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Towards the derivation of an integrated process cost modelling technique for complex manufacturing systems

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Towards the derivation of an integrated process cost modelling technique for complex manufacturing systems

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Cost modelling is used to support business decisions, especially, when the objective is to remain competitive on price and be able to realise outputs at low cost. Many Researchers and Industrialist have proposed and experimented with different cost modelling techniques with the view to influence design and production decisions at an early stage of the development process. This has led to cost modelling methods which have been broadly classified in this paper as qualitative and quantitative.

The paper identifies current best practice cost modelling techniques and their performance in complex and dynamic manufacturing environments. The review served as a platform to support the recommendation for an integrated cost modelling methodology. The integrated methodology is based on the strengths of Cost Engineering, Enterprise Modelling, System Dynamics and Discrete Event Simulation Modelling techniques. The method can help in the redesign and reengineering of products and processes for better cost and value indications; support investment decision analysis; help determine appropriate business and manufacturing paradigms; influence 'make, buy or outsourcing' decisions and serve as a key process improvement tool.

Keywords: Cost modelling; Manufacturing Enterprises (MEs); Enterprise Modelling (EM); Simulation Modelling (SM); complexities

1. Introduction

Cost Engineering and its associated modelling techniques have been used dominantly in research and academia to support cost estimation of projects, lifecycle analysis, technology down selection and assessment of economic viability of engineering projects (Humphreys 1996). Because of inherent complexities and dynamics associated with current design and production systems, it is fairly difficult to estimate, control and monitor cost consumption appropriately and instantaneousness without incurring errors (Son 1991; Wiendahl and Scheffczyk 1999). A study reported by

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Maskell (Maskell 1991) shows that cost estimations in MEs have become very complex since the adoption of IT systems. In essence, manufacturing practices have advanced tremendously, making traditional cost accounting practices unsuitable for dynamic manufacturing environments (Agyapong-Kodua, Wahid et al. 2007).

This paper is centred on: 1) reviewing current cost modelling methods; 2) observing advancement in manufacturing practices and 3) based on understandings gained from 1) and 2), specifying requirements for a next generation cost modelling methodology. A State of the Art (SOA) survey on current methods and processes for cost modelling in academia and industry is reported. Based on the observed limitations of existing cost modelling techniques in the literature, and with an understanding of the needs of MEs, a new cost modelling method capable of meeting the requirements for effective cost modelling in MEs is proposed. The authors are of the view that the proposed cost modelling method is capable of managing aspects of risk, uncertainty, change and complexities associated with dynamic MEs.

2.0 Development of cost modelling practices in Manufacturing Industries

In general terms, manufacturing industries have moved from highly data-driven environments to more cooperative information-driven environments, taking into account more of enterprise knowhow, commonsense and application semantics (Vernadat 1996; Agyapong-Kodua 2009). In recent times, cost engineering principles and modelling methods have been applied by some researchers to support cost estimation, business analysis and planning, project management, profitability analysis and scheduling of major engineering projects (Curran, Raghunathan et al. 2004). However in most environments today, Business Administrators and Economists take

*Corresponding author

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hold of the overall business planning and management, pushing the cost engineer into his core elements of cost estimation, scheduling and cost control (Samid 1990).

To effectively estimate and control cost in manufacturing environments, three sub layers have been recommended (Liebers 1998). These are: 1) production monitoring; 2) cost calculation and evaluation; and 3) cost modelling. Many researchers (Roy and Palacio 2000; Rush and Roy 2000; Curran, Watson et al. 2003; Agyapong-Kodua 2009) in the domain of cost engineering have reported that many cost estimating projects broadly consist of: 1) first sight estimate, usually at the early stage of the design process and 2) detailed estimate for precision costing. They explained that first sight estimates are suitable for 'Rough Order Magnitude' (ROM) estimates (Curran, Watson et al. 2003) and provide good background for initial product definition but are not very useful for detail product specifications and manufacturing process designs and optimization (Curran, Raghunathan et al. 2004; Agyapong-Kodua, Wahid et al. 2007). The next section is dedicated to reviewing State of the Art (SOA) cost modelling systems as expressed in academia and industries.

2.1 SOA survey of cost modelling methods

The Association of Cost Engineers (ACE) has indicated that because of the increased changes in manufacturing industries and the need to adjust product designs and manufacturing systems to meet market needs, Cost Engineers are required to play key roles in cost estimation and control. To achieve this, scientific methods and frameworks are required to capture existing data and using the existing data to generate estimates that are timely, relevant and meaningful (Rush and Roy 2001). Cost modelling provides the platform on which cost estimation and project planning

*Corresponding author

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may be built (Roy, Bendall et al. 1999). Also researchers in the domain of enterprise and systems engineering (Bernus and Nemes 1996; Kosanke 1996; Baines, Harrison et al. 1998; Weston 1999; Agyapong-Kodua, Ajaefobi et al. 2009) have proposed that to scientifically support cost control and modelling, especially in complex and dynamic organizations or industries, there is the need to develop well structured enterprise models to form the baseline for process analysis. Such models represent organizations as fairly independent sets of processes with interacting entities and flows which can be (re)designed to meet corporate objectives (Ajaefobi 2004; Chatha and Weston 2005). In specific terms, some researchers in Cost Engineering (Johnson and Kaplan 1987; Beltramo 1988; Son 1991; Asiedu, Besant et al. 2000; Curran, Raghunathan et al. 2004; Agyapong-Kodua, Wahid et al. 2007; Caputo and Pelagagge 2008) have proposed and tested several cost estimating, production monitoring, cost calculation and evaluation and cost modelling techniques which are currently being used in academia and industry. The following sections provide a detailed review of some of these techniques.

