, the effort required to convert Computer Aided Design (CAD) models into process plans can be reduced. Much research has been devoted to mapping Computer-Aided Design (CAD) model data to a process planning system (Ahmad et al., 2001). There are two general approaches: variant CAPP and generative CAPP (Groover, 2001). Variant CAPP is based on group technology and standard process plans. It often includes manual editing. Generative CAPP utilises decision logic, formulas, manufacturing rules and geometry-based data (e.g. CAD features). In a fully generative CAPP system, there is no need for human assistance or standard plans.

CAPP requires CAD model parsing for the identification of manufacturing features. There are two approaches to identify features in a CAD model for process planning which will determine the manufacturing operations and their sequences: feature recognition and design by feature (McMahon and Brown, 1998). Feature recognition searches data structure of an existing solid model for combinations of geometric elements and tries to identify pre-defined manufacturing features that correspond to operations. In design by feature, the process of converting features to operations is implemented in the construction of the solid model through the use of standard shape features that correspond to manufacturing operations.

3.2.4 Main Issues of Current Research

At the early design stage, a number of costing approaches have been proposed, mainly based on the parametric approach as there is no detailed information available at that stage. The use of parametric methods requires access to historical data of previous products for the definition of parametric expressions. The use of a specific parametric method is restricted to products similar to the ones used for setting up the parametric relations. The possibility to change a product's design is at its greatest at the early design stage in order that it will comply with the intended manufacturing resources. However, many of the methods used at the early stages can not be used to identify areas for improvements as the level of detail and accuracy in the estimations is low.

At the detailed design stage, material cost can be estimated quite easily based on CAD geometry data. The challenging task is the estimation of the manufacturing cost as it depends on the principles and resources for manufacturing which are determined through process planning. Process planning requires mapping of design features to manufacturing features and knowledge about the methods considered for the manufacturing. The research effort in feature recognition has been significant – nevertheless there is a limited supply of commercial application software for feature recognition to date. The limitations with the design by feature approach are that: different applications programs used in different engineering disciplines requires different features; different manufacturing processes require different sets of manufacturing features; the intended manufacturing processes are not always known in advance, and it is not always suitable to restrict the design to a specific manufacturing process.

Many small to medium sized enterprises (SMEs) are subcontractors acting in an environment of continuous demands on cost reduction and ability to respond on quotations. It has been made clear in discussions with a number of these companies that there is an emerging need of support in the quotation process (ranging from product preparation and cost estimation of a single component to an engineered-to-order multi-component product). The cost estimation must be at a level that satisfies the customer and at the same time guarantees product profit. The ever-increasing competition reduces the gap between these two, which implies that a higher level of accuracy of the cost estimations in the quotation process is a necessity.

4.3 Operating Cost

3.3.1 Operation Cost Estimation

The operation cost means the cost incurred during the product usage. For example for the assets, it normally includes direct labour, direct materials, direct expenses, indirect labour, indirect materials and establishment costs. The estimation of these costs is driven by both predicted and actual experience of the performance of similar assets (Woodward, 1997). This necessitates consideration of various cost drivers that contribute to total operational costs. Research to predict operation costs has largely focused on uncertainties that arise over the operating life time span concerning energy costs, maintenance, fees, staff level and regulatory changes. For instance, Campbell et al., (1982) focus on consideration of supply side uncertainties and their effects on estimating cost in electric utility planning. Boussabaine (2001) focuses on modelling energy costs within a sports facilities context. However, the centre of challenges lies in the availability and reliability of data. Furthermore, it is relatively easy to find data sources providing reliability data, however it is difficult to find data sources for operation data and cost data (Kawauchi and Rausand, 1999).

The consideration of operation costs has commonly been made in association with service costs. However, cost estimation approaches have varied across operation and service tasks. Table 1 shows the main approaches for estimating operating cost.

Insert Table 1

3.3.2 Service Cost Estimation

The importance of the service contents has grown across manufacturing industries due to a number of reasons such as diminishing customer budget, need for increased efficiency and interest in transferring risks (Erkoyuncu et al, 2009). The shift of manufacturers from selling products to services has been studied in the servitization literatures, where product-service systems (PSS) form a specific case (Roy and Cheruvu, 2009). A PSS aims to deliver value by integrating products and services (Baines et al. 2007, Huang, et al. 2009, Goh et al 2010) and it has been formed typically through Contracting for Availability (CfA) in the defence and the aerospace industries. These involve a commercial process which seeks to sustain a system or capability at an agreed level of readiness, over a period of time, by building a partnering arrangement between the MoD and Industry. Service costing considers various activities, e.g. maintenance, repair, asset and operation management service, supply chain management and engineering service and training, that enable or enhance the operational life of given equipment (Asiedu and Gu, 1998). However, most of the literatures are focused towards costing the service associated with stand-alone products (Datta and Roy, 2010). Furthermore, the two main areas of interest in relation to the service phase relates to the prediction of the service life and performance modelling, and cost estimation approaches vary being either deterministic or stochastic methods (Kirkham et al., 2004). This process covers a number of areas including the prediction of the remaining service life of the facility components and the prediction of the rate of their deterioration (NASA, 2004). Some of the main objectives that need to be identified and assessed at this stage include (Boussabaine and Kirkham, 2004), survey condition of the existing facility components, assumptions about the remaining service lives of components, updating budget requirement, priority of components updating-critical components, quality of maintenance and replacement components, assumption about time-lag replacement or maintenance delays, the effect of delayed maintenance on budget and deterioration of facility, evaluating the economic viability with a view to disposal.

