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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

\*Corresponding author

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4 Maskell (Maskell 1991) shows that cost estimations in MEs have become very  
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6 complex since the adoption of IT systems. In essence, manufacturing practices have  
7  
8 advanced tremendously, making traditional cost accounting practices unsuitable for  
9  
10 dynamic manufacturing environments (Agyapong-Kodua, Wahid et al. 2007).  
11  
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13  
14 This paper is centred on: 1) reviewing current cost modelling methods; 2)  
15  
16 observing advancement in manufacturing practices and 3) based on understandings  
17  
18 gained from 1) and 2), specifying requirements for a next generation cost modelling  
19  
20 methodology. A State of the Art (SOA) survey on current methods and processes for  
21  
22 cost modelling in academia and industry is reported. Based on the observed  
23  
24 limitations of existing cost modelling techniques in the literature, and with an  
25  
26 understanding of the needs of MEs, a new cost modelling method capable of meeting  
27  
28 the requirements for effective cost modelling in MEs is proposed. The authors are of  
29  
30 the view that the proposed cost modelling method is capable of managing aspects of  
31  
32 risk, uncertainty, change and complexities associated with dynamic MEs.  
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## 38 **2.0 Development of cost modelling practices in Manufacturing Industries**

39  
40 In general terms, manufacturing industries have moved from highly data-driven  
41  
42 environments to more cooperative information-driven environments, taking into  
43  
44 account more of enterprise knowhow, commonsense and application semantics  
45  
46 (Vernadat 1996; Agyapong-Kodua 2009). In recent times, cost engineering principles  
47  
48 and modelling methods have been applied by some researchers to support cost  
49  
50 estimation, business analysis and planning, project management, profitability analysis  
51  
52 and scheduling of major engineering projects (Curran, Raghunathan et al. 2004).  
53  
54 However in most environments today, Business Administrators and Economists take  
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3  
4 hold of the overall business planning and management, pushing the cost engineer into  
5  
6 his core elements of cost estimation, scheduling and cost control (Samid 1990).  
7  
8

9 To effectively estimate and control cost in manufacturing environments, three  
10 sub layers have been recommended (Liebers 1998). These are: 1) production  
11 monitoring; 2) cost calculation and evaluation; and 3) cost modelling. Many  
12 researchers (Roy and Palacio 2000; Rush and Roy 2000; Curran, Watson et al. 2003;  
13 Agyapong-Kodua 2009) in the domain of cost engineering have reported that many  
14 cost estimating projects broadly consist of: 1) first sight estimate, usually at the early  
15 stage of the design process and 2) detailed estimate for precision costing. They  
16 explained that first sight estimates are suitable for 'Rough Order Magnitude' (ROM)  
17 estimates (Curran, Watson et al. 2003) and provide good background for initial  
18 product definition but are not very useful for detail product specifications and  
19 manufacturing process designs and optimization (Curran, Raghunathan et al. 2004;  
20 Agyapong-Kodua, Wahid et al. 2007). The next section is dedicated to reviewing  
21 State of the Art (SOA) cost modelling systems as expressed in academia and  
22 industries.  
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### 43 ***2.1 SOA survey of cost modelling methods***

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

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*Derivation of process cost modelling technique*

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4 may be built (Roy, Bendall et al. 1999). Also researchers in the domain of enterprise  
5 and systems engineering (Bernus and Nemes 1996; Kosanke 1996; Baines, Harrison  
6 et al. 1998; Weston 1999; Agyapong-Kodua, Ajaefobi et al. 2009) have proposed that  
7 to scientifically support cost control and modelling, especially in complex and  
8 dynamic organizations or industries, there is the need to develop well structured  
9 enterprise models to form the baseline for process analysis. Such models represent  
10 organizations as fairly independent sets of processes with interacting entities and  
11 flows which can be (re)designed to meet corporate objectives (Ajaefobi 2004; Chatha  
12 and Weston 2005). In specific terms, some researchers in Cost Engineering (Johnson  
13 and Kaplan 1987; Beltramo 1988; Son 1991; Asiedu, Besant et al. 2000; Curran,  
14 Raghunathan et al. 2004; Agyapong-Kodua, Wahid et al. 2007; Caputo and Pelagagge  
15 2008) have proposed and tested several cost estimating, production monitoring, cost  
16 calculation and evaluation and cost modelling techniques which are currently being  
17 used in academia and industry. The following sections provide a detailed review of  
18 some of these techniques.