A formal classification of cost modelling methods was provided by Boehm (Boehm 1984). In his extensive research on the economics of software engineering, he classified and described 7 cost modelling techniques as: 1) Parametric; 2) Expert judgement; 3) Analogy; 4) Parkinson; 5) Price to win; 6) Top down; and 7) Bottom-up. Later researchers such as Hughes (Hughes 1996) and Curran (Curran, Raghunathan et al. 2004) explained that although Boehm's classification is representative, 'Parkinson method' is not a cost estimation model but a management technique which defines the scope of a project. Another classification offered by Shehab and Abdalla (Shehab and Abdalla 2001) shows that cost modelling techniques

*Corresponding author

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can broadly be classified as intuitive, parametric, variant-based and generative. However from a methodological point of view, cost estimating techniques may be based on qualitative or quantitative approaches (Layer, Brine et al. 2002; Foussier 2006). Cost models based on qualitative methods adopt expert judgement and heuristic rules as means of estimating cost (Caputo and Pelagagge 2008). Gray (Gray, MacDonell et al. 1999) argues that cost judgements from experts and knowledgeable people cannot be done away with considering the fact that it takes a relatively long time to collect and analyse cost information. But Caputo (Caputo and Pelagagge 2008) is of the view that efforts should be concentrated on quantitative cost modelling techniques since basically qualitative methods only indicate whether an alternative is better or worse without absolute values. To put a structure around qualitative cost modelling, Agyapong-Kodua (Agyapong-Kodua 2009) proposed the use of system dynamic causal loops as a decision support tool. Some researchers have further classified quantitative cost modelling methods (Asiedu, Besant et al. 2000; Layer, Brine et al. 2002; Caputo and Pelagagge 2008) into: 1) statistical; 2) analogous 3) generative or analytical and 4) feature based. They explained that statistical models adopt statistical criteria to identify causal links and correlate cost and product characteristics to obtain a parametric function with one or more variables. As a result they classified parametric, neural networks and fuzzy logic cost models as being the main examples. Analogous cost models identify the cost models of products or projects of similar characteristics and features. Thus the strength of the similarity is proportional to the correspondence of the relevant characteristics (Layer, Brine et al. 2002). Generative or analytical cost modelling methods attempt to decompose and model processes associated with the development of the product or project (Caputo

*Corresponding author

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and Pelagagge 2008; Agyapong-Kodua 2009). At each phase of the development process, based on technical data, cost related to resource and material consumption are determined.

Rush (Rush and Roy 2001) indicated that, in general terms, cost modelling requires a combination of high skills and extensive knowledge of multiple disciplines and relies on the accurate understanding of design and manufacturing capabilities of companies and their suppliers. This is illustrated in figure 1.

Figure 1: Skills and knowledge required for cost modelling

Some research work in supply chain cost control (Fitzgerald 2002; Handfield 2002) has shown that in general terms cost models can provide enormous benefits when:

- eliciting active support from top management
- integrating and modelling processes
- attempting to understand cost drivers in appropriate detail
- measuring the performance of suppliers, production systems and employees
- developing cooperative supplier relations
- delivering and establishing a culture of continuous improvement
- facilitating a cross-functional approach linked through cost
- managing and reducing cost across the whole business structure
- developing integrated data management systems and
- justifying investment

Detailed explanations of the SOA cost modelling methods are provided in the next sections.

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2.1.1 Parametric cost modelling technique

Parametric cost models are generally associated with cost estimates or techniques which deploy 'Cost Estimating Relationships' (CERs) together with mathematical algorithms or logics to establish cost estimates (DoD 1999). The origin of parametric cost models is often attributed to the early works of Wright (Wright 1936) when he first determined the unit cost of an aircraft as a function of the number of aircraft produced. Wright's work was extended by Stanford Research Institute and later by the Rand Cooperation (Crawford 1985). In general terms, Rand Cooperation is accredited with the following advancements in parametric cost modelling (Crawford 1985; Curran, Raghunathan et al. 2004):

1. Developing Cost Estimating Relationships (CER)
2. Merging CER with the learning curve to form the foundation of parametric estimating
3. Deriving CERs for aircraft cost as a function of speed, range and altitude
4. Observing statistical correlation in checking CERs
5. Developing families of curves data for different aircrafts

According to RAND (RAND 1995), the three most important factor relationships worth considering when developing parametric cost models are:

1. Performance and physical attributes are measures of technical capabilities
2. Technical risk and design maturity attributes of a part are measures of relative difficulty of developing and producing the part
3. Programmable parameters describe ways in which programs are operated.