In service cost estimation, historical data provides guidance in terms of costs and priority of required maintenance, rehabilitation and replacement. However, it is necessary for database cost estimates to be supplemented with expert opinions in order to perform whole-life cycle analysis and risk assessment (Roy, 2003). In terms of service cost estimation, interest has been growing recently. A commonly adopted methodology to estimate service costs includes 5 major steps (Brouwer 2001):

- Well-defined decision problem and clear objectives
- Detailed description of the service(s)
- Identification and classification of resource items and units of resources to deliver service
- Measuring resource consumption
- Placing monetary value on each resource item (goods, activities) and calculating the unit costs of a particular service

4.4 Disposal Cost

From a disposal costing perspective this area has been growing recently, as firms have become aware of the significance of the disposal segment of the life cycle. Many researchers have begun to study relevant subjects such as consumer demands for green products, and rising waste disposal costs (Woodward, 1997). However, research in disposal cost estimation is limited mainly due to ad-hoc applications that do not tend to tie-down disposal related responsibilities to any party at the design or operation phases (Boussabaine and Kirkham, 2004). This is mainly due to the lack of information that is available at the bidding stage of contracts. The lack of information particularly centres on the life of an asset where forecasts are challenged by the stochastic nature of equipment life cycle related variables (Asiedu and Gu, 1998). There are five possible determinants of an asset's life expectancy (Woodward, 1997):

- Functional life concentrates on the duration that an asset is needed
- Physical life focuses on the physical ability of an asset to last over a duration
- Technological life refers to the period until technical obsolescence dictates replacement due to the development of a technologically superior alternative
- Economic life relates to the period which obsolescence dictates replacement with a lower cost alternative
- Social and legal life considers the period until human desire or legal requirement dictates replacement

4.5 WLC (Integration)

Many researchers have undertaken and put on considerable amount of efforts on the investigation of modelling TLC on different products (Cheung, et al., 2007). For example Newnes and Mileham (2006) addressed the difficulties of performing TLC on innovative low volume and long life electronic defence systems, and Xu et al adopted Systems Engineering approach to develop a LCC model for aircraft wing for multi-disciplinary design optimisation (Y. Xu, J. Wang, et al 2008, Xu Y. et al. 2008).

There are a variety of different approaches for developing cost models of life cycle analysis. These estimation methods vary greatly depending on the type of product being modelled, stage of analysis and the level of detail required. Similarly to the design process where lower level functional requirements are produced through functional decomposition to enable design solutions to be easily developed, it is imperative that cost decomposition is produced. An alternative approach is the concept of function cost (French, 1990). This is based on the principle that many functions can be quantified and the costs associated with a function are often simply related to the quantity or qualities. This approach decomposes the product by function, and quantifies and costs of each function.

Some of the key measures that influence method selection include the relative size of the project, computational aids and skills, user understanding of the technique being applied and availability of useful data (Boussabaine and Kirkham, 2004). The consequences of decision making associated with the LCC is often significant, especially efforts to improve the availability of useful data for cost estimating, particularly from the in-service phase where most of the costs are encountered within the life cycle will be justifiable.

4.6 Uncertainty

Despite the significant presence of uncertainties in LCC, traditionally LCC was considered in a deterministic fashion. Recent emphasis in governmental agencies, public and defence sectors on understanding risks associated with LCC estimation has resulted in vast practices of probabilistic methods (Treasury 2003; Kishk 2004). In probabilistic methods, uncertainty in the cost data are represented by probability density functions (triangular and normal being most popular) and then propagated through cost models in order to assess the uncertainty in LCC. Analytical and computational methods such as Monte Carlo simulation are used for uncertainty propagation according to probability theory. However, probabilistic methods although suitable for characterising aleatory uncertainty, may be less useful when statistical data is seriously lacking or when the uncertainty is caused by lack of knowledge (epistemic uncertainty). This drawback has led to the investigation of the possibilistic and fuzzy set approaches (Kishk 2004; Oberkampf et al., 2001; Dubois and Prade, 2003). Possibility theory and fuzzy set theory are forms of artificial intelligence, which can be considered to be extensions to probability theory (Dubois and Prade, 2003). These approaches are capable of representing uncertainty with much weaker statements of knowledge and more diverse types of uncertainty (Oberkampf et al., 2001).

There have also been studies that have used deterministic approaches to assess uncertainty (Boussabaine and Kirkham, 2004). Typical approaches in the deterministic approach include sensitivity analysis, net present value and breakeven analysis. To this end, characterisation of epistemic uncertainties is found to be lacking, perhaps due to difficulty and resources required. Because both types of uncertainty are expected in LCC estimation, it is suggested that a modelling approach that is able to take into account both epistemic and aleatory uncertainty in LCC estimating may be useful. This is particularly driven by the notion that combining aleatory and epistemic uncertainty underestimates the total uncertainty (Oberkampf et al., 2001). Modelling uncertainties tend to be epistemic and can be reduced if further resources are expended to collect evidence, add details to the models, quantify boundary conditions etc. However, to date limited efforts have been observed in industry. Overall, much research has been emphasised on the techniques for modelling uncertainty, however there has been little work on integrating the whole process of uncertainty identification, quantification, response and management strategies (Erkoyuncu et al., 2010b). This implies that uncertainty assessment must guide investment in a holistic manner along the life cycle.

