CRANFIELD UNIVERSITY

S I DIMMOCK

MACHINED PART COST ESTIMATING IN SMEs: A FEATURE-DRIVEN CASE-BASED APPROACH

SCHOOL OF APPLIED SCIENCES

EngD THESIS
Academic year: 2009-2010

Supervisors: R.M. Greenough, B.E. Tjahjono, G. Clark
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This thesis is submitted in partial fulfilment of the requirements
for the degree of Doctor of Engineering

This thesis is dedicated to Amanda and Ryan

‘If I could choose when to live, I should choose the present because, for the first time, it recaptures the sense of an opening universe of new concepts and discoveries that once suffused the age of Newton. We have made a revolution in our total picture of the world, not just on technical level but by creating wholly new conceptions like relativity (and the burgeoning of astrophysics ever since).

As a result, we see science not as a book of facts, but as a continuing adventure in understanding – and an adventure that the man in the street shares as he did Newton’s in his day. No wonder that great discoveries outside physics have taken place at the same time: the minds of young men are inquisitive in all fields, in and outside science - in a famous poetic phrase, ‘the chariot wheels take fire from their own turning’. Perhaps science does not always have to be in a state of constant revolution, and will in time settle down to another 200 years of quiet elaboration. But no one with a sense of philosophic pride would quarrel at living now rather than then.’

Dr. J. Bronowski
August 1969

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Abstract

This thesis describes the application of a novel decision support process for machined part estimating in small and medium-sized engineering companies. Many SMEs tend to adopt manual estimating techniques, however this dependence on human expertise represents a risk to such organizations. Better information management in estimating can improve process performance and contribute to increased competitiveness.

The research which is the subject of this thesis investigated whether a systems approach to machined part estimating would extend the capacity of an SME to manage knowledge more effectively. The research explored the workplace learning context, the provision of learning opportunities and the management of organizational knowledge; before determining that an intelligent information system offered the most beneficial solution to the situation-of-interest.

The case study company produce low-volume, make-to-order, medium and large sized machined steel forgings; utilising conventional machine tool equipment. The application of the decision support system enabled novice estimators to produce viable cost estimates; reducing the risk from reliance on human expertise inherent in manual estimating. The hybrid feature-based costing / case-based reasoning estimating technique, which is the core of the novel METALmpe cost model, proved exceptionally well suited to the SME environment. Estimates produced using METALmpe were consistently more accurate than those of the human expert; with a level of accuracy that exceeds the initial research aim, i.e. a tolerance of -5% / +10%.

Significantly, implementation of METALmpe (hardware, software and support for 5 users), can be provided at a cost which is within the typical information technology budget of many SMEs. With demands on organizations to process and disseminate ever increasing volumes of information, METALmpe can improve an SME's information management capabilities and contribute to competitive advantage through strengthening strategic assets and core competencies.

KEYWORDS: estimating, feature-based costing; case-based reasoning

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Glossary

Any terms which are used in this thesis in a specific, restricted way are defined below:

Case	When each 'feature' of the machined part is designated as either an *operation* or a *process*, and its specific characteristics are defined, it becomes a 'case' to be referenced in the database. A case is defined as the description of a problem that has been successfully solved in the past, along with its solution. The case is partitioned within in the database for easy retrieval by firstly, selecting the feature group and sub-group from drop-down menus, then secondly by the specified material grade and operation / process parameters.
Case-based costing	The process by which new cost estimates are derived by adapting the actual costs of similar features stored in historical data. This process is based upon the intelligent system methodology *case-based reasoning*.
Case-based reasoning	Case-based Reasoning (CBR) provides a hierarchical case memory structure and context-based indexing method for retrieval and reuse of previous production data and associated costs. In METALmpe cases are selected from the database that best resemble the characteristics of the particular feature of the part which is being estimated. The information provided by the retrieved case is reused or modified using domain rules, providing a solution to the current estimating problem.

Feature	Any value-adding activity, such as heat treatment, machining, etc, applied during the manufacturing process. Each separate *feature* of the machined part forms a 'case' to be stored in the database.
Feature-based costing	Feature-based Costing (FBC) determines product cost by assigning costs to specific features of the product based on their attributes, size and complexity. All kinds of features must be taken into consideration, from physical features such as shape or materials, to process features such as heat treatment, testing etc.

List of Acronyms

ABC	Activity Based Costing
AI	Artificial Intelligence
CAD/CAM	Computer Aided Design / Computer Aided Manufacture
CE	Cost Estimating
CBR	Case-based Reasoning
CBR_{pa}	Case-based Reasoning (parameter adjustment)
CER	Cost Estimating Relationship
COTS	Commercial Off-the-shelf Software
EJ	Expert Judgement
EPSRC	Engineering and Physical Science Research Council
ES	Expert System
FBC	Feature Based Costing
ICT	Information and Communication Technology
IDEF	Integrated Function Definition Modelling
KBS	Knowledge-based System
KBV	Knowledge-based View
KE	Knowledge Elicitation
KEN	Knowledge = Expert – Novice
METALmpe	Material and Engineering Transaction Application: Machined Part Estimating
MS	Microsoft
PE	Parametric Estimating
RBV	Resource-based View
RFQ	Request for Quote
SME	Small and Medium Enterprise

Statement of original authorship

Except where otherwise stated, this thesis is the result of my own research and does not include the outcome of work done in collaboration.

Chapter 1 Introduction

1.1 Background to the research

This thesis describes research conducted at Schmolz + Bickenbach UK Ltd, aimed at improving the company's manual approach to cost estimating at their machining department in Oldbury, England.

Schmolz + Bickenbach UK Ltd process and distribute steel long products and custom steel forgings. The company has three sites within the UK, with a turnover of circa £50 million in 2008. The divisions based in Chesterfield and Birmingham stock stainless and engineering steels and between them contribute the largest percentage of the UK turnover. The tool steel and machining division at Oldbury contributed circa £8 million in 2008.

Schmolz + Bickenbach UK Ltd are the UK distributor for product manufactured by the Schmolz + Bickenbach Group around the globe. The Group is 'the world's largest manufacturer, processor and distributor of special steel long products. As a producer, the Group is number 1 in the global market for both stainless long steels and tool steels. In alloy and high-alloy special and engineering steels the Schmolz + Bickenbach Group rank among the top ten (Schmolz + Bickenbach, 2009).'

The Group focuses on three strategic business segments: production, processing, and distribution. By doing so, they 'combine the competences of a steel producer with those of a steel processor and distributor to enable customers to obtain all-round support from one single source (Schmolz + Bickenbach, 2007).'

The corporate goal is to 'create a stable, robust, and globally based group of companies which, thanks to its own sources of supply, service and cross-regional compensation, reacts only minimally to external market fluctuations (Schmolz + Bickenbach, 2007).' In 2008, Schmolz + Bickenbach Group revenue exceeded €4,000 million, with total assets exceeding €2,600 million and over 11,000 employees worldwide.

The Schmolz + Bickenbach Group own six steelworks across Europe and North America (Schmolz + Bickenbach, 2009a):

- Deutsche Edelstahlwerke (Germany) produces high-grade tool steels, stainless steels and engineering steels.

- Swiss Steel (Switzerland) produces bright steel, engineering and free-cutting steel.
- Ugitech (France) produces stainless long products.
- A. Finkl & Sons (U.S.A) and Sorel (Canada) manufacture high-grade tool steel and custom forgings.

The Schmolz + Bickenbach Group are leaders in tool steel production and material technology. Integrated production facilities, superior product quality, research and development activities and a high level of technical support, differentiate Schmolz + Bickenbach from many other suppliers competing for business in the UK tool steel sector. Integrated production creates competitive advantages over competitors who purchase materials and machining services from separate sub-contractors; Schmolz + Bickenbach's operating strategy shortens the supply chain, controls costs and facilitates improved quality control. The Schmolz + Bickenbach brand and reputation assists the UK operation to gain entry into market segments which are traditionally difficult to penetrate; where the opportunity exists to supply small quantity batches of high value speciality machined forgings. The Group holds considerable stocks of material, including speciality forgings to customer specifications, enabling a fast response to customer requirements; dramatically reducing lead time for forged product at times of high activity and increased worldwide demand.

Prior to its consolidating with Schmolz + Bickenbach UK Ltd in 2007, the Oldbury division formerly traded as Finkl UK Ltd, who were themselves a subsidiary of the North American steel producer A. Finkl & Sons. The research described in this thesis commenced at Finkl UK Ltd in 2005, where at that time, the machining department turnover exceeded £1 million per annum; supplying rough machined and finish machined forged products to the Oil & Gas, Power Generation and General Engineering sectors. In 2005 the company employed 18 full time personnel, 6 of whom worked as machine tool operators.

The challenges faced by the machining department at Finkl UK Ltd, and subsequently Schmolz + Bickenbach UK Ltd, drew close comparison to those challenges faced by similar small and medium sized engineering enterprises, where machined product was being produced by skilled machinists using conventional, manually controlled machine tools.