Many industries have adopted parametric estimation as the main means of cost estimation for their design, development and production or implementation phases of engineering projects. Major users include the Construction Industry (Akintoye and

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Fitzgerald 2000), Aeronautic Industry (Sanchez, Kundu et al. 1999) and Component Part Manufacturing Industries (Curran, Raghunathan et al. 2004). In the Construction Industry, parametric cost estimation has featured well in the determination of project cost, based on historical data (Akintoye and Fitzgerald 2000). In the Aeronautic Industry, parametric cost estimates play key role in bidding and target cost estimation, whilst for most component manufacturing industries, parametric cost estimates are used to determine the cost of components manufacture. Quite recently, parametric cost models have gained popularity through the support work of organizations such as International Society of Parametric Analyst (ISPA), Society of Cost Estimating and Analysis (SCEA) and Space Systems Cost Analysis Group (SSCAG) (Curran, Raghunathan et al. 2004).

The activity diagram shown in figure 2 was created to provide an overview of the approaches adopted by Quin and Ben-Arieh (Qian and Ben-Arieh 2008) and Curran (Curran, Raghunathan et al. 2004), which collectively provide a methodology for developing parametric cost models..

Figure 2: Development of parametric cost models

This methodology assumes that parametric cost modelling is based on data capture. This requires developing required templates and identifying data sources. Most data for parametric cost modelling are obtained from Accountants, Engineers and Process Managers in companies. After the collection of data, there is the need to evaluate variables and respective data attached. By doing this a decision is taken to identify variables which change or are likely to change with time. These variables are called

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'cost drivers'. By adopting regression analysis, a statistically observed correlation is established between the cost drivers and cost. These relationships are validated, approved and saved in the CER data base which provides necessary inputs to the cost model. As required the modelling loop is reversed for revalidation of CERs.

A number of researchers (Beltramo 1988; Hughes 1996; Briand, Emam et al. 1998; Shepperd and Cartwright 2001) have reported that the major limitation to parametric cost modelling is the availability of data of adequate quality. With this observed limitation, Gray (Gray, MacDonell et al. 1999) indicated that in real life situations, poor and inadequate data is always the case, hence expert judgement is sometimes necessary. Quite critically, Beltramo (Beltramo 1988) has indicated that parametric cost models are unable to predict cost of projects or products outside the scope of CER databases. This is a major limitation and hence the Parametric Handbook (DoD 1999) shows that, to make good use of parametric models:

1. Parametric models should not be used outside their database range
2. they should be used only after they have been verified and validated
3. should be constant adjusted to reflect changes in requirements
4. they should not be used until a realistic data corresponding to cost drivers can be obtained

2.1.2 Analogous cost modelling method

The analogous cost modelling technique identifies a similar completed product, process or project and reuses cost information associated with this entity to estimate the cost of the new entity, taking into consideration adjustments for the differences between the two. The effectiveness however depends on how accurate the historic data is and how accurate the difference between the two cases are established (Asiedu

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and Gu 1998). It has been reported that analogous costing is the best-established method of costing in many industries although normally it is applied in an ad hoc manner (Hughes 1996; Shepperd, Schofield et al. 1996). A survey conducted by Curran (Curran, Raghunathan et al. 2004) revealed that best industrial analogous cost modelling process can be classified into six stages:

1. Definition of the entity that requires costing. This involves defining the project or product in terms of characteristics such as design parameters, production requirements, operation and support attributes; reliability and maintenance.
2. Identification of data sources. This requires identifying sources of data related to the two entities under consideration. Most often data will include quantities, design and performance characteristic
3. Actual data collection. Data is collected in two folds, qualitatively and quantitatively. This is done for as many historical cases as possible. Where possible, inputs from specialist who are familiar with historic patterns will be required at this point.
4. Generating a range of factors that characterise the product in terms of features. These factors are used to define cost ratios with the underlining assumption that performance and design ratios influence cost ratios. Three unit ratios are often derived. These are complexity, miniaturisation and productivity.
5. Generating the actual cost estimates. This is based on the product of historic cost of the case and the ratios for complexity, miniaturisation and productivity.
6. The derivation of the total programme cost which involves the addition of profits, and any adjustments management may deem fit.

Typical examples of the use of analogous cost modelling can be found in (Shepperd, Schofield et al. 1996; Shepperd and Schofield 1997; Taylor 1997; Bashir and Thompson 2001; Curran, Raghunathan et al. 2004)

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2.1.3 Generative-analytical cost modelling technique

As proposed by Caputo (Caputo and Pelagagge 2008), generative cost modelling is one of the quantitative methods of estimating cost of projects, products and processes. Caputo (Caputo and Pelagagge 2008) claims that generative-analytical cost modelling produces the most accurate cost estimate because the technique is able to depict the actual production processes. Recent research has advanced the scope of generative-analytical cost modelling by applying enterprise modelling and decomposition techniques to manufacturing processes (Agyapong-Kodua, Wahid et al. 2007; Agyapong-Kodua 2009). This involves detailed analysis of production processes and is based on a well structured decomposition formalism previously defined as part of the CIMOSA approach to Enterprise Modelling (Weston 1999; Agyapong-Kodua 2009; CEN/ISO 19440). Here processes are decomposed to their 'elemental activity level'. At the elementary activity level, cost and values are assigned to each activity to determine the elementary cost. The cost derived through the realization of each activity depends on the resource consumed. Thus labour and machine rates, material quantities and prices are used to determine the actual direct activity realization cost. In addition to this, 'activity based costing' method is used to assign overheads or indirect cost to the various operations. After the estimation of elementary activity cost, based on the decomposition technique, respective cost of activities belonging to well defined business process are grouped together. The cost of individual business processes are further grouped together to form the total production cost.