The importance of the in-service phase has grown for manufacturers as customers in many industries such as defence, aerospace, automotive, and construction have adopted an approach that transfers responsibilities to manufacturers (i.e. through equipment availability agreements). The two major aspects that have caused challenges for manufacturers in managing uncertainty within this new context include (1) uncertainties move away from the sale of the equipment towards its utilisation in a bundled and concurrent manner, (2) service contracts require a 'left-shift' of the point-in-time at which uncertainties are addressed at the bidding stage (Erkoyuncu et al., 2009). An important challenge in facilitating this transition towards service orientation is driven by the ability of the customer to transfer data to manufacturers and/or ability of manufacturers to make use of historical data. A summary of the typical issues that arise from using the data are represented in Figure 4 (Durugbo et al., 2009):

4.7 Affordability

As a research area that becomes important in recent years, many researchers looked at the definition of affordability because definitions provide a platform for quantitative measures (Milne, 2004). A review by Bankole et al (2009) examined the definitions of affordability across industries. Within the software sector, it is described as the ability to be able to bear the cost of something (Bever and Collofello, 2002). A 'measure of whether housing can be afforded by certain groups of households' (Semple, 2007) which is concerned with 'securing some given standard of housing (or different standards) at a price or rent which does not impose, in the eyes of some third party (usually government) an unreasonable burden on household incomes', within the construction sector (Hancock, 1993). In the utilities sector, it is described as the provision of services which can be afforded by customers at different income levels (Milne, 2000). It is 'the share of monthly household income that is spent on utility services such as electricity, heating and water (Frakhauser and Tepic, 2007). It also defined as the ability to procure a system as the need arises, within a budget, operate at a required performance level and maintain and support it within an allocated life-cycle budget (Kroshl and Pandolfini, 2000). The North Atlantic Treaty Organisation (NATO) described it as 'the degree to which the life cycle cost of an acquisition programme is in consonance with the long-range investment and force structure plans of national defence administrations'. It provides the foundation for supporting greater programme stability through the assessment of programme affordability and the determination of affordability constraints (NATO, 2007). Lastly within the aerospace and defence industries, the Network of Excellence in Affordability Engineering (NoE in AE) at Cranfield University defined affordability as 'the degree to which the Whole Life Cycle Cost (WLCC) of an individual project or program is in consonance with the long range investment capability and evolving customer requirement' (Ray, et al., 2006). These definitions reflect the understanding of affordability in different sectors. Whilst there are similarities between the definitions especially within the aerospace and defence industry; most definitions refer to a comparison between the total cost of the product or service and the customer's income.

Affordability is affected by certain factors or drivers. From the literature review, factors such as cost, income or revenue, customer value and customer willingness to pay have been identified. It should be noted that the factors affecting affordability are not limited to those mentioned in this paper. There are more affecting factors on affordability which are specific to each company sector, also depending on the business relationships, either Business-to-Business or Business-to-Customer. The factors listing as follows are the common factors identified across different industries:

- Cost: refers to the financial investment that is required for the product or service to be produced or provided. In the case of long-term projects or offerings which combine products and services, it could refer to the investment involved throughout the life cycle of the product, service or project (Bankole et al, 2009).

- Income or revenue: influences the financial ability of the customer to pay for the product or service provided by the supplier. This could be represented by the customer's budget (Bankole et al, 2009).

- Customer value refers to the perceived worth in monetary units of the set of economic, technical, service and social benefits received by a customer firm in exchange for the price paid for a product, taking into consideration the available suppliers' offerings and prices (Anderson et. al., 1993).

There are also a number of qualitative factors which affect affordability namely risk, world economic climate, requirement, global competition, political situation, legislation, performance related measures, environment, supply chain and quality (Nogal, 2006; Bankole et al., 2010). The impact of each factor on affordability varies from one project to another. This requires a subjective assessment performed on each project (for the qualitative factors).

One important measurable parameter - Affordability Index (AI) -has been developed in different sectors in order to measure the affordability. Two examples are given in here.

Within the construction sector, Affordability Index (AI) is used to measure the affordability of housing for individual consumers. This is expressed as below:

$$\text{Affordability Index} = \frac{\text{Housing Costs} + \text{Transportation Costs}}{\text{Income}} \qquad (1)$$

This index does not only include the direct cost of housing, but also the additional cost of transport. (Centre for Transit-Oriented Development and Centre for Neighbourhood Technology, 2006).

Within the defence sector, an AI is used to measure the affordability of defence projects for individual consumers, as shown below, which was refined through interaction with industrial experts:

$$AI = \frac{CATS}{WLCC}\left(1-\left(\sum_{i=1}^{n}\frac{(C_i - S_i)}{S_i}\right)\frac{1}{n}\right) \quad (2)$$

Where,

CATS = what the Customer has Available to Spend/ customer budget

WLCC= Whole life cycle cost

C_i = Cost incurred in the ith year

S_i = Expected spending ability of the customer for the ith year

i = the years where cost exceeds the expected spending ability of the customer

n = total number of years the cost has exceeded the spending

An affordability score equals to 1 means it is just affordable, a score greater than 1 is more affordable while a score less than 1 is less affordable (Nogal, 2006).