The Oldbury plant was established in 1991 to promote and distribute A. Finkl & Sons Co forged products in Europe; stocking hot work die steels, plastic mould steels and die-casting die steels. Customer perception of the company, as an experienced producer of machined forgings (for oil tool equipment, rollers for continuous casting plants and 'medium to heavy' general engineering applications) is enhanced by the comprehensive machining facilities and highly skilled engineers working at the company. Schmolz + Bickenbach UK Ltd aim to continue to provide this high service level, with product realization processes from steelmaking to the finished article controlled within the group whenever possible.

The company produces a varied range of machined forgings (and also provides subcontracted machining services) either individually or in small scale production batches, with capacity for rough or finished turning, milling, boring and drilling of components up to 30,000 kg in weight. Further processing capabilities include extensive sawing capacity and heat treatment equipment for forgings up to 5,000 mm in length and 20,000 kg in weight, including water quenching facilities.

Cost estimating within the organization is a critical business process. An accurate, dependable estimating process is crucial for the business to remain both competitive and profitable. The company recognized that improving their ability to react to customer enquiries in a more timely and dependable manner can lead to a competitive advantage. The estimating processes at A. Finkl & Sons in Chicago, U.S.A. were reviewed to establish whether similar problems existed in their processes, with the expectation of transferring any relevant available solution for use in the UK situation. However, the operating environment at Oldbury proved to be unique within the A. Finkl & Sons Group rendering any potential existing or planned technology solution non-transferable. Later in October 2007 (following the acquisition of the Finkl Group by Schmolz + Bickenbach AG), further discussions were held with the senior management team responsible for worldwide IT infrastructure. Held at Schmolz + Bickenbach Group headquarters in Düsseldorf, these meetings investigated once again if any existing systems or technologies could be adopted in the UK. The initial meeting was subsequently followed by site visits to both the UK site in Oldbury and the Deutsche Edelstahlwerke machining facilities at Witten and Krefeld in Germany. Following a period of reflection the team of information technologists from Schmolz + Bickenbach and partner consultants from SAP, concluded that the UK operation required a bespoke development and hence could not benefit from any existing estimating system. The management of Schmolz + Bickenbach AG considered that any solution originating from this research would measured against the return on investment, in the context of an annual turnover of less than £1.5 million – comparable with many similar small and medium sized engineering enterprises.

Considering that many SMEs have constraints on resources which result in little opportunity for investment of time, expertise and capital in development of business information systems; any solution developed for Schmolz + Bickenbach UK may potentially provide a generic low-cost solution for other SMEs with operations of a similar type and scale.

Schmolz + Bickenbach UK rely almost entirely on manual estimating procedures, depending upon the expert knowledge of experienced individuals - as is often the case in similar SME machine shops (Dimmock, 2007). Dependence on human expertise is in itself a risk (MacCarthy *et al*, 2001), as an individual may be taken ill, decide to retire or leave the organisation to progress their career elsewhere. Machining operations contribute significantly to the 'added value' of products at Schmolz + Bickenbach but there is no fully reliable way to predict time and effort due to the complexity of product realization processes and variance in individual performance (Wallace, 2002). The estimator utilizes a high degree of judgement and experience when manually calculating an estimate, hence their tacit knowledge is considered 'simultaneously valuable, rare; imperfectly imitable and imperfectly substitutable (Barney, 1991).' In order to remain competitive, cost estimates need to be accurate, but without a *system* which supports the estimating process this essential factor is reliant on individuals.

The importance of generating good estimates cannot be over emphasised, the consequences of poor estimating decisions can prove to be very expensive. In the competitive tool steel market, customers are in a strong negotiating position; hence they often command prices from their suppliers which only allow a small gross profit margin for the supplier. If the estimating process does not accurately represent the realistic lead time and cost of production, this creates a major obstacle for the sales team which seriously reduces the likelihood of winning profitable business. Uncompetitive pricing or extended lead times due to over estimates may result in a competitor winning the business. Underestimating the production requirements may win the order, but the cost of production is likely to result in an operating loss and potential failure to meet delivery commitment; all of which may seriously jeopardize future business with that customer and damage the company's wider reputation.

Schmolz + Bickenbach had identified that by the year 2010 both of the expert estimators employed at the company were due to retire, hence, actions were required to stabilize the estimating function into the long term future. The company wanted to investigate how the estimating process could be made more robust and dependable, and whether information technology could provide an alternative to complete reliance on human expertise.

This thesis describes the research undertaken at Schmolz + Bickenbach UK Ltd, which considered the use of information technology to support and enhance the estimating process. The research set out to establish a dependable method of estimating which would:

(i) Continually improve the accuracy and reproducibility for calculations of processing times and costs.
(ii) Make the estimating process more accessible to non-experts.
(iii) Shorten the time taken to produce estimates and quotations.

1.2 Research problem

This thesis describes case study research conducted at the case study company, which evaluates the cost engineering processes required in the production of medium and large sized machined steel forgings. An accurate and consistent estimating process is critical to the organisation's competitive strategy, however opportunities for improvement were identified in the existing estimating practice. The company witnessed that the existing process often resulted in significant differences between the original estimate for a machined part and its actual cost. Empirical analysis of actual production records for the whole of 2005 shows (i) inaccuracy in the estimated time for machining operations and (ii) inherent variation in the reproducibility for specific machining operations; suggesting a significant level of variability, see Figure 1.

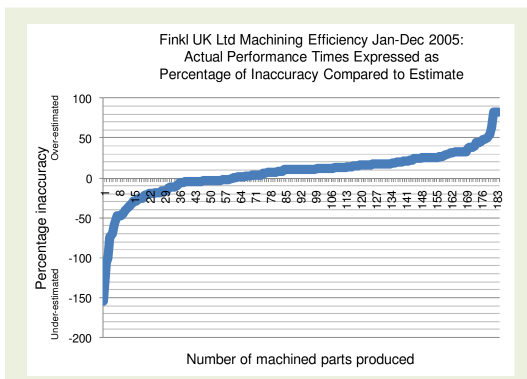


Figure 1. Summary of estimating accuracy at the case-study company for 2005 (total finished part times)

In this sample of 186 machined parts produced between 1st January 2005 and 31st December 2005, the average 'efficiency' was 12%, i.e. the numbers of hours booked as *direct costs* totalled 6,143 compared to the estimate of 6,969. This overall measure is relatively good, e.g. both the case study company and Deutsche Edelstahlwerke agree that estimating accuracy of +/- 10% is 'good'. The 2005 level of performance provides a benchmark to approve upon – as it represents 826 hours of potential capacity for which orders *may* have been lost owing unnesscessarily excessive lead times being offered. For example, a particular customer may have two semi-finished plastic mould tools which require a significant amount of gun-drilling to produce cooling circuits; typically each tool may have 60 hours of machining time estimated. In this instance, the customer would be quoted one tool in 7 days with the second in 14 days. However, if the customer must have both tools available for the subsequent machining operations in 10 or 11 days maximum, the result would be that the case study company could unnecessarily lose the order for the second tool, simply due to the perception that the required delivery could not be achieved.

Conversely, the implications are also severe from instances where a commitment may be undertaken to meet a strict delivery requirement but an under-estimation of machining time leads to a failure to delivery to the contract requirements; such occurrences may have an immediate financial impact (premium rate overtime, penalty charges) or more importantly damage the company's reputation and jeopardize future business.

Returning to Figure 1, this shows only the total hours booked to piece parts, which illustrates the difficulty in quoting lead times to customers but is far from defining the complete problem. Of equal importance to the case study company is next level of manufacturing information, how much machine time is required for specific machined features of each part. For example, a Caster Roll would be produced using a rough-machining lathe, a deep-hole boring machine, a horizontal boring machine and finally a finish-machining lathe; inaccuracy in the estimating at each stage of the production route compounds scheduling problems. Resulting *queuing* problems (bottlenecks at particular operations or 'down-time' at down-stream machining stations), can be very damaging to business performance and ultimately profitability. Inaccurate estimates of machine time result in inefficiency (manifested in either excessive costs or lost revenue) with the consequence of failure to optimize the allocation of resources, reducing the organisation's potential to maximise profits. With many orders running concurrently, organisation and communication are key issues and effective resource planning is essential. However, before effective planning can take place, confidence and reliability must be achieved in the estimating process. Hence, if successful this research will be seen to make a significant contribution to improving operating performance.

It is recognized that the situation is made difficult due to the company's chosen speciality - small scale production. Whilst low volume niche business creates a diverse customer base, it restricts the company from benefiting from economies of scale and builds complexity into estimating and resource planning requirements. The product mix comprises (i) 'repeat' orders, often in small production batches e.g. quantities of 5 or 10, and (ii) random 'specials', which are typically small quantities but high gross profit margins. However, regardless of which particular product is being produced, the company fails to learn from either the successes or failures in historical performance. There are no demonstrable processes for performance reviews of *actual* times versus estimated times, and certainly no control mechanism for updating production route information to reflect current performance levels or the effect of processing trends.