It has been reported (Curran, Raghunathan et al. 2004; Caputo and Pelagagge 2008; Agyapong-Kodua 2009) that common features of generative-analytical cost models are:

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1. Performed at a detailed level within the Work Breakdown Structure (WBS).
2. Cost is estimated for basic tasks such as engineering design, tooling, fabrication of parts, manufacturing engineering, and quality control.
3. The cost of materials is estimated or obtained from the supplier.
4. The approach requires detailed and accurate data and should be undertaken by an experienced engineer

In a related work by Shehab (Shehab and Abdalla 2002), databases of standard times, cost rates and best practice manufacturing methods were integrated with computer-aided process planning software and knowledge based methods to derive an iterative technique for cost modelling. Also as part of a recent work by Agyapong-Kodua (Agyapong-Kodua 2009), the application of static generative cost models was enhanced via the use of system dynamics and discrete event simulation modelling tools. This has derived a flexible basis for cost modelling, suitable for analysing dynamic impacts of various causal effects on cost generation in manufacturing systems.

In practice, analytical cost modelling techniques support concurrent engineering approaches especially in domains of 'design-to-cost' and 'design-for-manufacture' projects (Evershiem, Neuhausen et al. 1998; Boothroyd, Dewhurst et al. 2001). Further examples of the application of generative-analytical cost models can be found in the literature (Pengelly 1995; Shing 1999; Shehab and Abdalla 2002; Tang, Evershiem et al. 2004; Agyapong-Kodua 2009)

2.1.4 Feature based cost modelling technique

Feature based cost modelling is a product design approach for linking the cost of products to their design features. This approach rests on the premise that (Wierda

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1991): 1) functions that describe cost can be derived for classes of similar objects and 2) factors which affect cost can be influenced by design decisions. Based on these assertions, feature drivers are derived and used as basis to estimate product cost. For most manufacturers, significant data on historic geometrical data exists which can be used to estimate cost of designs (Bronsvoort and Jansen 1994; Ou-Yanang and Lin 1997). In recent times, many researchers are using feature based cost models to integrate design, process planning and manufacturing. This is considered possible because Rush and Roy (Rush and Roy 2000) argue that the growth of CAD/CAM and 3D modelling helps both the designer and manufacturer to relate to common features such as holes, faces, edges, etc. Although many Design and Manufacturing Engineers seem to understand the concept of features, Curan (Curran, Raghunathan et al. 2004) reports that feature-based cost modelling is not fully established in Industries. Another observation reported by these same authors is that features differ from one industry to the other and for a given industry several features might be required to fully describe the product. In reality the major challenge with feature based cost modelling is that as products change, companies have to cope with re-defining product features. This can be very tedious considering the amount of new product changes that may be required in a dynamic manufacturing environment.

2.1.5 Fuzzy logic cost modelling method

The fuzzy theory was first introduced by Lotfi Zadeh in 1965 as an artificial intelligence tool which formulates the human thought when dealing with uncertainty and imprecision (Kishk and Al-Hajj 1999; Nachtmann and Needy 2001). Since the inception of fuzzy theory, literature shows that it has proven suitable for representing value and imprecise knowledge in a well structured and controlled manner (Cordon,

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Gomicide et al. 2003). Many cost modellers with a strong mathematical background have applied fuzzy theory to model dynamic factors which impact on cost (Joumier 1999; Kishk and Al-Hajj 1999; Nachtmann and Needy 2001; Shehab and Abdalla 2002). This has helped to improve cost practices since, basically, many traditional cost modelling tools are deterministic and most suitable for static analysis (Ting, Zhang et al. 1999). The theory of fuzzy logics is described in a number of literature including (Joumier 1999; Kishk and Al-Hajj 1999; Pedrycz, Peters et al. 1999; Cordon, Gomicide et al. 2003; Xiong and Helo 2006; Chrysafis and Papadopoulos 2009; Chen and Huang 2010).

Shehab and Abdalla (Shehab and Abdalla 2002) noted that several steps are required to develop a fuzzy theory-based cost model. Three main procedures have been reported (Mamdani and Gaines 1981; Klir and Ruan 1996; Curran, Raghunathan et al. 2004). These are:

1. recognition of physical conditions that need analysis and control
2. processing of inputs according to fuzzy 'if then' rules
3. averaging and weighting the outputs from all individual rules into a single defuzzyfied output that provides the solution for the system

In general terms Kishk (Kishk and Al-Hajj 1999) is of the view that fuzzy logics are most applicable when: 1) models of processes or products are highly complex and understandings about them are limited or 2) when there are processes for which human decision making is inextricably linked.

A key advantage in the use of fuzzy logics in cost modelling is indicated by Curran (Curran, Raghunathan et al. 2004) as:

1. The mathematical concepts deployed are transparent and traceable
2. It posses the ability to match sets of input-output behavioural data

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3. It can be integrated with traditional techniques

Although these advantages are recorded, it is however evident that fuzzy logic cost modelling is not fully established in industries (Joumier 1999; Curran, Raghunathan et al. 2004). It remains limited to experts of 'fuzzy sets' and artificial intelligence (Blattberg and Hoch 1990).