4.8 Value Engineering

Target costing works with value engineering (Ibusuki and Kaminski 2007) to first identify the cost to make profit to be realised via Value Engineering. Cost Reduction can be affected through Design for Manufacture and Assembly (Boothroyd 2004), target costing, Quality Function Deployment, Value Engineering (Younker 2003) and all associated methods. Cranfield University have developed a methodology called Creative Value Improvement, in which the cost reduction methods require a creative phase in which the input of experts should be maximised. The Creative Value Improvement process uses creative design methods for re-design ideas in value engineering. Zhang et al (2009) concur about the requirement to improve the creative input into cost reduction methods and use Triz to improve the treatment of the creative phase of value engineering. Triz is said to make this part of value engineering "more systematic and more organised and to enable the VE team to control the creativity process". This synthesised Creative Design and Value Engineering. Van Dam and Pruijdsem (2008) exemplified many of the sub methods involved in target costing and value analysis. They developed a cost reduction methodology involving learning curve, DFMA, FAST and the six rules of cost. The major components of Value Engineering were present. It was important to include the life cycle cost when apportioning cost per function. FAST involved asking how and why? These correspond to two different logical directions in the Value Engineering process. The Value Engineering effort also involved the Cfx matrix in which the cost to value index was calculated. The cost to value index is an important metric in identifying where re-design effort should be directed. Kaminski et al (2007) made focus on a tear down of function rather than of the component labour, material and expenses. They develop what they call concept VE rather than validation VE. Some of the typical validation VE cost reduction heuristics are provided by Kaminski et al (2007), such as "reduce the number of parts, designing parts which do not require special high precision or increasing productivity". In cost reduction it is all so common for re-design to be only directed at areas of the product development cycle where the maximum benefit cannot be felt. Of key importance is top management support if cost reduction and value engineering processes are to be successful (Ibsuki and Kaminski 2007). Value Engineering was usually deployed as part of lean manufacturing. Now value is the focus of the full life cycle. Kumar et al (2007) examine perceived value flow across the full life cycle.

5. Discussion and Future Research

5.1 Design and Manufacturing cost

Aiming to reduce total effort and lead time in a product design and development project, the detailed understanding of factors influencing design rework needs to be unveiled as attempted in Arundachawat et al. (2009b). Also, in-depth study for causes of design rework probability of occurrence and design rework efforts which previously were not clearly stated in literatures should be studied.

In Manufacturing Cost, based on the issues identified in current research, five of them for future research can be outlined:

- How to bolster the sharing of product and manufacturing information?
- How to estimate manufacturing cost at early design stage with a high level of accuracy?
- How to support process planning at detail design stage?
- How to support process planning in the quotation process?
- How to do automatic costing based on CAPP information?

To enable timely and accurate cost estimation the access to product and manufacturing information is crucial. One approach for sharing and managing information is to set up an information infrastructure based on a shared conceptual model – ontology. Within an ontology approach, work within domains production engineering and engineering design can be integrated and their information exchange supported (Elgh and Sunnersjö, 2009). Areas for further research are: principles, methods and models supporting the development, use and management of ontology models and ontology based information systems supporting sharing of concepts and information necessary for manufacturing cost estimation. According to Roy (2003), a tool that can be used to predict and estimate the cost with acceptable accuracy requires different types of input as depicted in Figure 5.

Insert Figure 5

To support the process planning at the detailed design stage two approaches needs to be further explored and developed: feature recognition and design by feature. Feature recognition has mainly focused on material removing processes. However, material removing processes require both pre-processing and post-processing. Furthermore, a significant number of products are manufactured by other processes and requires assembling operations. Design by feature implies that the manufacturing method is known in advance and that a method for the geometry definition, based on the manufacturing operations, is used. One area for research would be a more general approach where a limited number of manufacturing alternative are defined in advance and for each of these a model is created concurrently by a rule base executed automatically as the geometry is defined. For variant based design the process can be automated (Elgh, 2004). Research has to be conducted to support the development of systems for automated process planning of product variants.

To support the process planning and cost estimation in the quotation process with a high level of accuracy requires generative cost estimating, where the manufacturing operations are determined. This implies the recognition of manufacturing features in relation to intended manufacturing resource. One solution could be to further exploit feature recognition as previously described. Another approach is to focus on the manual process planning carried out at SME's and develop methods and tools to support the different tasks while increasing the efficiency, shorten the lead time and improve the accuracy of process planning (Elgh, 2008). The questions are: how can this be achieved and how to develop tools that are applicable for SMEs?

Automated cost estimation of products requires mapping between product design, process plans, utilized resources and costing method (Elgh, 2004). The selection of the costing method has implications on the information required for its completion. To enable cost estimation based on CAPP information requires that the information in the process plans and the information about company resources contain necessary information for costing. Therefore, it is of vital importance that the principles and methods for costing are specified, information required defined, the information sources traced and that the information is complete and applicable for its intended use. How to practically do this is in an industrial setting is an area for further investigation and research.

5.2 Operating Cost and Disposal Cost

At the bidding stage of contracts optimism continues to highly influence the initial appraisal of projects. Furthermore, understanding uncertainties that arise from operations, services and disposal requires better understanding particularly at the bid stage. Within a whole life cycle cost (WLCC) model it is necessary to acquire approaches that take into account the stochastic nature of operations, services and disposal. For instance, the MoD Strategy of Incremental Acquisition requires a series of equipment upgrades throughout its service life to enhance performance and/or to reduce cost. The challenge lies in the modelling ability to capture these uncertainties up-front at the bidding stage. Furthermore, the cost of such upgrades must take account of all the consequences, including any retraining and requalification.

5.3 WLC

A further research issue in WLC is to develop a set of rules that can be used to identify specific sub-systems and components that drive the cost. For example, the interdependencies between various subsystems might create additional costs and differences in life span and upgrade characteristics are usually difficult to predict and manage.