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

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*Derivation of process cost modelling technique*

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4 can broadly be classified as intuitive, parametric, variant-based and generative.  
5  
6 However from a methodological point of view, cost estimating techniques may be  
7  
8 based on qualitative or quantitative approaches (Layer, Brine et al. 2002; Foussier  
9  
10 2006). Cost models based on qualitative methods adopt expert judgement and  
11  
12 heuristic rules as means of estimating cost (Caputo and Pelagagge 2008). Gray (Gray,  
13  
14 MacDonell et al. 1999) argues that cost judgements from experts and knowledgeable  
15  
16 people cannot be done away with considering the fact that it takes a relatively long  
17  
18 time to collect and analyse cost information. But Caputo (Caputo and Pelagagge  
19  
20 2008) is of the view that efforts should be concentrated on quantitative cost modelling  
21  
22 techniques since basically qualitative methods only indicate whether an alternative is  
23  
24 better or worse without absolute values. To put a structure around qualitative cost  
25  
26 modelling, Agyapong-Kodua (Agyapong-Kodua 2009) proposed the use of system  
27  
28 dynamic causal loops as a decision support tool. Some researchers have further  
29  
30 classified quantitative cost modelling methods (Asiedu, Besant et al. 2000; Layer,  
31  
32 Brine et al. 2002; Caputo and Pelagagge 2008) into: 1) statistical; 2) analogous 3)  
33  
34 generative or analytical and 4) feature based. They explained that statistical models  
35  
36 adopt statistical criteria to identify causal links and correlate cost and product  
37  
38 characteristics to obtain a parametric function with one or more variables. As a result  
39  
40 they classified parametric, neural networks and fuzzy logic cost models as being the  
41  
42 main examples. Analogous cost models identify the cost models of products or  
43  
44 projects of similar characteristics and features. Thus the strength of the similarity is  
45  
46 proportional to the correspondence of the relevant characteristics (Layer, Brine et al.  
47  
48 2002). Generative or analytical cost modelling methods attempt to decompose and  
49  
50 model processes associated with the development of the product or project (Caputo  
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3  
4 and Pelagage 2008; Agyapong-Kodua 2009). At each phase of the development  
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6 process, based on technical data, cost related to resource and material consumption  
7  
8 are determined.  
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10  
11 Rush (Rush and Roy 2001) indicated that, in general terms, cost modelling  
12  
13 requires a combination of high skills and extensive knowledge of multiple disciplines  
14  
15 and relies on the accurate understanding of design and manufacturing capabilities of  
16  
17 companies and their suppliers. This is illustrated in figure 1.  
18  
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### 20 21 22 **Figure 1: Skills and knowledge required for cost modelling** 23

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26 Some research work in supply chain cost control (Fitzgerald 2002; Handfield  
27  
28 2002) has shown that in general terms cost models can provide enormous benefits  
29  
30 when:  
31

- 32
- 33 • eliciting active support from top management
- 34 • integrating and modelling processes
- 35 • attempting to understand cost drivers in appropriate detail
- 36 • measuring the performance of suppliers, production systems and employees
- 37 • developing cooperative supplier relations
- 38 • delivering and establishing a culture of continuous improvement
- 39 • facilitating a cross-functional approach linked through cost
- 40 • managing and reducing cost across the whole business structure
- 41 • developing integrated data management systems and
- 42 • justifying investment
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52 Detailed explanations of the SOA cost modelling methods are provided in the  
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54 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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4 Fitzgerald 2000), Aeronautic Industry (Sanchez, Kundu et al. 1999) and Component  
5  
6 Part Manufacturing Industries (Curran, Raghunathan et al. 2004). In the Construction  
7  
8 Industry, parametric cost estimation has featured well in the determination of project  
9  
10 cost, based on historical data (Akintoye and Fitzgerald 2000). In the Aeronautic  
11  
12 Industry, parametric cost estimates play key role in bidding and target cost estimation,  
13  
14 whilst for most component manufacturing industries, parametric cost estimates are  
15  
16 used to determine the cost of components manufacture. Quite recently, parametric  
17  
18 cost models have gained popularity through the support work of organizations such as  
19  
20 International Society of Parametric Analyst (ISPA), Society of Cost Estimating and  
21  
22 Analysis (SCEA) and Space Systems Cost Analysis Group (SSCAG) (Curran,  
23  
24 Raghunathan et al. 2004).

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29  
30 The activity diagram shown in figure 2 was created to provide an overview of  
31  
32 the approaches adopted by Quin and Ben-Arieh (Qian and Ben-Arieh 2008) and  
33  
34 Curran (Curran, Raghunathan et al. 2004), which collectively provide a methodology  
35  
36 for developing parametric cost models..  
37  
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39  
40

### 41 42 **Figure 2: Development of parametric cost models**

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44  
45 This methodology assumes that parametric cost modelling is based on data capture.  
46  
47 This requires developing required templates and identifying data sources. Most data  
48  
49 for parametric cost modelling are obtained from Accountants, Engineers and Process  
50  
51 Managers in companies. After the collection of data, there is the need to evaluate  
52  
53 variables and respective data attached. By doing this a decision is taken to identify  
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55 variables which change or are likely to change with time. These variables are called  
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4 'cost drivers'. By adopting regression analysis, a statistically observed correlation is  
5  
6 established between the cost drivers and cost. These relationships are validated,  
7  
8 approved and saved in the CER data base which provides necessary inputs to the cost  
9  
10 model. As required the modelling loop is reversed for revalidation of CERs.  
11  
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14  
15 A number of researchers (Beltramo 1988; Hughes 1996; Briand, Emam et al.  
16  
17 1998; Shepperd and Cartwright 2001) have reported that the major limitation to  
18  
19 parametric cost modelling is the availability of data of adequate quality. With this  
20  
21 observed limitation, Gray (Gray, MacDonell et al. 1999) indicated that in real life  
22  
23 situations, poor and inadequate data is always the case, hence expert judgement is  
24  
25 sometimes necessary. Quite critically, Beltramo (Beltramo 1988) has indicated that  
26  
27 parametric cost models are unable to predict cost of projects or products outside the  
28  
29 scope of CER databases. This is a major limitation and hence the Parametric  
30  
31 Handbook (DoD 1999) shows that, to make good use of parametric models:  
32  
33  
34