'Improved accuracy' is considered to be the key measure of process performance when evaluating whether the project is successful. The company also recognized that customers increasingly requested faster response times to their enquiries, thus improving the ability to react to customers in a timely and dependable manner is considered a strategic objective.

Two experienced estimators are employed by the case study company but these key individuals are approaching retirement. A strategic review of the provision of workplace training, undertaken in December 2004, identified the need to reappraise company policy towards workplace learning to ensure continuity in the estimating function. The case study company's traditional apprenticeship model of learning was compared with alternative concepts of organizational learning (notably knowledge management). The existing estimating process raises particular concerns owing to its reliance on human expertise and knowledge (both explicit and tacit), managing this knowledge more effectively is crucial for a successful future, hence the case study company's sponsorship of the project that is the subject of this thesis. Knowledge considered valuable for future estimating should be captured and stored independently of the human estimator in order to reduce the risk from dependence on human expertise. Therefore the viability of a technological solution which reduces the risk from reliance on individual experts is investigated.

A survey of small sized engineering machine shops (Dimmock, 2007) indicated a tendency for this type of organisation to rely on human expertise in estimating, and reluctance to engage with ICT as a potential alternative to the manual approach to estimating. The survey found that the estimating function is predominately a part-time role, hence estimating knowledge is only one of the demands on the individual's cognition. Whilst a significant proportion of the sample considered the manual approach satisfactory, the inherent risk from relying on one key individual's expertise (or a small number of experts), the likelihood of inaccuracy and potential for human error were also recognised.

Engineering cost estimating (Cazzaniga, 2003) is an activity using technical information about product design and production processes which utilises an engineer's judgement and experience (applying scientific principles and techniques) for estimation, cost control and profitability. The importance of generating good estimates cannot be over-emphasised (Daschbach and Apgar, 1998; Rush and Roy, 2000; Rush and Roy, 2001).

Manual methods of estimating are laborious and time consuming, rely on individual expertise and compound the risk of human error. Manual estimating practices often require a breadth of knowledge across many business functions, which creates significant levels of demand on the knowledge structures of expert estimators. When detailed and accurate estimates are required the implementation of a cost estimating system can help to satisfy a company's requirements (Olaopa, 2003). Progress has been made in addressing these problems through the use of decision support systems (Souchoroukov *et al*, 2002; Kingsman and de Souza, 1997; Bertens, 1997). Whilst it can be difficult to reliably predict manufacturing times owing to complexity of business processes and variance in individual productivity, using information technology to help extract information from empirical data can shorten the time taken to produce estimates significantly. In addressing the issue of decision support, an important factor to be considered was that compared with larger organisations, SMEs often have less opportunity for investment of time, expertise and capital in development of information systems to support effective decision making.

For effective decision making, estimators require knowledge which relates to processes, suppliers, risk, materials, costing process, product, company strategy, design, market trends and customer contact (Mishra *et al*, 2002). Developers of intelligent systems face considerable challenges when aiming to mimic this extensive human expertise because the experience and tacit knowledge of cost estimators proves challenging to replicate. Knowledge-based systems can seek to reduce reliance on human expertise but are unlikely to replace it; hence there are both potential benefits and risks involved in the implementation of 'expert systems' for decision support (Darlington, 2000). The potential benefits include knowledge retention, knowledge distribution, enriched training, competitive advantage and cost reductions. However, the risk with a systems approach is the potential loss of human expertise; in that humans can be creative, flexible, easily adaptable, possess common sense and retain exceptional capabilities for learning.

This research considered the application of a knowledge-based decision support system, adopting a hybrid approach of feature-based and case-based costing methods to derive estimates. The system contains a repository of (i) past case histories including real machining times, and (ii) algorithms that codify estimating knowledge elicited from existing manual estimating practice. These algorithms are applied to the costing of similar products, mimicking the behaviour of the human expert by utilising the potential similarity between empirical information and new requirements (Kandal *et al*, 2001).

Understanding process integration was an important aspect this interdisciplinary, cross-boundary research, which can be seen to match many to the drivers of knowledge management (Open, 2002):

- Wealth from knowledge
- Knowledge interdependence
- Technology
- Human resources
- Organizational learning
- Innovation

The knowledge-based view (KBV) of the firm (Grant, 1996) considers that *knowledge* is the principle source of value in an organisation and the organisation's most strategic asset (Prahalad and Hamel, 1990; Spender, 1996). The core capabilities and competitiveness of SME machine shops stem from the knowledge and expertise gained through experience of producing machined parts in their own specific environment.

The key assumptions of the KBV (Grant, 1996) are:

- individuals and knowledge conversion ['the process of converting tacit know-how into explicit knowledge (Nonaka and Toyama, 2003)'] are the source of knowledge creation;
- efficiency in knowledge production requires that individuals specialise in a particular area of knowledge;
- the essential task of the organisation is knowledge integration.

The differing core competences of individual SME machine shops reflect the diversity within such businesses. Whilst these strengths help a business to differentiate from their competition, such unique organisational characteristics require knowledge management processes which address the specific needs of the individual company; i.e. there are no 'off-the-shelf' solutions. This thesis describes the development of a process which effectively manages manufacturing knowledge, and application software that can be tailored to meet the specific requirements of individual SME machine shops. This process method captures both implicit and explicit resources; creating a tangible asset which can contribute to a sustainable competitive advantage, avoid expensive mistakes, assist employee development and improve customer service (Smith and Irving, 1997). Effective management of both estimating and process performance knowledge is a highly desired strategic capability, creating valuable information for effective future decision making in estimating.

To react quickly to changes in market conditions, organisations need to work closely with their customers and demonstrate agility in their operations. To deliver improved performance all organisational levels have to be much better informed, more skilled and more adaptable. The knowledge structures of individuals, quality of information and provision of sufficient time in which to make judgements, are vital elements of effective decision making. A critical challenge is the problem of information overload (Sparrow, 2000) and the potential risks and errors it generates by overburdening individuals. Much of the information within organisations is problematic: either poor quality, ambiguous or quickly redundant. Making sense of problematic data not only wastes time but at a personal level it leads to feelings of inability to cope, inadequacy of knowledge and increased stress (Weick, 1995). Managing the quantity of information and quality of information processing has become a key strategic management skill.

Organisations have to recognise that everyone has cognitive limits, and where necessary implement processes for managing knowledge and organisational learning which strengthen their strategic assets. In organisations where the management of knowledge is closely linked with their value chain it is important that learning is encouraged within the organisation, this ensures key activities are not wholly dependent on specific individuals. Such dependence is a risk as an individual may be taken ill, decide to retire or leave the organisation to progress their career elsewhere.

1.3 Justification

In considering the justification for this research, it was important to focus on the key stakeholder expectations from the case study company's perspective, which are ranked by order of importance below.

Customer expectations are the primary consideration:

(i) product must meet or exceed quality requirements;

(ii) pricing must be competitive and

(iii) delivery of service must be reliable.

Next, the expectations of the parent:

(iv) effective participation in the world-wide sales strategy;

(v) improving net profitability and

(vi) providing evidence of business growth and development.

Finally, further expectations from within the case study company:

(vii) increase market share;

(viii) improve manufacturing efficiency and reduce costs and

(ix) ensure continuity of operations, when faced with an aging workforce.

The decline in UK manufacturing over the recent years has impacted on the company. With decreasing opportunities in many of the core material markets, the company recognizes the importance of developing other aspects of their product mix, specifically their niche manufacturing lines. The case study company have in recent years adopted a mix of growth strategies including limited diversification and horizontal integration through acquisition.

The *product proposition*, providing a service which integrates all aspects of production from steelmaking to machining of the finished products, is a significant differentiator from their competitors. Evaluation of the external environment in these 'niche market' sectors, using the 'Five Forces' model (Porter, 1985), suggests these markets are not attractive to new entrants, particularly as high sunk costs act as a barrier to entry. Many of the case study company's customers have standard design specifications and are traditionally slow to take up new materials, hence there is less of a threat from substitution. The bargaining power of both customers and suppliers are comparable, few customers/few suppliers and both risks and costs associated with 'switching'; driving competitive rivalry within the industry. However, the core competencies behind the case study company's strategy of related limited diversification are not easily imitable and therefore remain source of sustainable advantage. Volderba (1998) observed that 'organisations need to be able to adapt while remaining stable enough to exploit any changes made', the case study company need dynamic capabilities in order to gain strategic flexibility and respond to change.

Whilst the UK company benefits from corporate parenting in terms of corporate functions and services; development initiatives; additional finance and transfer of technology and core competencies; they also experience the practical everyday problems of comparable SME machining enterprises:

- Competitive markets.
- Balancing production resources between frequent low margin orders and scarce, yet more desirable, higher margin orders.
- Satisfying production requirements through flexible utilisation of limited resources.
- Limited scope for investment.
- Difficulties in managing the supply of labour – adjusting production activity to sudden hikes in demand; and the scarcity of skilled labour when seeking to fill vacancies.