One of the other challenges in WLC is the lack of research emphasis on the 'in-service' stage of innovative low volume defence systems, in particular product availability from "Power by the Hour" point of view. According to Operational Availability Handbook, (2003), operational availability is the main factor to predict product availability. At the in-service of a product-services system, operational availability is used to evaluate operational performance through-out the system life cycle. Therefore, further research is needed to investigate and develop a method to capture the relevant information that drives operational availability and makes it ready at the early design stage to support the prediction of in-service availability.

Prediction of low volume systems availability is limited, particularly in methods that used to address the lack of statistically significant data. Therefore a methodology to improve product availability and reliability by predicting spares provisioning is needed, for example, the availability of subsystems and components.

New techniques are also needed to store all the information in a centralised-controlled environment, for example the application of databases. To make use of the data, a navigation-tree technique coupled with data query searching techniques to link all the relevant spreadsheets are also required. Some technical solutions include:

(1) All the factors that affect the prediction of the 'availability' of a product from the early stage of a design should be identified. For instance, cost categories that drive 'Power-By-The-Hour' in aerospace industry are cost of spare support and logistic cost (Knowledge Wharton, 2007). Cost of spare support could include inventory cost, cost of support equipment, cost of labour and spares cost etc.; and typical factors that drive 'logistic cost' could include transportation, storage, inventory, field support, maintenance etc.

(2) Derive a new methodology for an integrated costing modelling approach. This integrated approach will focus on 'data acquisition and collection' from different stake holders in the supply chain.

(3) A generic method of linking proprietary cost estimation systems with the proposed integrated approach.

5.4 Uncertainty

Commonly across the world there is a trend of service orientation which is influencing the nature of uncertainties that affect cost estimation for all partied involved. Especially OEMs are facing the challenges of understanding the shift in the types of uncertainties that are affecting operations. On one hand, it is necessary to set a framework to capture all or most important uncertainties that affect the LCC estimation in order to maximise effectiveness of decisions that are made early on. On the other hand, it is necessary to understand how uncertainties may vary through the life cycle, in order to associate these with appropriate modelling techniques to the levels of data and knowledge available. In this respect, it is necessary to address the wide scope of uncertainties encountered such that suitable mitigation approaches can be adopted to reduce and manage the effects of uncertainties. In terms of improving estimation, uncertainty modelling methods that enable consideration of aleatory and epistemic uncertainties separately can be useful. It is emphasised that for addressing aleatory uncertainty, issues associated with availability and quality of data are most critical. Efforts in collecting life cycle information from the in-service phase are particularly important for ensuring meaningful LCC estimation. For addressing epistemic uncertainty, there needs to be verification and validation strategies associated with the cost estimating process, in particular, uncertainties in the cost models have not been fully investigated. As the estimated costs may be highly sensitive to these uncertainties, given the importance of decisions associated with the estimated LCC, expenses in these efforts should be justifiable.

5.5 Affordability

It would be useful to further identify the link between the customer affordability, manufacturer profitability and supplier sustainability. Also, when considering the qualitative factors which impact affordability, there is need to define standard measures of weighting to represent the impact of each affordability factor on an individual project. Also guidelines could be provided based on the qualitative factors on how to improve the affordability of a project.

The major factors affecting affordability are the customer budget and WLCC. From the customer side, it is important to ensure that the budget is well set in order to cover the WLCC of the project. Hence, future research could investigate the process of budget setting (especially in the defence sector) in order to discover ways of improving the process to deliver the right result. From the manufacturer side, it would be useful to examine possible ways of reducing WLCC but maintaining the Customers Willingness To Pay (CWTP) in order to improve profitability over the life cycle of the project. Some techniques were mentioned within this paper, but there is a need to study economic techniques to determine their applicability across different sectors.

5.6 Value Engineering

Value should be considered across the full life cycle and in the context of new manufacturing strategy like agile manufacturing and in production networks. The components of methods deployed during the full life cycle are opportunities for improvement to value engineering. The creative phase has been a target for researchers as well as the ability to lever and store knowledge using knowledge management tools. New business models are affecting the way value engineering is thought of. Product Service Systems means that service design is included in the scope of value engineering (Kimita et al 2009). Future research should agree on a definition of value and how best to maximise that value under the manufacturing strategy.

6. Conclusions

This paper covers a number of key areas in Cost Engineering, including Cost of Design, Production Costing, Operating Cost analysis, Disposal Cost analysis, Whole Life Costing, Uncertainty in Cost Engineering, Affordability Assessment, and Value Engineering. In each area, the current research is reviewed and the critical issues are highlighted first, and then the scientific challenges in each area are discussed, and finally some future research issues in each area are identified. In summary, the future research in Cost Engineering should cover the following aras. :

- Further understanding the factors impacting design rework;
- How to bolster the sharing of product and manufacturing information;
- How to estimate manufacturing cost at early design stage with a high level of accuracy;
- How to support process planning at detail design stage;
- How to support process planning in the quotation process;
- How to do automatic costing based on CAPP information;
- Understanding uncertainties through life cycle
- Develop approaches that take into account the stochastic nature of operations, services and disposal.
- Understand the full scenario of lifecycle and integrate this knowledge into the LCC model.
- Develop new techniques for storing all the relevant information in a centralized-controlled environment
- Identify the factors that affect the prediction of 'availability' of a product from the early design stage
- Set a framework to capture all or most important uncertainties that affect the LCC
- Understand how uncertainties may vary through the life cycle
- Develop uncertainty modelling methods that enable consideration of aleatory and epistemic uncertainties separately
- Develop verification and validation strategies for epistemic uncertainty in cost estimation
- Further identify the link between the customer affordability, manufacturer profitability and supplier sustainability to assess the affordability;
- Investigate the process of budget setting (especially in the defence sector) to better assess the affordability