- 35 1. Parametric models should not be used outside their database range
- 36 2. they should be used only after they have been verified and validated
- 37 3. should be constant adjusted to reflect changes in requirements
- 38 4. they should not be used until a realistic data corresponding to cost drivers can  
39  
40  
41  
42  
43  
44 be obtained

#### 45 46 47 *2.1.2 Analogous cost modelling method*

48 The analogous cost modelling technique identifies a similar completed product,  
49  
50 process or project and reuses cost information associated with this entity to estimate  
51  
52 the cost of the new entity, taking into consideration adjustments for the differences  
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54 between the two. The effectiveness however depends on how accurate the historic  
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56 data is and how accurate the difference between the two cases are established (Asiedu  
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4 and Gu 1998). It has been reported that analogous costing is the best-established  
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6 method of costing in many industries although normally it is applied in an ad hoc  
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8 manner (Hughes 1996; Shepperd, Schofield et al. 1996). A survey conducted by  
9  
10 Curran (Curran, Raghunathan et al. 2004) revealed that best industrial analogous cost  
11  
12 modelling process can be classified into six stages:  
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14

- 15  
16 1. Definition of the entity that requires costing. This involves defining the project  
17 or product in terms of characteristics such as design parameters, production  
18 requirements, operation and support attributes; reliability and maintenance.  
19
- 20  
21 2. Identification of data sources. This requires identifying sources of data related  
22 to the two entities under consideration. Most often data will include quantities,  
23 design and performance characteristic  
24
- 25  
26 3. Actual data collection. Data is collected in two folds, qualitatively and  
27 quantitatively. This is done for as many historical cases as possible. Where  
28 possible, inputs from specialist who are familiar with historic patterns will be  
29 required at this point.  
30
- 31  
32 4. Generating a range of factors that characterise the product in terms of  
33 features. These factors are used to define cost ratios with the underlining  
34 assumption that performance and design ratios influence cost ratios. Three unit  
35 ratios are often derived. These are complexity, miniaturisation and  
36 productivity.  
37
- 38  
39 5. Generating the actual cost estimates. This is based on the product of historic  
40 cost of the case and the ratios for complexity, miniaturisation and productivity.  
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- 42  
43 6. The derivation of the total programme cost which involves the addition of  
44 profits, and any adjustments management may deem fit.  
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52 Typical examples of the use of analogous cost modelling can be found in  
53  
54 (Shepperd, Schofield et al. 1996; Shepperd and Schofield 1997; Taylor 1997; Bashir  
55  
56 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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4 1991): 1) functions that describe cost can be derived for classes of similar objects and  
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6  
7 2) factors which affect cost can be influenced by design decisions. Based on these  
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9 assertions, feature drivers are derived and used as basis to estimate product cost. For  
10  
11 most manufacturers, significant data on historic geometrical data exists which can be  
12  
13 used to estimate cost of designs (Bronsvort and Jansen 1994; Ou-Yanang and Lin  
14  
15 1997). In recent times, many researchers are using feature based cost models to  
16  
17 integrate design, process planning and manufacturing. This is considered possible  
18  
19 because Rush and Roy (Rush and Roy 2000) argue that the growth of CAD/CAM and  
20  
21 3D modelling helps both the designer and manufacturer to relate to common features  
22  
23 such as holes, faces, edges, etc. Although many Design and Manufacturing Engineers  
24  
25 seem to understand the concept of features, Curan (Curran, Raghunathan et al. 2004)  
26  
27 reports that feature-based cost modelling is not fully established in Industries. Another  
28  
29 observation reported by these same authors is that features differ from one industry to  
30  
31 the other and for a given industry several features might be required to fully describe  
32  
33 the product. In reality the major challenge with feature based cost modelling is that as  
34  
35 products change, companies have to cope with re-defining product features. This can  
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37 be very tedious considering the amount of new product changes that may be required  
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39 in a dynamic manufacturing environment.  
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#### 48 *2.1.5 Fuzzy logic cost modelling method*

49 The fuzzy theory was first introduced by Lotfi Zadeh in 1965 as an artificial  
50  
51 intelligence tool which formulates the human thought when dealing with uncertainty  
52  
53 and imprecision (Kishk and Al-Hajj 1999; Nachtmann and Needy 2001). Since the  
54  
55 inception of fuzzy theory, literature shows that it has proven suitable for representing  
56  
57 value and imprecise knowledge in a well structured and controlled manner (Cordon,  
58  
59 value and imprecise knowledge in a well structured and controlled manner (Cordon,