One view of market strategy is based upon the competitiveness factors - quality, diversity and cost. 'Niche' firms such as the case study company focus on quality and diversity, accepting the associated higher costs. However, if costs can be reduced through process innovation the potential exists for improved financial performance. This research aims to provide an innovative process for estimating; reducing the time and cost of producing a quotation, managing risk and helping to eliminate costly mistakes.

The scope and scale of the machining enquiries received vary considerably; on the one hand sub-contract drilling can be taken on at short notice, with for example a 3 day turnaround, when in comparison orders for multiple continuous caster rolls which could take 6 months to complete. The significance of estimating production times and costs (and subsequent production scheduling) is increased when planning and controlling complex combinations of production activities, typical examples of which are shown in Figure 2. These factors demand that an accurate and dependable estimating process is operated.

The perception of being both competitive and reliable is essential for the survival of any manufacturing or engineering organisation. Larger organisations are practiced in the use of business improvement methodologies and information technology to produce organisational excellence, usually supported by significant investment of capital and resources.

Figure 2. Typical products and production activities at the case study company

The project at the case study company aimed to establish an approach to estimating which enables the company to address the following challenges they face:

- An accurate, dependable estimating process is critical to the competitiveness of the organisation.
- Improving the ability to react to customer enquiries in a more timely and dependable manner would be a competitive advantage.
- Dependence on human expertise in the estimating process is a risk.
- Constraints on resources mean there is little opportunity for investment of time, expertise and capital in development of an information system.

A number of potential routes to a solution to the problem were considered before a commitment was made to the project which is the subject of this thesis. Each of these options was evaluated against the strengths, weaknesses, opportunities and threats of that particular potential solution. It became clear, even before a specific approach was adopted, that particular management themes were common to all of the options being considered:

- *Knowledge management*: ‘Knowledge comes in two basic varieties: tacit and explicit, also known as informal/uncodified and formal/codified. Explicit knowledge comes in the form of books and documents, white papers, databases, and policy manuals. The tacit/uncodified variety, in contrast, can be found in the heads of employees, the experience of customers, the memories of past vendors. Tacit knowledge is hard to catalogue, highly experiential, difficult to document in detail, ephemeral and transitory. Both types of knowledge are important (O’Dell and Grayson, 1998).’
- *Organisational learning*: For organizations, and in particular workplaces, ‘learning is not only identified as possible and perhaps desirable, but is constructed as an important element of success and survival. It is increasingly suggested that learning should be placed at the centre of activities within these settings. (Open, 2002b)’
- *Change management*: ‘Change is the replacing of a state of affairs that exists now with something different. This change happens over time and the future will not look like the past. Change management involves the conscious attempt to control, or at least to influence, the change that is going to happen to your organization. (Elearn, 2005).’

The options identified and evaluated as potential solutions for a future estimating strategy were:

(i) Continue with a manual approach to estimating, employing or retraining an individual(s) to work alongside the existing estimators until their retirement: a master/apprentice approach to workplace learning and developing fully trained ‘expert’ estimators.

(ii) Controversially, eliminate the cost estimating function and rely on a commercial decision maker to compete for the work based upon adopting intuitive pricing / becoming a ‘price taker’ and winning business based upon close relationships with customers.

(iii) Invest significant resources in modern machining technologies: upgrading or replacing machine tools with CNC equipment, installing CAD facilities with engineers and retraining machine operators.

Developing a model for cost estimating and production control based upon Deutsche Edelstahlwerke's machining facility.

(iv) Implement a decision support system to enable non-experts and novice estimators to produce accurate estimates by either:

a) A task support system based upon the use of industrial hypermedia technology (Greenough, 1999) (Tjahjono, 2003).

b) An intelligent system (Hopgood, 2001): a hybrid approach combining 'Feature-based Costing' (knowledge-based) and 'Case-based Reasoning' (computational intelligence).

In the lead up to the retirement of the case study company estimators, the assumption had always been that someone would be employed to supersede the retiring estimators in their roles. The presumption was a younger engineer would work with the existing estimators during their final year, in a master/apprentice relationship, in order that no significant change would occur in the estimating function for the future operating of the business. However, it had become apparent that simply replacing the estimators without significantly changing the estimating process, would leave the company still facing many of their current problems i.e. the company would still rely on human expertise. Persevering with a manual approach to estimating would continue to be laborious and it would be difficult to foresee any significant improvement in the accuracy of the estimates. Therefore this scenario was considered to be the final fall back point, to which plans would be adapted should no alternative approach to estimating meet the business requirements of the company.

The idea that perhaps the company did not actually need an estimator, rather estimates could be intuitively compiled by the Commercial Manager, was considered. In some circumstances, where the customer/supplier relationship was already strong, this approach could have been satisfactory as the case study company already are 'price-takers' in some instances. This is particularly relevant to work sub-contracted to the case study company from other machine shops, where a relatively accurate estimate of the processing time and cost is known to the customer. However, for new products and complete-supply enquiries from end-users, the inaccuracy of this approach compared to a more quantitative estimating method, renders this option an unrealistic, high risk strategy. There was no support for this option within the company's management and therefore the option was closed out.

Senior managers at the case study company (Hadley, 2005) (McHardy, 2005) had conceded that their operations were not at the optimal technological level, which they believed frequently hindered their competitiveness, e.g. the company does not operate CNC machine tools; utilize CAD technologies or use any automated estimating software. A detailed cost/benefit analysis (Dimmock and Dumpelmann, 2008) on the requirements for transition to a fully CNC machining facility with a CAD department (comparable with the Deutsche Edelstahlwerke facilities at Witten and Krefeld in Germany – but on a significantly smaller scale), demonstrated an unacceptable *payback period* (PP). Therefore a strategic decision was made at Management Board level not to invest in significant enhancements to machine tool operation or CAD technical support for estimating or programming purposes. This decision signalled that any solution to the problem at the case study company would need to demonstrate a likely PP within two years of implementation to be considered worth pursuing. Hence, a low cost technology solution would be highly desirable.

Having ruled out options i, ii, and iii; the proposal which was perceived to represent the best potential solution was option iv, a project to develop a decision support system. All key stakeholders in the research considered that significant process improvements could evolve from a project which aimed to:

(i) Improve upon existing practice through incremental development.

(ii) Bridge the knowledge gap between predominately manual approaches to estimating and high-end, sophisticated computational or CAD driven approaches.

1.4 Initial approach to managing the project

In order to construct a robust project plan for the research described in this thesis, it was important that the project was considered from multiple perspectives. The specific areas of research and management disciplines which were reviewed to identify useful theories, methods and practices were:

- Systems practice
- Change management
- Knowledge management
- Lifelong learning
- Intelligent systems
- Cost estimating

A review of these disciplines identified both whole and partial frameworks, models and strategies, which proved insightful in developing a 'model of planned change' to address the specific situation of interest defined in this research.

A 'general model of planned change' Figure 3, provided the initial template upon which the research methodology elaborated. Each stage of this model was developed to further levels of decomposition, where complimentary and sometimes concurrent methods, tools and techniques were overlain to produce the robust model described in Figure 4.

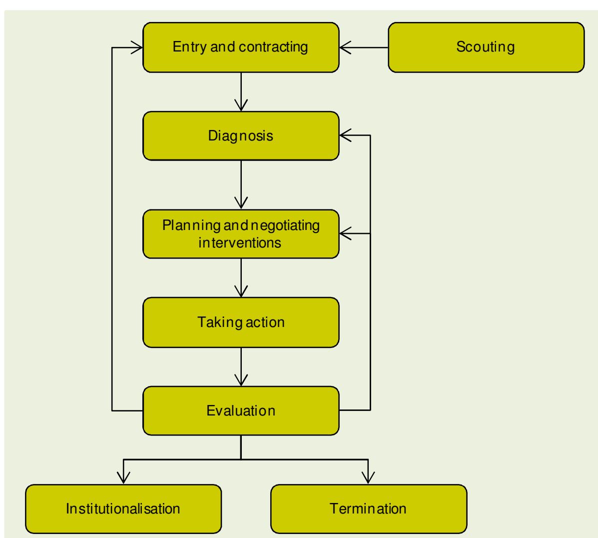


Figure 3. General model of planned change (based on Kolb and Frohmann, 1970 and Neumann, 1997