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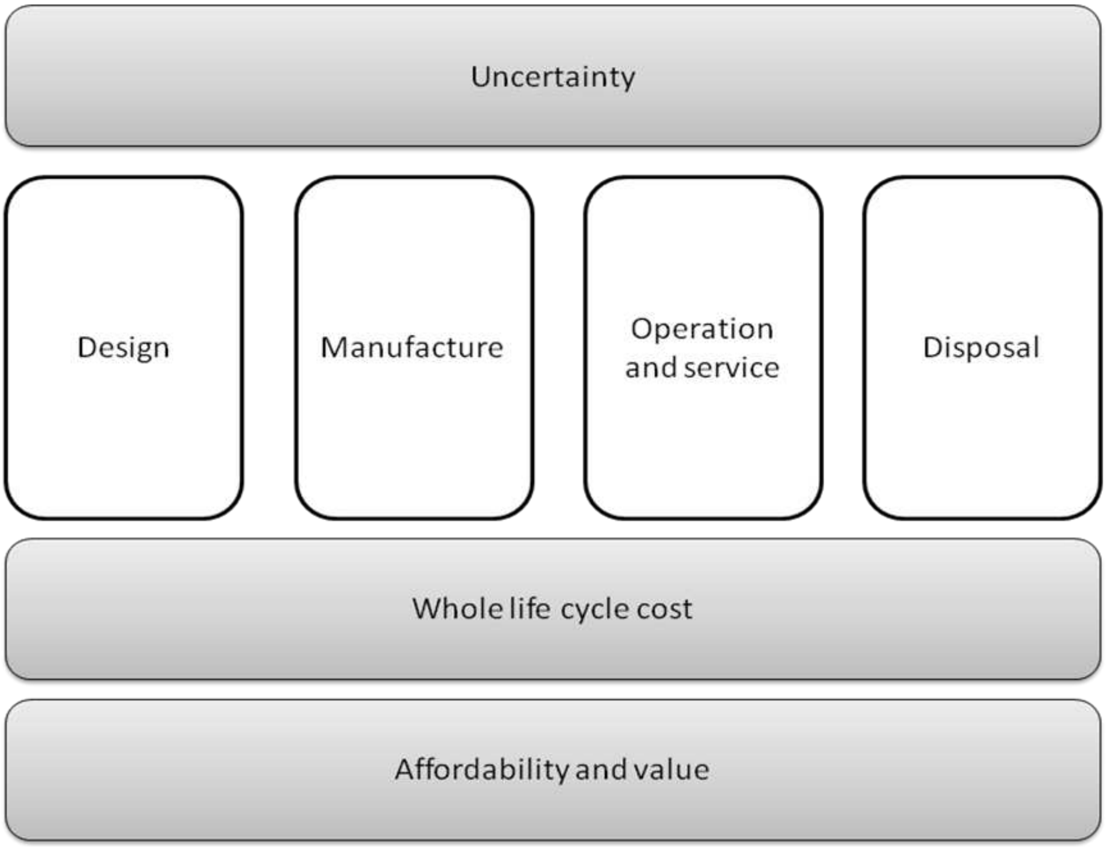