60 \*Corresponding author

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4 Gomicide et al. 2003). Many cost modellers with a strong mathematical background  
5  
6 have applied fuzzy theory to model dynamic factors which impact on cost (Joumier  
7  
8 1999; Kishk and Al-Hajj 1999; Nachtmann and Needy 2001; Shehab and Abdalla  
9  
10 2002). This has helped to improve cost practices since, basically, many traditional  
11  
12 cost modelling tools are deterministic and most suitable for static analysis (Ting,  
13  
14 Zhang et al. 1999). The theory of fuzzy logics is described in a number of literature  
15  
16 including (Joumier 1999; Kishk and Al-Hajj 1999; Pedrycz, Peters et al. 1999;  
17  
18 Cordon, Gomicide et al. 2003; Xiong and Helo 2006; Chrysafis and Papadopoulos  
19  
20 2009; Chen and Huang 2010).  
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25  
26 Shehab and Abdalla (Shehab and Abdalla 2002) noted that several steps are  
27  
28 required to develop a fuzzy theory-based cost model. Three main procedures have  
29  
30 been reported (Mamdani and Gaines 1981; Klir and Ruan 1996; Curran, Raghunathan  
31  
32 et al. 2004). These are:  
33

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

38  
39 In general terms Kishk (Kishk and Al-Hajj 1999) is of the view that fuzzy  
40  
41 logics are most applicable when: 1) models of processes or products are highly  
42  
43 complex and understandings about them are limited or 2) when there are processes for  
44  
45 which human decision making is inextricably linked.  
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50  
51 A key advantage in the use of fuzzy logics in cost modelling is indicated by  
52  
53 Curran (Curran, Raghunathan et al. 2004) as:  
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- 55 1. The mathematical concepts deployed are transparent and traceable
- 56 2. It possesses the ability to match sets of input-output behavioural data

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4 3. It can be integrated with traditional techniques  
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6 Although these advantages are recorded, it is however evident that fuzzy logic  
7  
8 cost modelling is not fully established in industries (Joumier 1999; Curran,  
9  
10 Raghunathan et al. 2004). It remains limited to experts of 'fuzzy sets' and artificial  
11  
12 intelligence (Blattberg and Hoch 1990).  
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17 *2.1.6 Neural networks based cost modelling method*

18 Neural network cost modelling techniques constitute a form of artificial intelligence  
19  
20 that is used to derive cost as an effect associated with some cost drivers (Zhang, Fuh  
21  
22 et al. 1996). Neural network cost models are based on cost attributes which relate to  
23  
24 the product or system under consideration. They possess unique advantage in the field  
25  
26 of statistical cost modelling because they can model cases where functional  
27  
28 relationship between case data cannot simply be expressed in polynomial form  
29  
30 (Caputo and Pelagagge 2008). Caputo (Caputo and Pelagagge 2008) indicated that  
31  
32 basically artificial neural network cost models 'accept as input shape-describing and  
33  
34 semantic product characteristics' and generate outputs in the form of product cost.  
35  
36 Key research contributions in neural network cost models were provided by: Seo  
37  
38 (Seo, Park et al. 2002) for the life cycle costing in conceptual designs; Zhang and Fuh  
39  
40 (Zhang, Fuh et al. 1996) for estimating packaging cost based on product dimensions;  
41  
42 Shtub and Versano (Shtub and Versano 1999) for processing operations and Cavalieri  
43  
44 (Cavalieri, Maccarrone et al. 2004) for the estimation of manufacturing cost of disk  
45  
46 brakes. Other authors have compared the effectiveness of artificial neural network  
47  
48 cost models with parametric cost models in engineer to order industries (Shtub and  
49  
50 Versano 1999; Cavalieri, Maccarrone et al. 2004; Caputo and Pelagagge 2008), and in  
51  
52 general terms (Bode 2000). A study of the above literature shows that artificial neural  
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4 networks show better results than parametric cost models. However it has been shown  
5  
6 that in some cases neural network models are limited in terms of accuracy, variability,  
7  
8 model creation and model examination (Smith and Mason 1997). Elhag (Elhag and  
9  
10 Boussabaine 1998) also noted that neural network cost models are not suitable for  
11  
12 highly innovative products which deviate largely from historic precedents.  
13  
14

### 17 **3.0 Analysis of literature**

18 The foregoing literature on costing (engineering, estimating, and modelling) shows  
19  
20 that whilst there have been a number of stepwise developments in the principles of  
21  
22 costing; these have not translated holistically in to working practices. Case studies  
23  
24 reported by a number of authors have all been towards highly specialised and bespoke  
25  
26 solutions that have not then been generalised for wider application domains. This is a  
27  
28 reflection of practice seen and experienced by the authors of this paper. Generally, the  
29  
30 widely reported cost modelling techniques can be classified as shown in figure 3. This  
31  
32 figure shows there is no indication of integration of cost modelling methods and most  
33  
34 of the methods described in the literature are 'product based'.  
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#### 42 **Figure 3: Classification of cost modelling methods**