2.1.6 Neural networks based cost modelling method

Neural network cost modelling techniques constitute a form of artificial intelligence that is used to derive cost as an effect associated with some cost drivers (Zhang, Fuh et al. 1996). Neural network cost models are based on cost attributes which relate to the product or system under consideration. They possess unique advantage in the field of statistical cost modelling because they can model cases where functional relationship between case data cannot simply be expressed in polynomial form (Caputo and Pelagagge 2008). Caputo (Caputo and Pelagagge 2008) indicated that basically artificial neural network cost models 'accept as input shape-describing and semantic product characteristics' and generate outputs in the form of product cost. Key research contributions in neural network cost models were provided by: Seo (Seo, Park et al. 2002) for the life cycle costing in conceptual designs; Zhang and Fuh (Zhang, Fuh et al. 1996) for estimating packaging cost based on product dimensions; Shtub and Versano (Shtub and Versano 1999) for processing operations and Cavalieri (Cavalieri, Maccarrone et al. 2004) for the estimation of manufacturing cost of disk brakes. Other authors have compared the effectiveness of artificial neural network cost models with parametric cost models in engineer to order industries (Shtub and Versano 1999; Cavalieri, Maccarrone et al. 2004; Caputo and Pelagagge 2008), and in general terms (Bode 2000). A study of the above literature shows that artificial neural

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networks show better results than parametric cost models. However it has been shown that in some cases neural network models are limited in terms of accuracy, variability, model creation and model examination (Smith and Mason 1997). Elhag (Elhag and Boussabaine 1998) also noted that neural network cost models are not suitable for highly innovative products which deviate largely from historic precedents.

3.0 Analysis of literature

The foregoing literature on costing (engineering, estimating, and modelling) shows that whilst there have been a number of stepwise developments in the principles of costing; these have not translated holistically in to working practices. Case studies reported by a number of authors have all been towards highly specialised and bespoke solutions that have not then been generalised for wider application domains. This is a reflection of practice seen and experienced by the authors of this paper. Generally, the widely reported cost modelling techniques can be classified as shown in figure 3. This figure shows there is no indication of integration of cost modelling methods and most of the methods described in the literature are 'product based'.

Figure 3: Classification of cost modelling methods

A compilation of literature on costing and their years of publication (not shown) revealed that developments in costing saw increased activity from the 1990's to 2000 (see figure 4). In terms of cost modelling and estimating, techniques exist as discussed, but it is noted that their application is of limited scope i.e. neither has it been holistic nor integrated. Methods, that is to say instances of techniques, are often isolated and consider cost on a piecemeal basis e.g. by product, sub-product, business

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domain, lifecycle phase or investment decision. Additionally, cost is normally considered in relative isolation of other metrics.

Figure 4: Literature according to year

The literature indicates that cost considerations are by and large made during the preliminary design stages of a product's development to aid engineering managers in selecting the most cost effective solution (see figure 5).

Figure 5: Literature lifecycle stage focus

Cost Modelling and Estimation are however not part of an integrated approach and appear to be under the development and ownership of engineering functions with little application to wider fields of interest, mainly with results being reported to management.

Cost models can be scrutinised for accuracy, utilising statistical uncertainty in conjunction with cost estimation to produce a cost risk methodology. These do however remain largely qualitative and depend on the subjective opinions of experts to decide upon risks and their associated likelihoods and severities. Another factor to consider is that not only do we have uncertainty related to the biases of experts; there is another dimension of the product build configuration. As this is prone to change through the development phases, additional levels of risk and uncertainty are introduced. This implies the need for enhanced openness and sharing of information between various parts of an organization throughout lifecycle phases. The objective of modelling and estimating costs is to improve design through making cost information available further upstream in the realization of products and processes. Such decisions

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can then be documented and design rules created, as the early design stages are where the majority of costs are built into a product.

Cost models are largely seen as a means to determining absolute figures for product or process within certain degrees of confidence, through structured methods. The behaviours of costs are often neglected in terms of the 'cause and effect' issues associated with change decisions. In this respect, it is evident from the literature that, performance indicators that were once traditionally the onus of managerial and accounting functions, are now filtered down in such a way that they are the concern of every element in value and supply chains. This is to the extent that non-accountants are assuming a much more direct responsibility for, and interest in, the financial (and non-financial) outcomes of their performance. However, this has occurred without the necessary methods, approaches, and techniques to support modelling and analysis.

Cost engineering not only encompasses monetary expenditure during the realisation of objectives but also other aspects such as time, material and resources. It can therefore be seen that cost engineering is not just confined to the control of monetary costs. The remit of the cost engineer is to facilitate and inform design such that products that are cost effective during production and later lifecycle stages are produced. There is therefore an increased need to make design considerations based on appropriate lifecycle drivers, some of which are easily quantified, whilst others less so.