Figure 1. Key topics related to Cost Engineering

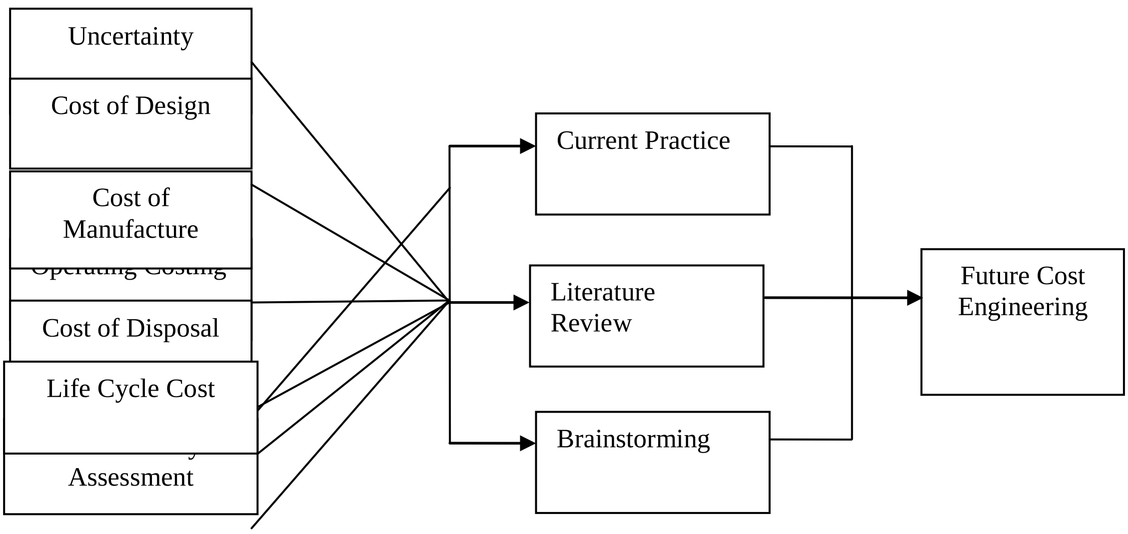


Figure 2: Adopted methodology

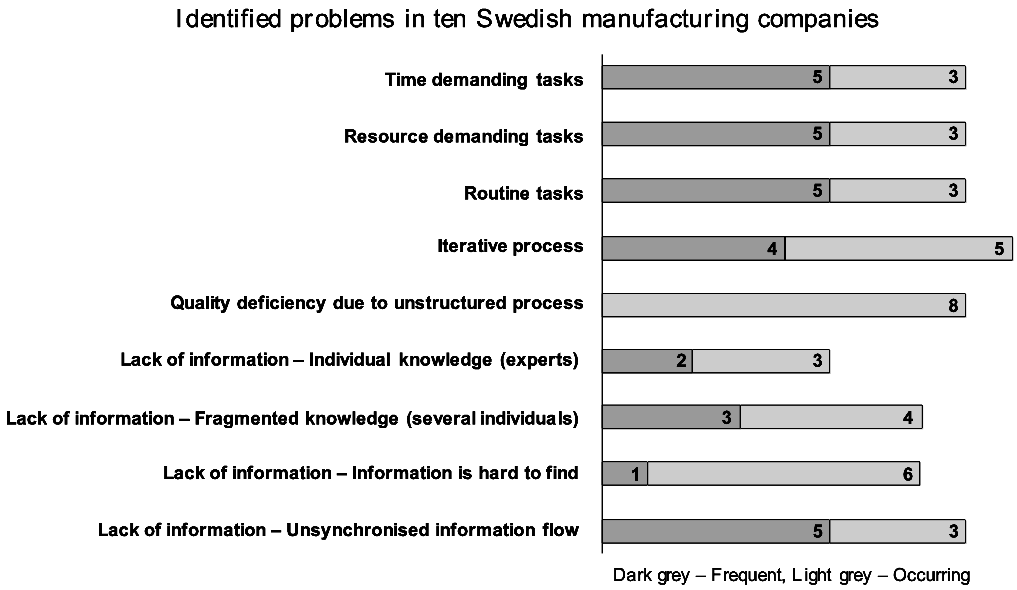
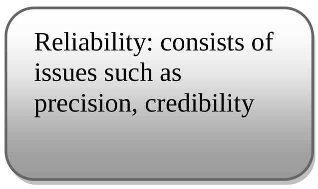
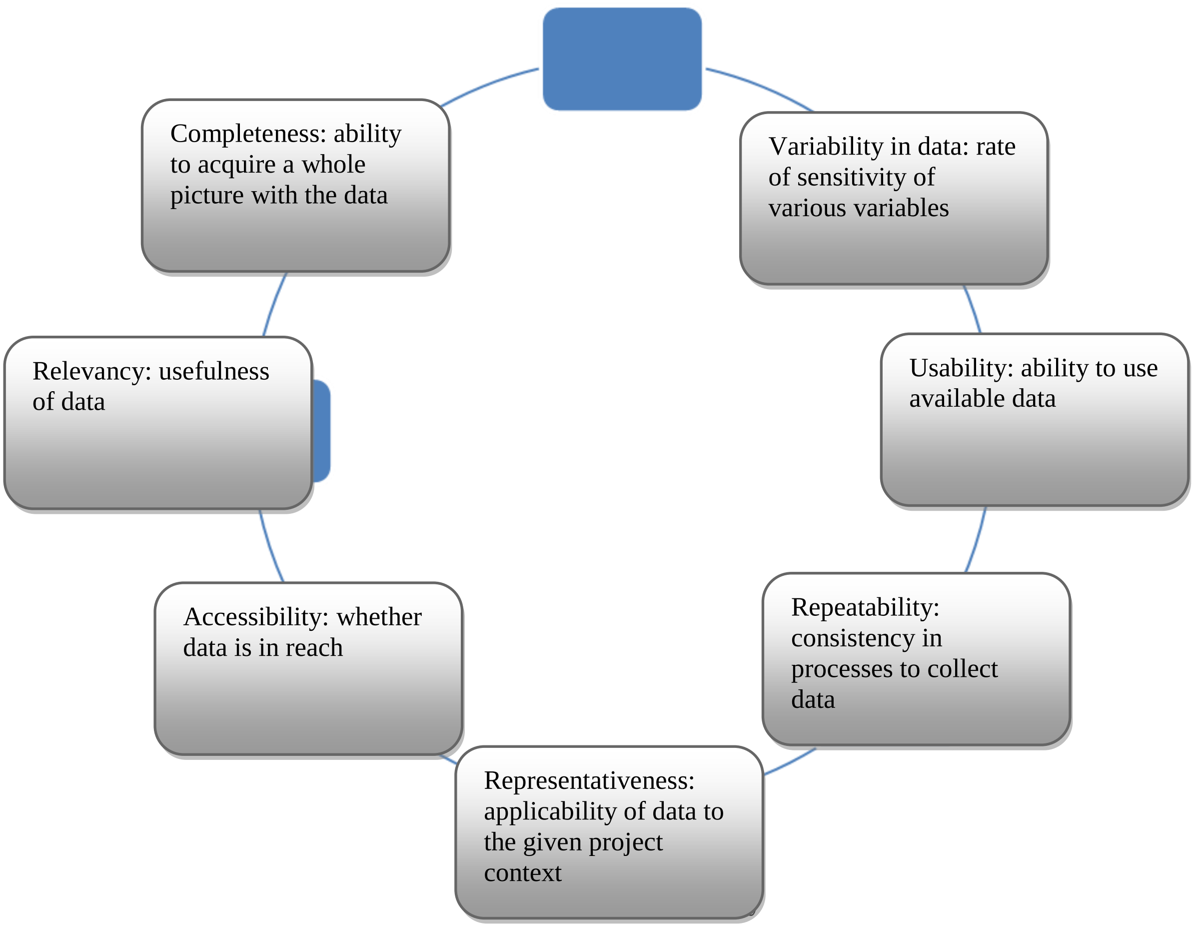