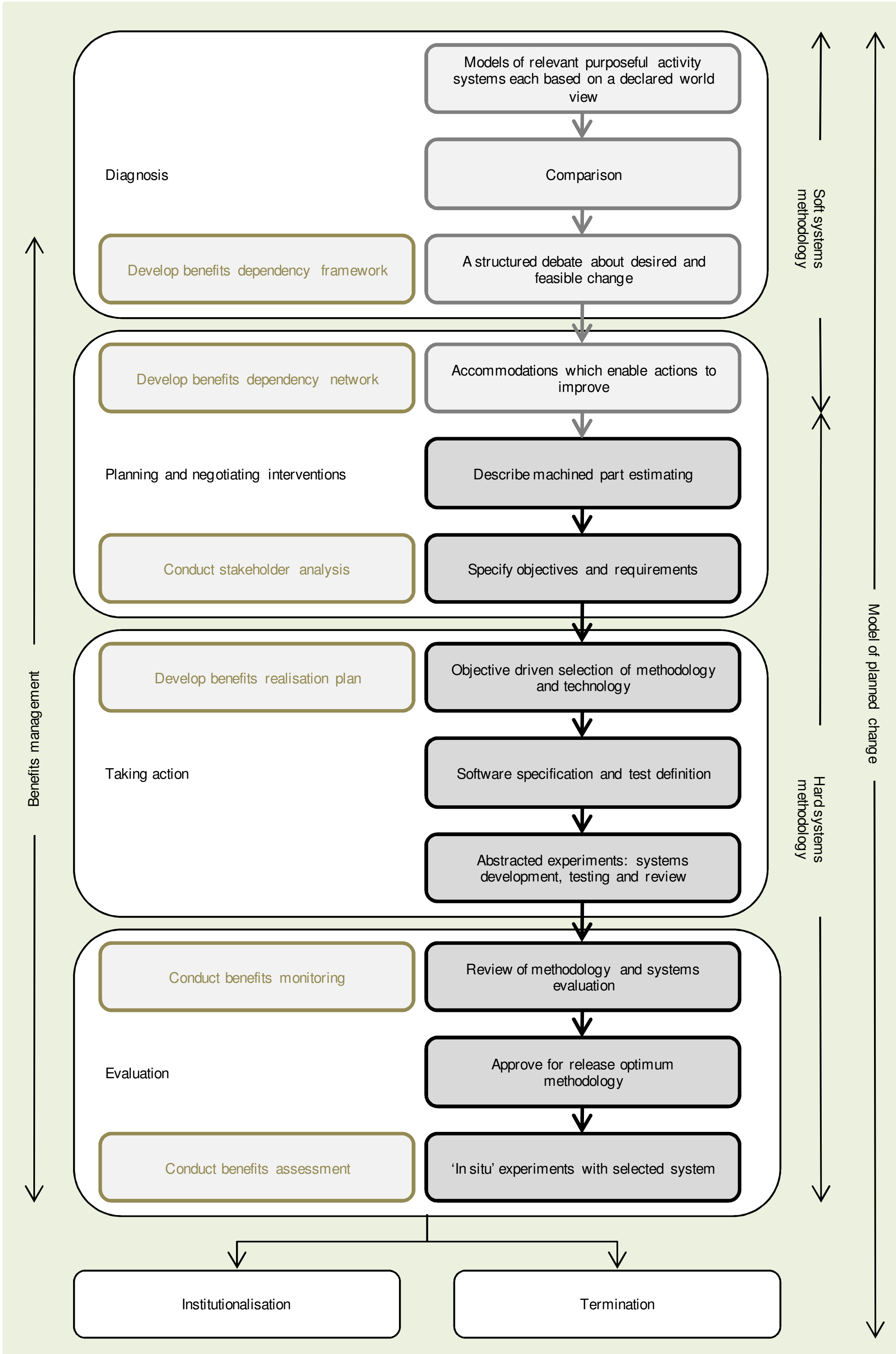


Figure 4. The developed 'model of planned change' representing the project plan

The principle influences on the development of the project plan shown in Figure 4, are: Soft Systems Methodology (Checkland and Scholes, 1990); Hard Systems Methodology (Open, 2000) and Benefits Management (Hotchkiss, 2006).

Soft Systems Methodology (Checkland and Scholes, 1990), Figure 5, was to be applied as an interpretive 'process method' during the diagnosis stage of the research. This enables analysis of the complex 'system-of-inquiry' (multiple perspectives and emotional complexity), to determine the existing estimating practices and generate potential routes to improvement; focusing on the discourses:

(i) learning opportunities, operating within a

(ii) system of provision, which is influenced by

(iii) culture and power in the community of practice.

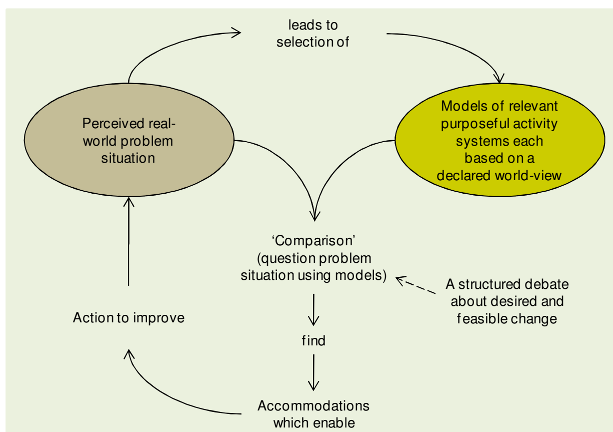


Figure 5. An activity sequence diagram of the Soft Systems Method (Checkland and Scholes, 1990).

Following the diagnosis stage, the Hard Systems Method (Open, 2000) Figure 6, is applied across the subsequent stages *planning and negotiating interventions*, *taking action* and *evaluation*, planning the step-by-step research phases and control mechanisms, ensuring so far as possible an effective outcome. Whereas Soft Systems Methods are very useful in making sense of an apparently complex, unstructured organizational situation; determining what is going on, and what it might be effective to do about. The Hard System Method can be useful, once a route to improvement is identified, for measuring and improving the structure's operational efficiency.

Once it became apparent that information technology would feature significantly in the research, a process for monitoring IT system development was included in the project planning. The approach of applying benefits management to IT projects, Figure 7 (Hotchkiss, 2006), is used to quantify total project benefits; expressed as monetary benefits, tangible benefits and intangible benefits.

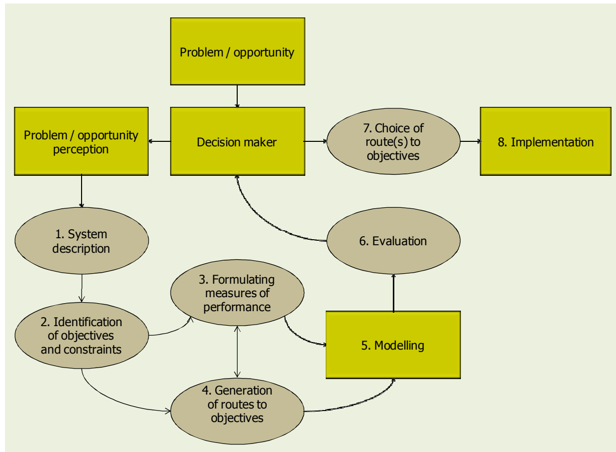


Figure 6. An activity sequence diagram of the Hard Systems Method in systems terms (adapted from Open, 2000)

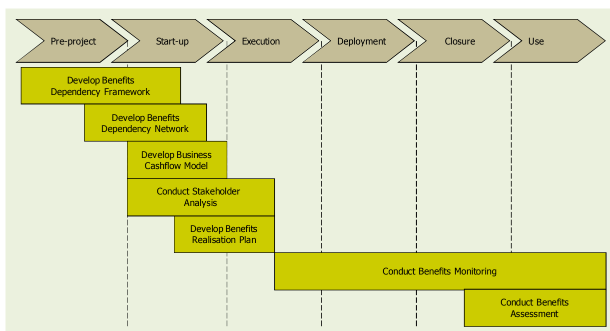


Figure 7. An activity sequence diagram for applying benefits management to IT Projects (Hotchkiss, 2006)

Engineering Doctorate research addresses a research problem of direct relevance to the industrial sponsor; it is expected that the work conducted will be multi-disciplinary in nature and demonstrate understanding of the business and commercial implications of the research work. Therefore, the dominant research method will be that of the *case study*. Case studies typically deal with real management situations and are carried out in close interaction with practitioners, seeking to study phenomena in their context.

1.5 Delimitation of scope

This research is concerned with very specific criteria of production capabilities, which influences the potential generic application of the methodology which has been developed. Whilst the broad system of interest - machined part estimating, is vast, with a significant body of knowledge supporting the application of a large variety of techniques and technologies; the particular situation of interest encompassed by this work, discussed in Section 1.2, is far less saturated with prior work.

This thesis describes the project at the case study company to develop a practical method for machined part estimating in SMEs operating manually controlled, conventionally operated, large-scale machine tool equipment.

The estimating method described in this thesis was therefore not intended for application in high volume manufacturing environments, or those producing extremely intricate, close tolerance components, or within organizations which have already progressed to computer numerical controlled machine tool operation.

1.6 Outline of thesis

This thesis is written in six chapters. The first, Chapter 1, is an introduction to the research leading to the development of feature-driven case-based estimating at the case study company. This chapter introduces the background to the research, indicating the area of research in terms of both its practical sub-problem and theoretical sub-problem. The significance of the research problem is established, and the aims and objectives of the investigation are introduced. Included in this chapter is a brief statement of the methodology used to address the research problem.