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44  
45 A compilation of literature on costing and their years of publication (not  
46  
47 shown) revealed that developments in costing saw increased activity from the 1990's  
48  
49 to 2000 (see figure 4). In terms of cost modelling and estimating, techniques exist as  
50  
51 discussed, but it is noted that their application is of limited scope i.e. neither has it  
52  
53 been holistic nor integrated. Methods, that is to say instances of techniques, are often  
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55 isolated and consider cost on a piecemeal basis e.g. by product, sub-product, business  
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4 domain, lifecycle phase or investment decision. Additionally, cost is normally  
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6 considered in relative isolation of other metrics.  
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#### 10 11 **Figure 4: Literature according to year** 12

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15 The literature indicates that cost considerations are by and large made during  
16  
17 the preliminary design stages of a product's development to aid engineering managers  
18  
19 in selecting the most cost effective solution (see figure 5).  
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21

#### 22 23 **Figure 5: Literature lifecycle stage focus** 24

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27 Cost Modelling and Estimation are however not part of an integrated approach and  
28  
29 appear to be under the development and ownership of engineering functions with little  
30  
31 application to wider fields of interest, mainly with results being reported to  
32  
33 management.

34  
35 Cost models can be scrutinised for accuracy, utilising statistical uncertainty in  
36  
37 conjunction with cost estimation to produce a cost risk methodology. These do  
38  
39 however remain largely qualitative and depend on the subjective opinions of experts  
40  
41 to decide upon risks and their associated likelihoods and severities. Another factor to  
42  
43 consider is that not only do we have uncertainty related to the biases of experts; there  
44  
45 is another dimension of the product build configuration. As this is prone to change  
46  
47 through the development phases, additional levels of risk and uncertainty are  
48  
49 introduced. This implies the need for enhanced openness and sharing of information  
50  
51 between various parts of an organization throughout lifecycle phases. The objective of  
52  
53 modelling and estimating costs is to improve design through making cost information  
54  
55 available further upstream in the realization of products and processes. Such decisions  
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4 can then be documented and design rules created, as the early design stages are where  
5  
6 the majority of costs are built into a product.  
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9 Cost models are largely seen as a means to determining absolute figures for  
10  
11 product or process within certain degrees of confidence, through structured methods.  
12  
13 The behaviours of costs are often neglected in terms of the 'cause and effect' issues  
14  
15 associated with change decisions. In this respect, it is evident from the literature that,  
16  
17 performance indicators that were once traditionally the onus of managerial and  
18  
19 accounting functions, are now filtered down in such a way that they are the concern of  
20  
21 every element in value and supply chains. This is to the extent that non-accountants  
22  
23 are assuming a much more direct responsibility for, and interest in, the financial (and  
24  
25 non-financial) outcomes of their performance. However, this has occurred without the  
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27 necessary methods, approaches, and techniques to support modelling and analysis.  
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35 Cost engineering not only encompasses monetary expenditure during the  
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37 realisation of objectives but also other aspects such as time, material and resources. It  
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39 can therefore be seen that cost engineering is not just confined to the control of  
40  
41 monetary costs. The remit of the cost engineer is to facilitate and inform design such  
42  
43 that products that are cost effective during production and later lifecycle stages are  
44  
45 produced. There is therefore an increased need to make design considerations based  
46  
47 on appropriate lifecycle drivers, some of which are easily quantified, whilst others  
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49 less so.  
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54 The literature has shown that, in general terms, some of the problems faced by  
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56 most design and manufacturing industries can be rooted to the phenomenon of  
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58 complexity which stems from the complexities involved in current markets. The  
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4 structural and dynamic complexity of markets impact on the structure and processes  
5 of the enterprise too, hence complex cost generation factors emerge. Advancing  
6 information and machine technologies have also impacted on how cost is created,  
7 measured and controlled. The development and utilization of microelectronics;  
8 CAD/CAM/CAE; computer communication networks; software engineering; object  
9 oriented database systems; distributed artificial intelligent systems; multimedia and  
10 multimodal environments as well as open systems architectures are impacting greatly  
11 on design and manufacturing industries. All these technologies influence processes  
12 and especially how cost is developed. Depending on an industry's need, automation  
13 can be very high and complex, and cost modelling methods will have to recognise this  
14 new complex dimension of production systems. Another clear observation is that,  
15 many industries are focussing on their core competences and forming partnership with  
16 other organizations which can support aspects of their. From a manufacturing point of  
17 view, the decision to either 'make' or 'buy' is crucial, if a business is to survive in  
18 current dynamic markets. The onus therefore lies on cost engineers to better develop  
19 models which can support critical decision making. The added challenge for designers  
20 and manufacturers is that cost modelling methods must be able to analyse capabilities  
21 of systems and the cost implication of management decisions. The observed need for  
22 a scientific cost estimation approach to match the ever-growing manufacturing  
23 industry is obvious.