The literature has shown that, in general terms, some of the problems faced by most design and manufacturing industries can be rooted to the phenomenon of complexity which stems from the complexities involved in current markets. The

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structural and dynamic complexity of markets impact on the structure and processes of the enterprise too, hence complex cost generation factors emerge. Advancing information and machine technologies have also impacted on how cost is created, measured and controlled. The development and utilization of microelectronics; CAD/CAM/CAE; computer communication networks; software engineering; object oriented database systems; distributed artificial intelligent systems; multimedia and multimodal environments as well as open systems architectures are impacting greatly on design and manufacturing industries. All these technologies influence processes and especially how cost is developed. Depending on an industry's need, automation can be very high and complex, and cost modelling methods will have to recognise this new complex dimension of production systems. Another clear observation is that, many industries are focussing on their core competences and forming partnership with other organizations which can support aspects of their. From a manufacturing point of view, the decision to either 'make' or 'buy' is crucial, if a business is to survive in current dynamic markets. The onus therefore lies on cost engineers to better develop models which can support critical decision making. The added challenge for designers and manufacturers is that cost modelling methods must be able to analyse capabilities of systems and the cost implication of management decisions. The observed need for a scientific cost estimation approach to match the ever-growing manufacturing industry is obvious.

Also most process cost modelling techniques assume single flow manufacturing systems and underestimate the implication of multiple flows, resource sharing, product mix, reworks and other manufacturing dependent failures. The realization and capture of these process-related attributes is necessary because MEs

*Corresponding author

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are characterised by complex systems of processes which need to be resourced with technical and human systems. These systems need to be properly coordinated and controlled to allow variety of products to be realised through them over varying periods of time. Current approaches to the identification and modelling of cost has not been adequate because most of the cost modelling techniques do not encode time dependencies related to product flows, controls, process instants and time dependent causal effects. This implies that analysis of alternative flows of product (volume and mixes) through a shared process cannot accurately be modelled by current generation cost modelling techniques.

4.0 Future trends

Based on the analysis of literature; observed current cost modelling practices and the general trend of advancement in MEs, the authors are of the view that as a result of the dynamics associated with most MEs, there is the need for a comprehensive modelling methodology which satisfies the following requirements:

- The modelling methodology must suitably capture all different product types in a ME with the view of linking products to respective process routes. This is because a study of trends in MEs shows that most MEs need to realize multiple products to remain competitive, hence there are significant product mixes, shared resources with unsteady changes in information or material flow, as well as control. Thus there is the need to deploy cost modelling methods with capabilities to reflect the changes associated with multiproduct flow properties. Because of the varying range of products many MEs need to realise, coupled with external factors which invariably impact on their operations, process changes may be required over a short time. A cost modelling methodology which depicts the impact of process changes is

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therefore necessary to effectively describe the actual cost which is likely to be incurred on the account of changes in processes.

- Although some work has been done on process oriented cost modelling techniques, literature has shown that, in the main, product based quantitative cost modelling techniques abound. Despite the strengths of the product based cost modelling techniques, it is important to be able to deploy cost modelling methods which are able to depict or translate design solutions into equivalent manufacturing processes and their associated required resources. Thus process based modelling techniques have potential to model operational sequences for different product families and can be helpful in estimating, controlling and monitoring the generation of cost at a reasonable degree of accuracy. An enhancement and combined usage of existing product-based cost modelling techniques and process modelling techniques, with a definitive view of production systems design will help measure cost and process efficiencies more accurately.
- Also the cost modelling method should enable enhanced traceability of costs to specific products and processes to enable improved management of cost distortions whilst supporting the accurate estimation of process cost due to the deployment of alternative business process configurations.
- Because of changes, risks and dynamics associated with MEs, a virtual executable cost model experimentation tool will be useful if it enables design options, business ideas, production systems reconfiguration and process improvement suggestions to be tested before their implementation. This will save MEs from implementing decisions; in fact design decisions that have great impact on the business. System dynamics and discrete event simulation tools can help model and control some aspects of dynamics associated with current manufacturing systems
- Generally, a decomposition of enterprise requirements ensures that complex problems are characterised and modelled in modular forms, so that analysis and understanding becomes easier. The consistent utilization of appropriate cost modelling constructs will enable the contextual reuse of models. Thus the

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required cost modelling method should inherently possess decomposition formalisms and uniformly display a set of modelling constructs that facilitate model reusability in MEs. Process decomposition and integration can be enabled through the selection and appropriate utilization of enterprise modelling tools.

Based on this set of modelling requirements, the authors are of the view that the integrated use of concepts and techniques from Cost Engineering, Enterprise Modelling, System Dynamics Modelling and Discrete Event Simulation Modelling, will be useful. Research is underway to fully establish how relevant modelling techniques belonging to these separate domains can be integrated and supported with relevant data to help generate a multipurpose cost model useful for decision support in designing and manufacturing.