Chapter 2 develops the definition of the research further. It aims to identify the practical sub-problem, *machined-part estimating in the SME environment*, through analysis of relevant published work and demonstrates how the problem applies to the particular circumstances at the case study company. This chapter also provides an analysis of literature relevant to the theoretical sub-problem. The chapter provides a critical analysis of relevant bodies of literature, clearly describing how this research fits into previous work in the topic; and justifies the research questions addressed by the methodology described in Chapter 3.

The aims of Chapter 3 are to explain the methodology chosen for the research, explaining two levels of methodological decision: the strategic and the tactical. The chapter discusses the choices that were considered and explains why the particular research method was chosen in preference to others. This chapter sets out a clear explanation of the research tactics which were adopted and how the research was undertaken in an ethical manner.

Chapter 4 describes the application development for the METALmpe decision support system. The detailed knowledge elicited from the manual approach to estimating is examined and the process by which it is codified within METALmpe is discussed. A case study of estimating practice in the context of a large size manufacturer is discussed, and implications for the development of METALmpe are reviewed. This chapter provides a clear impression of how the *feature-driven case-based estimating* process functions, demonstrating the bespoke METALmpe software application at the case study company.

Chapter 5 presents the findings obtained as a result of the application of the methodology explained in Chapter 3 and the analysis of results in relation to the research questions defined in Chapter 2. This chapter provides the evidence obtained through the gathering process and the subsequent analysis of the findings it produced. There are two distinct aspects to the analysis: primarily the application of METALmpe at the case study company; and secondary, whether feature-driven case-based machined part estimating is a generic solution for SMEs.

Chapter 6 provides the conclusions made in respect to the research questions defined in Chapter 2. The chapter responds to the research questions, noting any limitations that should be placed on the conclusions and the implications for future researchers. This chapter also sets out the original contribution(s) to knowledge made by the thesis to the development of the cost estimating discipline in an SME environment.

1.7 Summary

This chapter provides an introduction to the case study company and describes the business conditions which lead to the commissioning of this research. Although part of a large international Group, the machining department at Oldbury displays many of the characteristics and faces many of the same problems associated with SMEs within this specialist business sector. The deliverable from this research needs to be a low cost solution, which integrates seamlessly the relevant business processes and does not demand significant additional human or financial resources.

An explanation of the practical research problem is presented, describing the need to negate risks arising from the company's reliance on key individuals, whilst at the same time improving the efficiency of the estimating function. Theoretical discussion is introduced, asserting the relevance of knowledge management disciplines to the situation of interest at the case study company, identifying the potential benefits from using an intelligent information system approach for decision support.

Once the significance of the research problem is established, justification is provided for development of METALmpe application software, with its aims to:

- reduce the time taken to produce estimates
- improve the reliability of the estimating process
- reduce reliance on human expertise
- improve the quality of information processing
- support and enhance opportunities for learning in the workplace

Included in this chapter is a brief statement of the project plan used to address the research problem, which is presented in a 'model of planned change' (Figure. 4). The project plan incorporates aspects of systems practice, change management, knowledge management and appropriate research methods, which are considered necessary to conduct rigorous research.

Chapter 2 Literature Review

2.1 Introduction to the literature

This Chapter introduces theoretical discussion through the critical review of literature relevant to the research problem. In the section headed 'Engineering cost estimating', the importance of accurate estimating in the business context is discussed. The role of the estimator is clarified and attention is drawn to the depth and breadth of knowledge required by the human estimator in order for them to develop their expertise. Specific estimating techniques and methodologies are summarised, with preferred techniques identified.

Section 2.2.1 'Machined part estimating in the SME environment' reviews literature which defines what an SME is, and how SMEs can make strategic decisions based upon their resources to lever competitive advantage. The management of technology and investment in SMEs is discussed, accompanied by supporting evidence from credible surveys.

The human factors relating to estimating and decision making in SMEs are highlighted in section 2.3, particularly the importance of human interaction and its place in the knowledge-based view of the firm. This section considers strategic decision making and the notion of power in organisations.

Section 2.4 addresses learning in organizations, discussing different perspectives on what learning is, and justifies learning in the context of a knowledge-based economy. Different approaches to adult learning are examined, in particular those based on experiential learning and reflection. An alternative approach for workplace learning is considered in knowledge management, with its focus on the outcomes of the learning process rather than the process of learning. The core themes of knowledge management are explained, specifically considering KM practice in SMEs. Managing information and knowledge technologies are discussed, with emphasis placed on managing intangible assets in an organisational context.

From the early stages of the research described in this thesis, there was an assumption that information and communication technology would be an influence in the problem resolution at the case study company. Section 2.5 provides an overview of *strategic information systems*, discussing the strengths and weaknesses of ‘knowledge-based systems’ (sometimes termed ‘expert’ systems) and hypermedia technology is considered as a potential solution.

Section 2.6 summarises the aim and objectives of the research, with research questions developed in section 2.6.2, and the early considerations on where this thesis might make an original contribution to knowledge are outlined.

2.2 Engineering cost estimating

'If it really does take two minutes, then we want to pay for two minutes for labour, burden, machine and profit. That is fair. It's the other dollar that might get added on – the safety factor that we don't want to pay (Jim Tormey, 2004).'

This sentiment is recognized at the case study company who through improving their estimating processes, seek to develop a better understanding of the costs of production, thus enabling 'smarter' decision making when quoting customers. In competitive markets there is no margin for building in a 'safety factor', a company must be satisfied that their estimating is a fair representation of production requirements (and the cost of all necessary activities); otherwise they risk losing the order to a competitor due to over-estimating either the price and/or the lead time. 'The quotation process tightly links the manufacturer and its suppliers and customers on a supply chain. An excellent record of successful quotes not only benefits trading partners, but also positions the manufacturer on the market in terms of its responsiveness, customer service, efficiency and competitive pricing (Buzby et al 2002)'. These authors suggest that the principles of lean manufacturing can be applied to the administrative function of the quotation process, and propose 'that electronic solutions are the best remedies for streamlining the process to reduce cycle time' – which they consider to be 'strategically and economically important'. To maximise both effectiveness and efficiency, workflow should be synchronised through successive value-adding processes without interruption. In terms of machine part production this means that an accurate estimate of machining time at upstream operations is critical to effective scheduling. It is envisaged that through the use of computerised decision support the quotation/estimating process will benefit from:

- Reduction in cycle time to produce quotes
- Elimination of tasks in the quotation process
- Efficient collation of shop floor data for accurate labour costing
- Reduction of paper use via electronic quoting
- Improved coordination with outside vendors

Roy (2003) identifies two major areas of research in cost engineering, which resonate with the estimating project at the case study company:

‘(i) integrating the cost engineering capability with the ERP environment so that data can be shared effectively; and

(ii) capture and reuse of human expertise in cost engineering for performance improvement.’

Whilst it is recognised that the *cost estimating* process at the case study company does not have the complexity experienced in advanced *cost engineering* applications, these same two areas of research apply. In fact, the need for simpler and cheaper cost engineering software for SMEs is recognised by Roy (2003).

The Society of Cost Estimating and Analysis defines cost estimating as ‘the art of approximating the probable cost or value of something based on information available at the time (SCEA, 2007).’ NASA take the view that cost estimating is ‘part science, part art’ – whilst there are well-defined processes with the discipline, ‘there is also a subjective element to cost estimating that makes the discipline an art (NASA, 2004).’ There are many theories and approaches to estimating, but no fully reliable way for predicting time and effort due to the complexity of business processes and the dramatic variance in individual productivity (Wallace, 2002). However, whilst the task of estimating is difficult, the importance of accuracy in cost estimation is highlighted by Daschbach and Apgar (1988), referring to the ‘Freiman Curve’ (Freiman, 1983) to illustrate the relevance of realistic estimates (Figure 8). ‘Underestimates lead to disaster, the greater the underestimate the greater the actual expense. Overestimates become self-filling prophecies, the greater the overestimate, the greater the final cost (Daschbach and Apgar, 1988).’

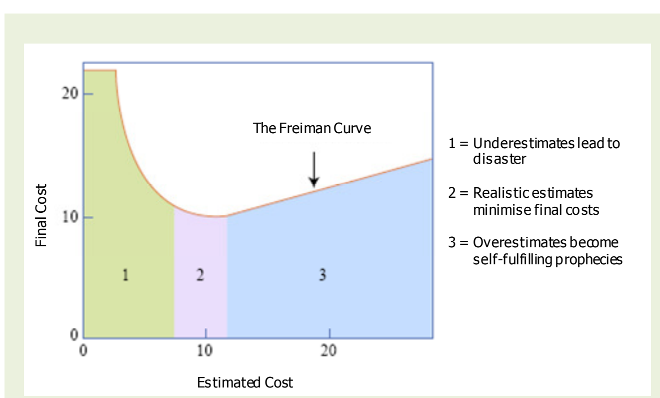


Figure 8. The Freiman Curve (Freiman, 1983)

The following tables (Table 1 and Table 2) provide benchmark levels of accuracy ranges, classified in relation to the purpose of the estimate.