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

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*Derivation of process cost modelling technique*

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4 are characterised by complex systems of processes which need to be resourced with  
5  
6 technical and human systems. These systems need to be properly coordinated and  
7  
8 controlled to allow variety of products to be realised through them over varying  
9  
10 periods of time. Current approaches to the identification and modelling of cost has not  
11  
12 been adequate because most of the cost modelling techniques do not encode time  
13  
14 dependencies related to product flows, controls, process instants and time dependent  
15  
16 causal effects. This implies that analysis of alternative flows of product (volume and  
17  
18 mixes) through a shared process cannot accurately be modelled by current generation  
19  
20 cost modelling techniques.  
21  
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#### 25 26 27 **4.0 Future trends**

28  
29 Based on the analysis of literature; observed current cost modelling practices and the  
30  
31 general trend of advancement in MEs, the authors are of the view that as a result of  
32  
33 the dynamics associated with most MEs, there is the need for a comprehensive  
34  
35 modelling methodology which satisfies the following requirements:  
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37

- 38  
39 • The modelling methodology must suitably capture all different product types  
40  
41 in a ME with the view of linking products to respective process routes. This is  
42  
43 because a study of trends in MEs shows that most MEs need to realize  
44  
45 multiple products to remain competitive, hence there are significant product  
46  
47 mixes, shared resources with unsteady changes in information or material  
48  
49 flow, as well as control. Thus there is the need to deploy cost modelling  
50  
51 methods with capabilities to reflect the changes associated with multiproduct  
52  
53 flow properties. Because of the varying range of products many MEs need to  
54  
55 realise, coupled with external factors which invariably impact on their  
56  
57 operations, process changes may be required over a short time. A cost  
58  
59 modelling methodology which depicts the impact of process changes is  
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4 therefore necessary to effectively describe the actual cost which is likely to be  
5 incurred on the account of changes in processes.  
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- 8 • Although some work has been done on process oriented cost modelling  
9 techniques, literature has shown that, in the main, product based quantitative  
10 cost modelling techniques abound. Despite the strengths of the product based  
11 cost modelling techniques, it is important to be able to deploy cost modelling  
12 methods which are able to depict or translate design solutions into equivalent  
13 manufacturing processes and their associated required resources. Thus process  
14 based modelling techniques have potential to model operational sequences for  
15 different product families and can be helpful in estimating, controlling and  
16 monitoring the generation of cost at a reasonable degree of accuracy. An  
17 enhancement and combined usage of existing product-based cost modelling  
18 techniques and process modelling techniques, with a definitive view of  
19 production systems design will help measure cost and process efficiencies  
20 more accurately.  
21  
22
- 23 • Also the cost modelling method should enable enhanced traceability of costs  
24 to specific products and processes to enable improved management of cost  
25 distortions whilst supporting the accurate estimation of process cost due to the  
26 deployment of alternative business process configurations.  
27  
28
- 29 • Because of changes, risks and dynamics associated with MEs, a virtual  
30 executable cost model experimentation tool will be useful if it enables design  
31 options, business ideas, production systems reconfiguration and process  
32 improvement suggestions to be tested before their implementation. This will  
33 save MEs from implementing decisions; in fact design decisions that have  
34 great impact on the business. System dynamics and discrete event simulation  
35 tools can help model and control some aspects of dynamics associated with  
36 current manufacturing systems  
37  
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- 39 • Generally, a decomposition of enterprise requirements ensures that complex  
40 problems are characterised and modelled in modular forms, so that analysis  
41 and understanding becomes easier. The consistent utilization of appropriate  
42 cost modelling constructs will enable the contextual reuse of models. Thus the  
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4 required cost modelling method should inherently possess decomposition  
5 formalisms and uniformly display a set of modelling constructs that facilitate  
6 model reusability in MEs. Process decomposition and integration can be  
7 enabled through the selection and appropriate utilization of enterprise  
8 modelling tools.  
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15 Based on this set of modelling requirements, the authors are of the view that  
16 the integrated use of concepts and techniques from Cost Engineering, Enterprise  
17 Modelling, System Dynamics Modelling and Discrete Event Simulation Modelling,  
18 will be useful. Research is underway to fully establish how relevant modelling  
19 techniques belonging to these separate domains can be integrated and supported with  
20 relevant data to help generate a multipurpose cost model useful for decision support in  
21 designing and manufacturing.  
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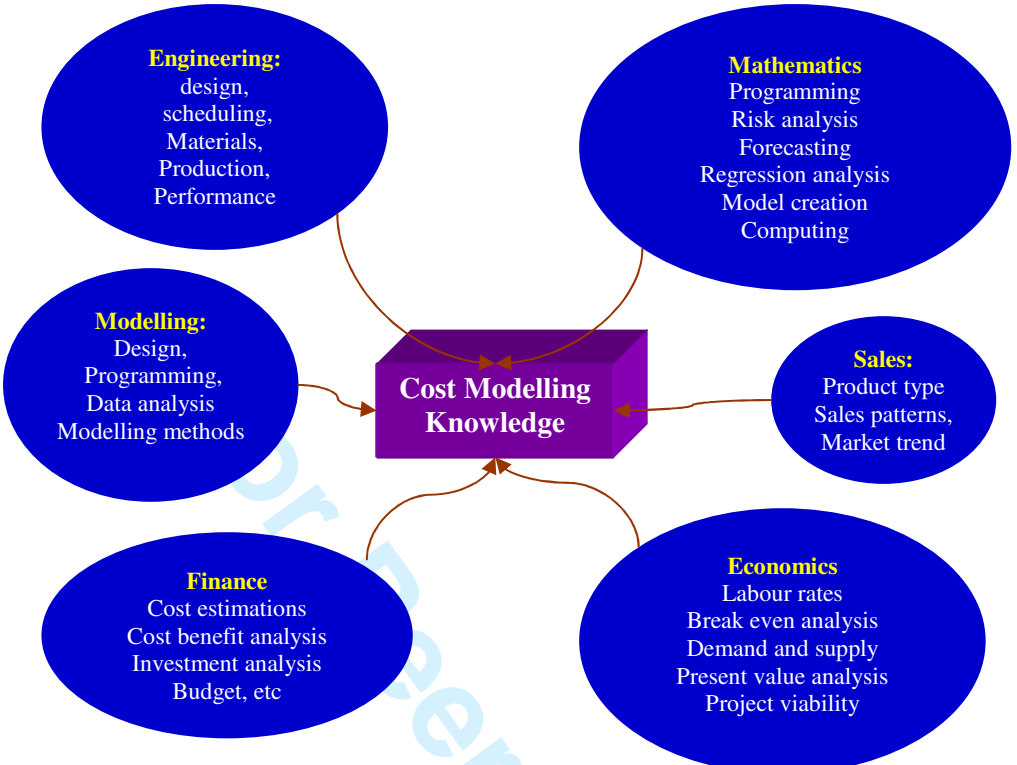