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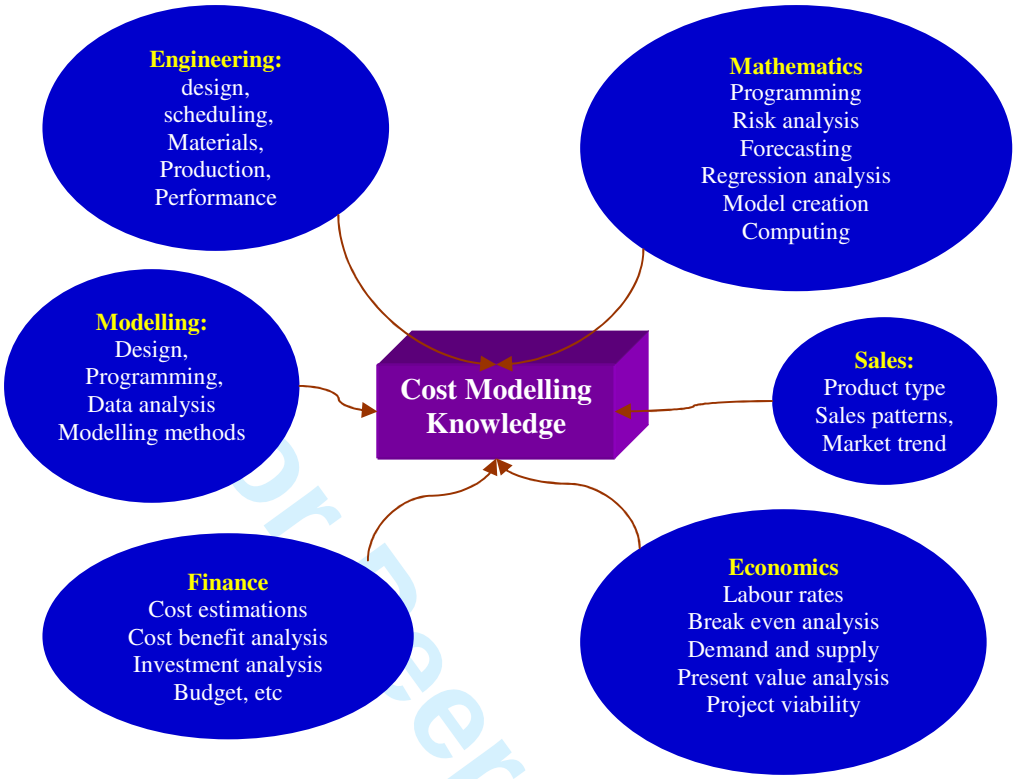