	Primary Characteristic	Secondary Characteristic			
ESTIMATE CLASS	LEVEL PROJECT DEFINITION Expressed as % of complete definition	END USAGE Typical purpose of estimate	METHODOLOGY Typical estimating method	EXPECTED ACCURACY RANGE Typical variation in low and high ranges (a)	PREPARATION EFFORT Typical degree of effort relative to least cost index of 1 (b)
Class 5	0% to 2%	Screening or feasibility	Capacity factored, parametric models, judgement or analogy	4 to 20	1
Class 4	1% to 15%	Concept study or feasibility	Equipment factored or parametric models	3 to 20	2 to 4
Class 3	10% to 40%	Budget, authorisation, or control	Semi-detailed unit costs with assembly level line items	2 to 6	3 to 10
Class 2	30% to 70%	Control of bid / tender	Detailed unit cost with forced detailed take-off	1 to 3	4 to 20
Class 1	50% to 100%	Check estimate bid / tender	Detailed unit cost with detailed take-off	1	5 to 100

Notes:
(a) If the range index value of '1' represents +10/-5%, then an index value of 10 represents +100/-50%.
(b) If the cost index value of '1' represents 0.005% of project costs, then an index value of 100 represents 0.5%
(a)+(b) are relative values to what is named 1.

Table 1. Generic Estimate Classification Matrix (AACE International, 2004).

AACE Classification Standard	AACE (2004)	ANSI Standard z94.0	ACostE	Creese and Moore (1990)
Class 5	L: -20% to -50% H: +30% to +100%	Order of Magnitude Estimate -30% to +50%	Order of Magnitude Estimate Class IV -30% to +30-%	Early planning and conceptual design stage -30% to + 50%
Class 4	L: -15% to -30% H: +20% to +50%	Budget Estimate -15% to +30%	Study Estimate Class III -20% to +30%	System design process -15% to +30%
Class 3	L: -10% to -15% H: +10% to +30%		Budget Estimate Class II -10% to +10%	
Class 2	L: -5% to -15% H: +5% to +20%	Definitive Estimate -5% to +15%	Definitive Estimate Class I -5% to +5%	Detailed design stage -5% to +15%
Class 1	L: -3% to -10% H: +3% to +15%			

Table 2. Table with accuracies from different sources (Planas, 2006).

This research investigates estimating practice from the perspective of the engineering cost estimator, faced by the challenges of estimating costs for commercial orders. Cazzaniga (2003) defines engineering cost estimating as ‘an activity using technical information about product design, material, production processes and utilises engineer’s judgement and experience, to apply scientific principles and techniques for estimation, cost control and profitability.’

In his study of the cost estimating processes in an engineering company, Bertens (1997) investigated whether ICT could be used to minimise the workload and improve efficiency. The estimating procedure studied by Bertens closely matched that of the case study company, particularly in that estimates were produced by hand. Further significantly similarities can be seen - there was no documented procedure for estimating and there was a reliance on time-served estimators with little ‘back up’ if they became ill or left the company. Other specific problems encountered included the length of time to complete estimates; risk of human error; time taken tracking errors; document storage and traceability. Bertens concluded that ICT solutions which offer good usability and reliability would decrease workload and improve the quotation procedure, enabling efficiency improvement and improving customer relationships. There has been further work in cost estimating systems and process planning for metal cutting businesses (Cakir and Cavdar, 2006) (Yongtaoa and Jingying, 2006); but the problem situation at the case study company remains unanswered.

Some of the problems with estimating have been addressed through the use of decision support systems (Souchoroukov *et a*l, 2002) (Kingsman and Artur de Souza, 1997) (Kingsman, Anderson, Mercer and De Souza, 1994). However, the issue of experience and implicit knowledge of cost estimators, their *expert* knowledge, has proven challenging to replicate. Intelligent systems can seek to reduce reliance on expert judgement but are unlikely to replace it (Stensrud and Myrtveit, 1998). Expert judgement is used with all estimating techniques (Rush and Roy, 2001a), therefore it is a fair assumption that some degree of evaluation will still be required by the human estimator in validating estimates, regardless of the cost model. ‘Cost estimators have to use their judgement concerning the validity of calibrated data; thus it is the cost estimator and their expertise that ultimately controls the output of any cost model (Rush and Roy, 2001a).’

It is the depth and breadth of knowledge and skills required by estimators (Figure 9) which makes replication by technology difficult, particularly where tacit knowledge or an intuitive input is required.

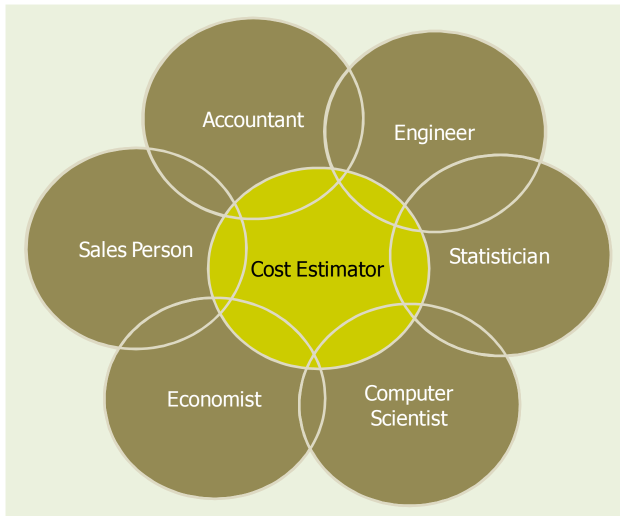


Figure 9. Skills and knowledge of cost estimating (adapted from Rush and Roy, 2001a)

Mishra *et al* (2002) and Cazzaniga (2003) point to the basic areas of cost knowledge which are the most significant, detailed in Figure 10.

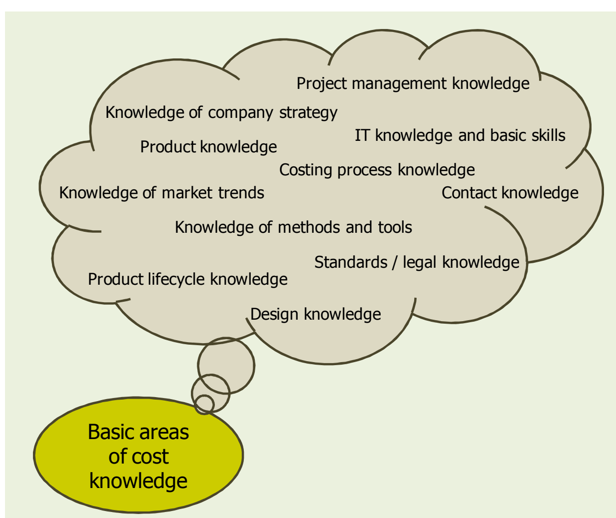


Figure 10. Basic areas of cost knowledge (adapted from Mishra *et al*, 2002; and Cazzaniga, 2003)

The basic disciplines involved in cost estimating cover both commercial and engineering areas of expertise (Roy, 2003). These *include commercial processes*:

engineering, testing, tooling, manufacturing, procurement, logistic support, and management; and *engineering activities* requiring detailed knowledge about the product, the manufacturing process and manufacturing capability of the organisation. It was from these basic areas where Cazzaniga believed 'organisations would derive their most basic cost estimating training requirements.' Examples of the knowledge domains identified as being required by the engineering cost estimator (considered relevant to the project at the case study company), are shown Figure 11.

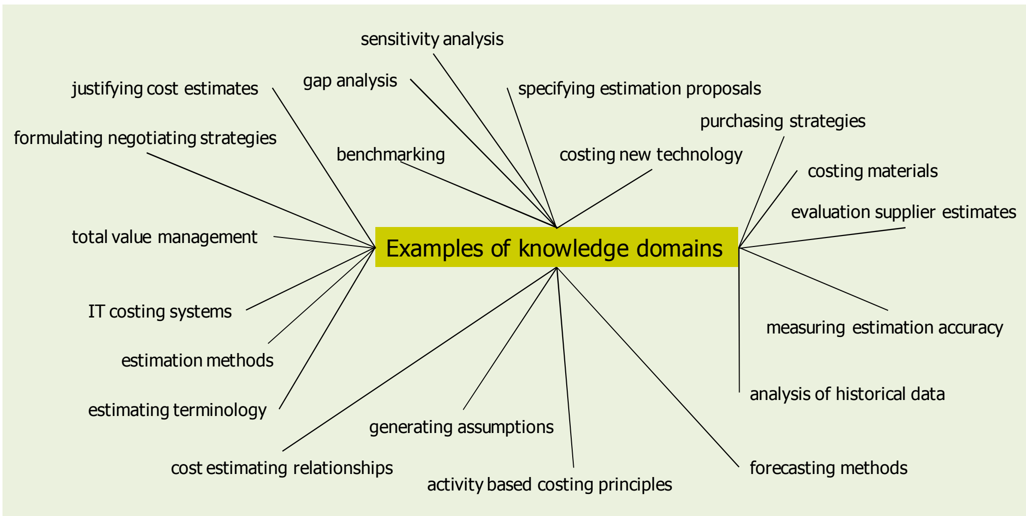


Figure 11. Examples of knowledge domains (adapted from Cazzaniga, 2003)

Considering the extent of the skills and knowledge required to be a successful estimator, it could reasonably be assumed (from outside the community of practice) that appropriate training provision would be relatively easily accessible. However, Roy (2003) suggests that 'internal communication within the cost engineering community is very weak, especially between commercial people and engineers' and that there is 'no formal education or effective training available for cost engineering.' It takes many years of experience to attain competence in estimating, which makes it difficult for novices to understand an estimate if they can not comprehend the decision making process, rationale or assumptions. This research investigates the potential to use information technology to provide decision support for novice estimators, tasked with producing sufficiently accurate estimates in a relatively short period of time.