Figure 1: Skills and knowledge required for cost modelling

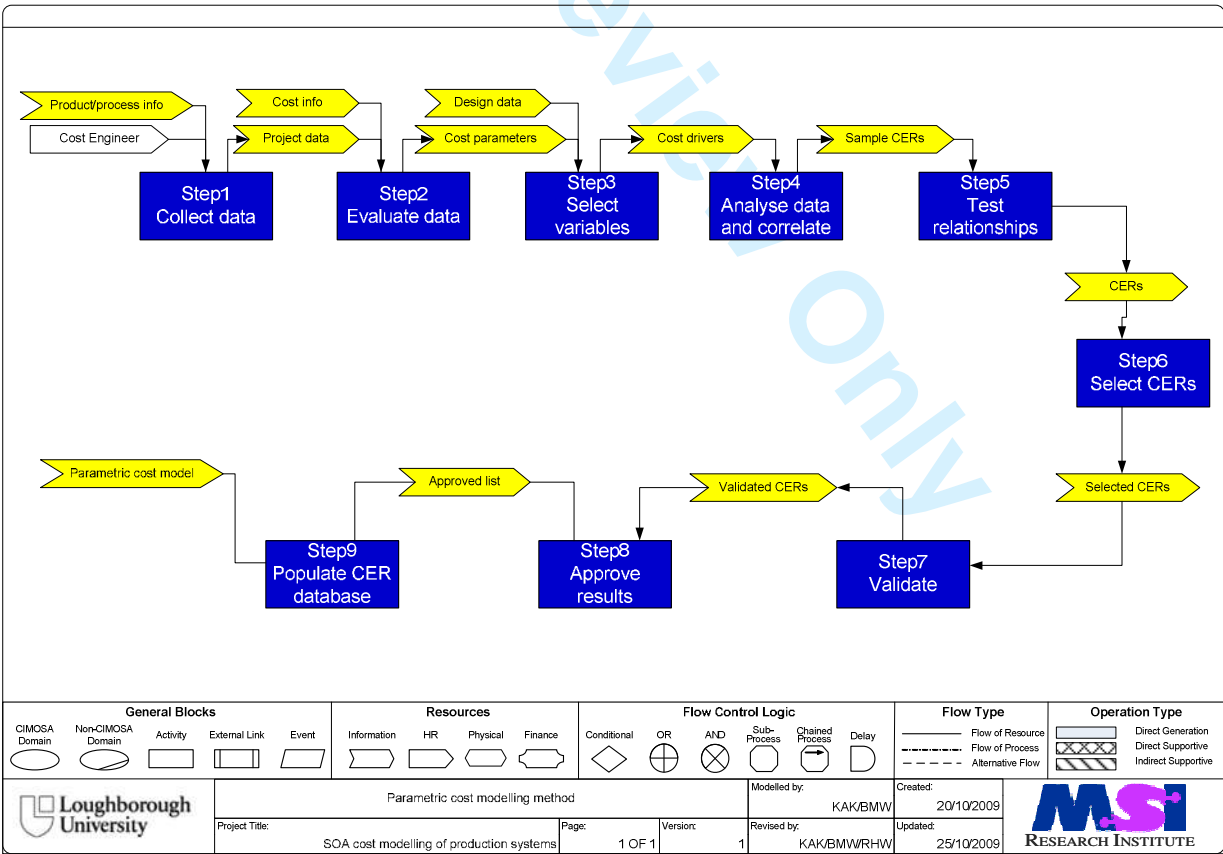


Figure 2: Development of parametric cost models

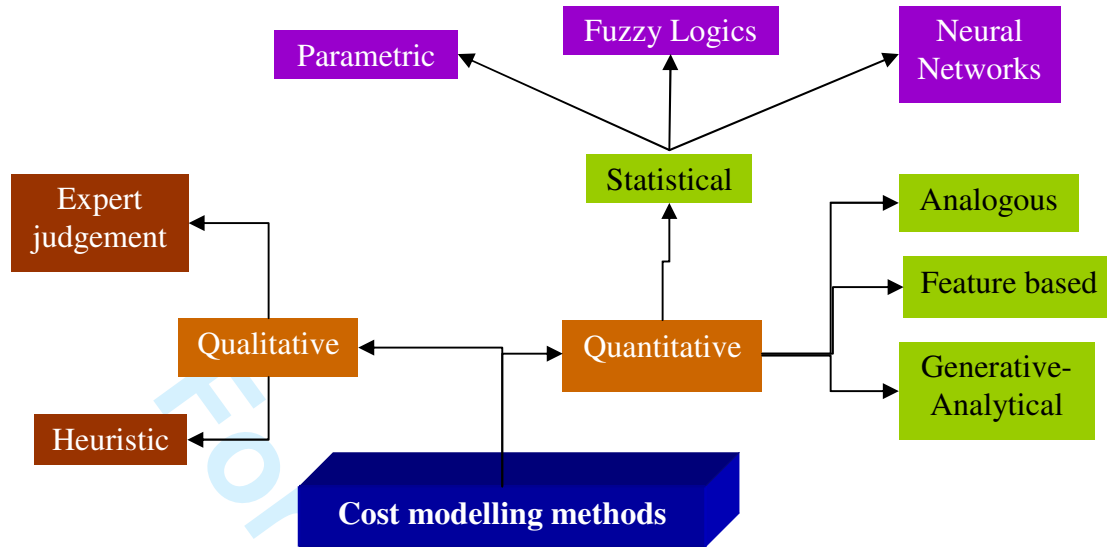


Figure 3: Classification of cost modelling methods