Figure 1: Skills and knowledge required for cost modelling

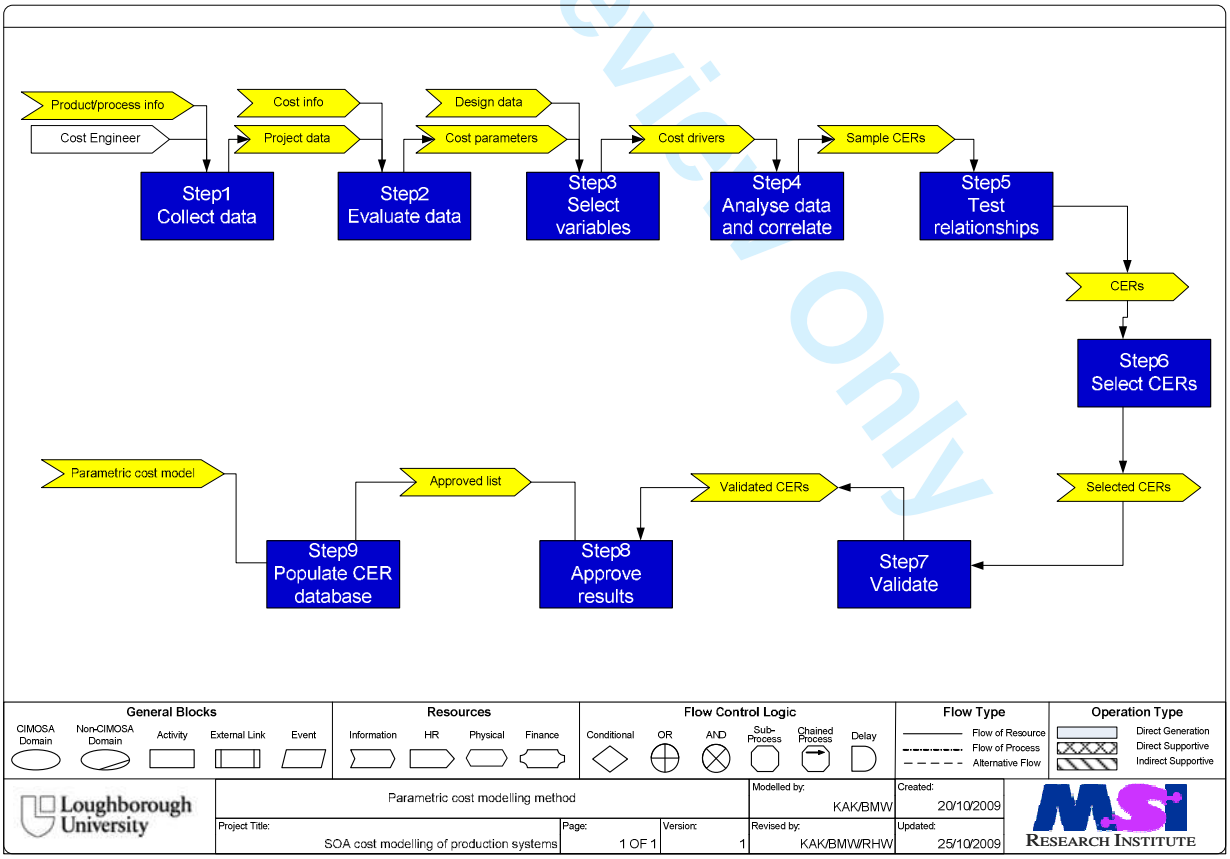

Figure 2: Development of parametric cost models

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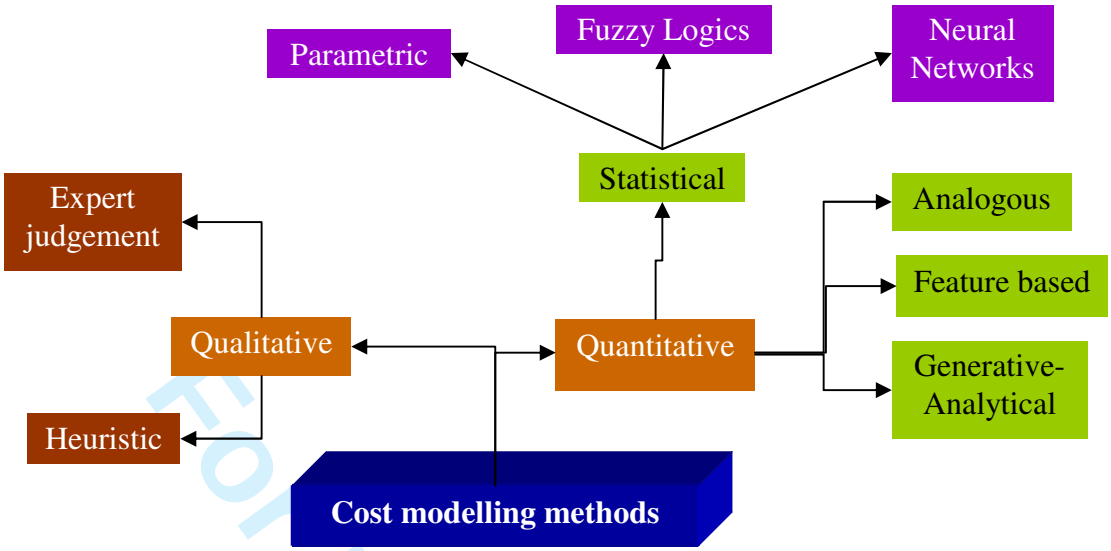

Figure 3: Classification of cost modelling methods

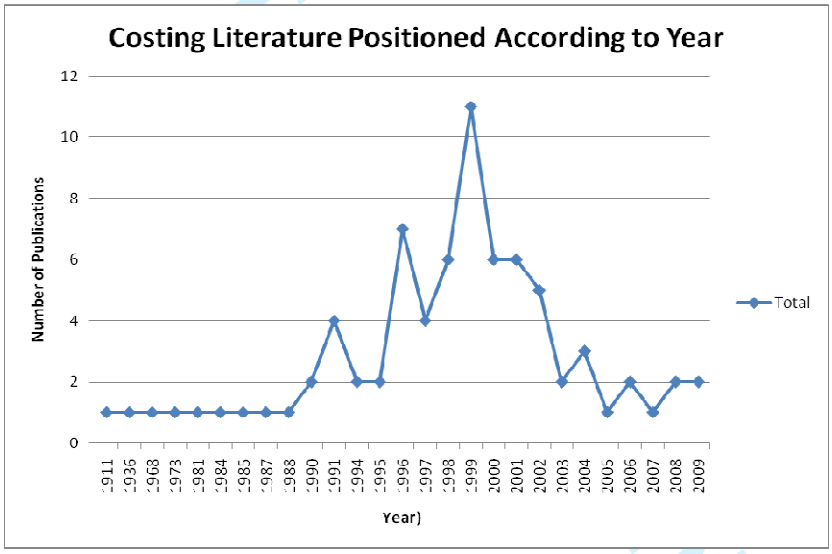

Figure 4: Literature according to year

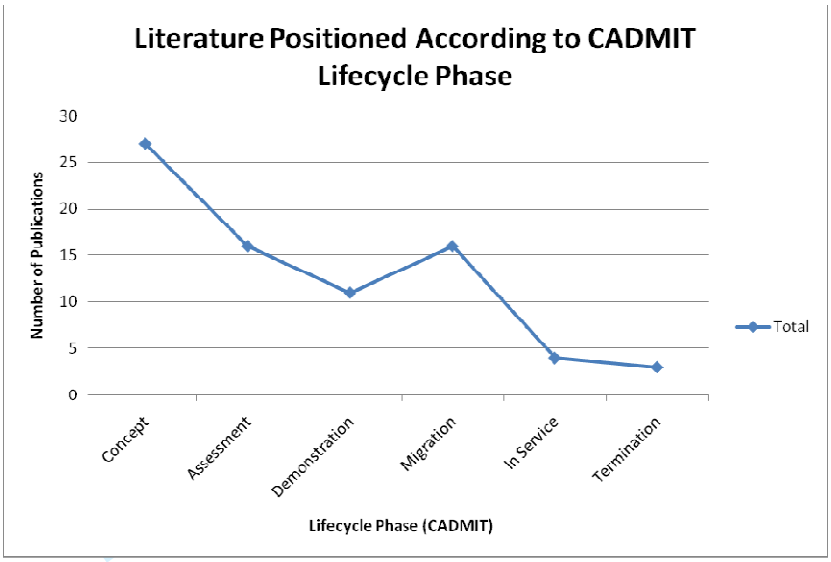

Figure 5: Literature lifecycle stage focus

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