Figure 3. Process and information issues in ten Swedish manufacturing companies (Cederfeldt and Elgh, 2005)





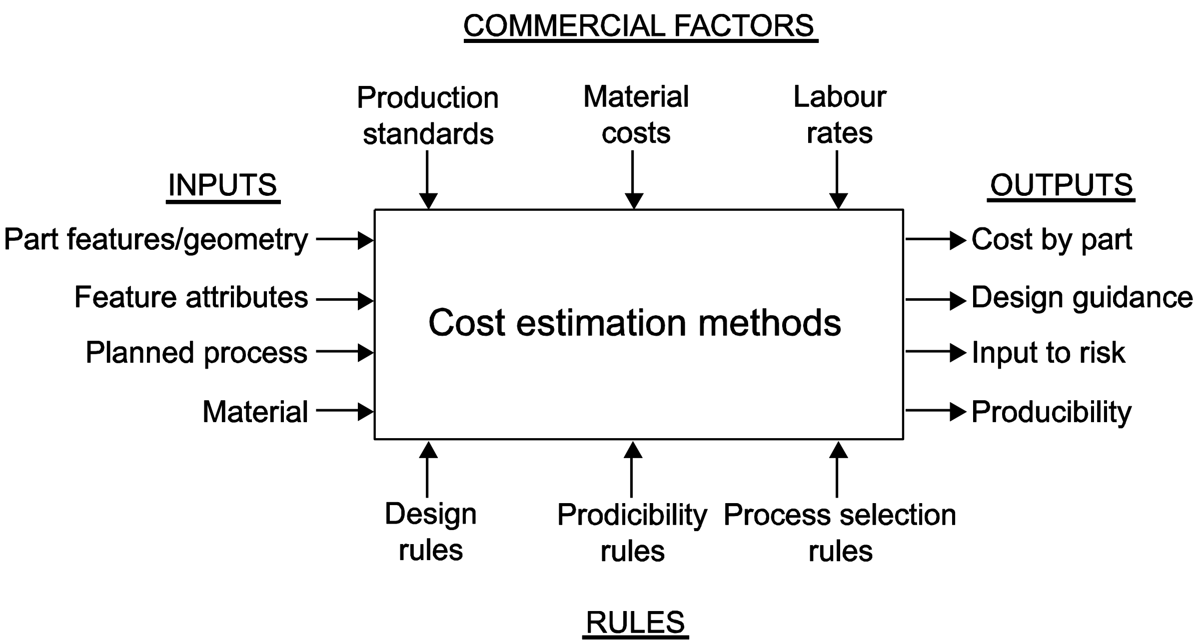


Figure 5 – Required information for cost estimation with acceptable accuracy (Roy, 2003).

Table 1 Approaches for operating cost estimation (Adapted from Boussabaine and Kirkham, 2004)

Approach	Key characteristics
Parametric model	• Set of equations to relate Operating and Support (O&S) costs to parameters such as operating environment • Used at the early stages of a project due to limited data
Accounting Model	• Set of equations to aggregate O&S costs from simple relationships or direct input
Simulation Model	• Computer simulation to determine effects on system characteristics, operational constraints, maintenance plan, support requirements etc. • Hardware parameters such as reliability, maintainability tend to be used • Data requirements to generate probability density functions • Includes approaches such as system dynamics, discrete event and Monte-Carlo

Table 2 Classification of uncertainties in cost data and models

	Classification	Source	Type	Example
Data Uncertainty	Variability	Inherent randomness	Aleatory	Repair time, Mean Time Between Failure
	Statistical error	Lack of data	Epistemic and aleatory	Reliability data
	Vagueness	Linguistic uncertainty	Epistemic and aleatory	The component needs to be replaced about every 2 to 3 months.
	Ambiguity	Multiple sources of data	Epistemic	Expert 1 and expert 2 provides different values to end-of-life costs.
	Subjective judgement	Optimism bias	Epistemic	Over confidence in schedule allocation.
	Imprecision	Future decision or choice	Epistemic	Supplier A or B
Model Uncertainty	Intuitive/expert opinion	Judgement	Epistemic	Similar manufacturing process will be used but geometrical changes are made

	Analogical	Selection of benchmark model (qualitative characteristics)	Epistemic	The system will have 20% higher capacity than existing system and consumes 10% less fuel
	Parametric	Cost drivers/parameters CER choice Regression fit Data uncertainty Extrapolation	Epistemic and aleatory	Missing key cost drivers Unsuitable CER function form
	Analytical/engineering	Scope Level of details Available data	Epistemic and aleatory	Simplification in WBS due to lack of time
	Extrapolation from actual costs	Changes in conditions Limited data	Epistemic and aleatory	Maintenance procedures are revised