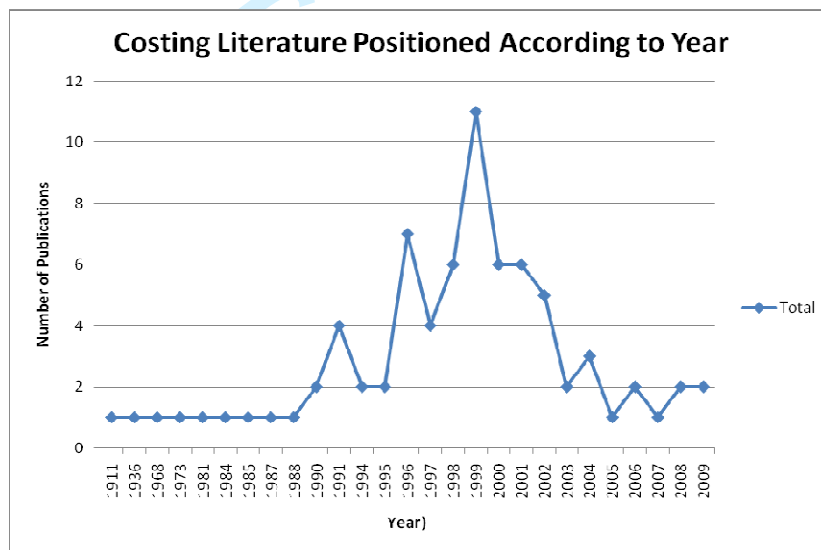


Figure 4: Literature according to year

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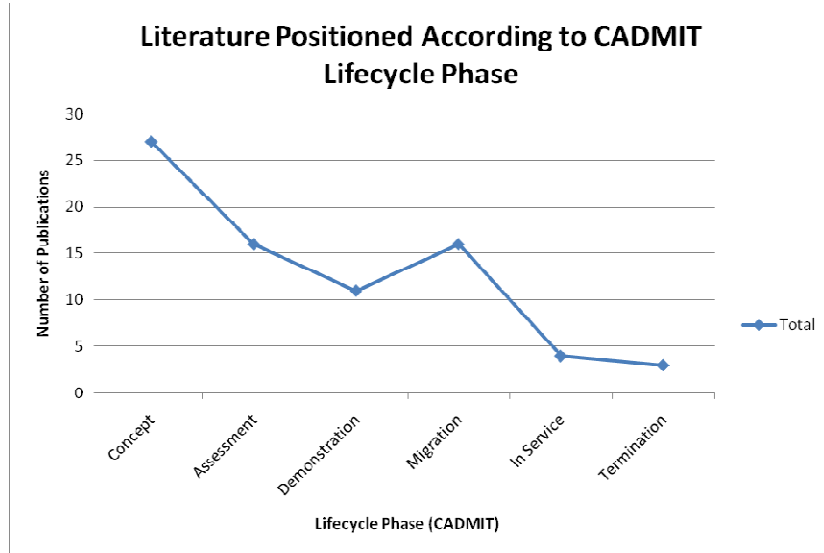


Figure 5: Literature lifecycle stage focus

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