Flyvbjerg (2001) provides definitions of novice and expert behaviour. A *novice* as 'an individual who experiences a given problem and a given situation in a given task area for the first time, recognises facts, characteristics and rules independently of the context. *Expert* behaviour is intuitive, holistic, and synchronic, understood in the way that a given situation releases a picture of problem, goal, plan, direction and action in one instant and with no division into phases (Flyvbjerg, 2001).'

Lavdas (2008) summarises the main problems faced by novice estimators:

- 'Lack of knowledge regarding the domain.'
- 'Experts are often busy. Thus, techniques and methods should aid novices in becoming less dependent on experts during the development of a cost estimate.'
- 'Limited time for developing a cost estimate due to the nature of a short CE lifecycle (Schehr, 1989).'
- 'Lack of structured methods to follow while developing a cost estimate (Joumier, 2006); to guide, and aid, them through the various subjective-prone processes.'
- 'Lack of experience in being able to judge whether their cost estimate is of good quality; and what the weaknesses are.'

The extent of knowledge required in estimating clearly indicates the considerable challenge faced by the developers of intelligent systems, who aim to mimic human expertise. At the case study company the specific knowledge domains required to estimate the cost of producing *varied shape, open-die forged and machined steel forgings* include:

- Procurement of forgings
- Bandsaw cutting
- Heat treatment and testing
- In-house machining (milling, turning and boring)
- Sub-contracted activities

The case study company's primary concern is estimating the 'works cost' of a product, comprising of material and value-added operations such as heat treatment and machining. The importance of generating good estimates cannot be over-emphasized (Rush and Roy, 2000), as these costing exercises enable a further commercial decision to be made on customer pricing. This is important in terms of make-or-buy decisions; selection of process routes and critically *contract tenders* (where the problems of inaccuracies are compounded by the commitment from all parties to supply at an agreed price for an agreed timeframe). Olaopa (2003) found that where detailed and accurate estimates are required, the implementation of a cost estimating system supported by a company's existing information system can satisfy requirements. Many large enterprises have in place cost estimating software that, combined with an expert system, provides good estimates (Shehab and Abdalla, 2002). An example of such an organisation in the context of machined part estimating is Deutsche Edelstahlwerke (Appendix H). 'However SMEs cannot afford such an expensive system, but they still need a procedure that allows accurate estimates in order to be competitive (Romero Rojo *et al*, 2009).'

In order to understand the complexity of the estimating process the case study company a knowledge capture exercise was undertaken using the XPat Approach (Adesola *et al*, 2000) (Roy, 2005). This approach is used to identify the *inputs*, *processes* and *outputs* of a system-of-interest (Appendix B) and the information elicited was used to define a functional model in IDEF0 (FIPS, 1993), see Appendix B.

There are three well-recognised estimating models of cost (Asiedu and Gu, 1998): estimating by analogy; parametric estimating and activity-based costing; and numerous estimating techniques which could have been applied to the problem at the case study company. Figure 12 details a hierarchy classification of possible techniques.

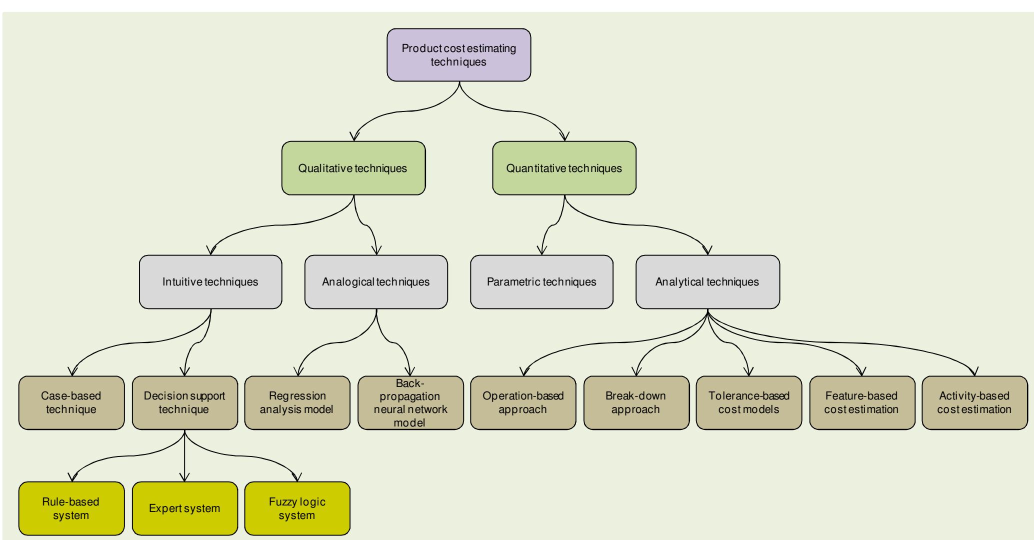


Figure 12. Detailed classifications of the cost estimating techniques (Romero, 2007; Niazi *et al*, 2006)

The techniques considered to be potential solutions for the case study company were reviewed further:

- Detailed cost estimating (Roy, 2000) (Layer *et al*, 2002):

  A 'detailed estimate' using detailed knowledge and understanding of the process involved and based upon direct labour, direct materials and overheads. Much of the information in a detailed estimate is based upon the internal times or costs based upon expected rates of work for any particular task. Detailed cost estimating is more accurate than parametric costing, expert judgement and analogy-based reasoning.

- Activity based costing (ABC)

  ABC measures both direct costs and the consumption of resources. ABC is based on the premise that activities use up assigned resources to produce products. It is a quantitative method used to measure the cost and performance of activities. ABC is a highly data intensive method and very costly, and therefore only really applicable when accuracy is critical.

- Parametric estimating (PE)

  PE requires the evaluation of historical and empirical data, with the objective of determining the links between the product characteristics and cost. PE is based on the use of cost estimating relationships (CERs) and mathematical algorithms to establish costs as a function of a products basic attributes (Bajaj *et al*, 2002) (Curran *et al*, 2004). Methods such as feature based modelling develop a direct relationship between the associated feature of a product and its cost. PE is a quicker method than both detailed cost estimating and activity based costing. PE does have limitations 'CERs are sometimes too simplistic to forecast costs. Furthermore, PE is primarily based upon statistical assumptions, which estimators should not rely upon (Roy, 2003).'

- Feature-based costing (FBC)

  FBC is a form of PE which has gained in popularity alongside developments in CAD/CAM technology. FBC is based on the belief that the same features appear in many different products, and the cost information attached to combinations of these features can be computed and used to determine product costs (Brimson, 1998). Total product cost is seen as the sum of all the costs from assignable features. 'Engineering intent can be encapsulated within features such as product functionality, performance, manufacturing processes, and behaviour characteristics (Roy, 2003).' A significant problem with FBC is that it is very difficult to define and then categorise features.

- Analogy-based reasoning / Case-based reasoning (CBR)

  Analogy-based costing compares costs according to similarities and differences with other products. This technique assumes that similar products have similar costs and can also be used when the cost for a product, with very little definition, needs to be estimated. Analogy-based reasoning (and of particular interest, CBR) has the ability of 'learning' from previous and new cases.

  CBR introduces intelligence into the analogy approach. It is used to model, store and re-use data about costing, which can later be adapted to estimate a similar case. Companies that use analogy estimates regularly may find CBR a robust, useful method (Roy, 2003). 'Case-based reasoning shows significant promise for improving the effectiveness of complex and unstructured decision making. It is a problem solving technique that is similar to the decision making process used in many real world applications (Shah *et al*, 2006).'

- Expert Judgement

  Expert judgement is used extensively during the generation of cost estimates, particularly to evaluate estimates produced by cost models, but 'very little research tackles the issues of capturing and integrating expert judgement and rationale into the cost estimating process' (Rush and Roy, 2001a). Expert judgement can provide a fast solution to an estimating problem (when a precise cost estimate is not required i.e. initial rough estimate) but the result will be highly subjective. Here there is a gap in the literature, where an opportunity exists to integrate decision support for estimating with a knowledge conversion process (converting tacit estimator 'know-how' into explicit, codified estimating rationale); which would improve the transparency of estimating and make participation by non-experts more practical.

Parekh et al (2009) discuss the challenges in managing uncertainty for cost estimates, 'uncertainty is regarded as the inherent variability around a most likely point. It is regarded as uncertainty due to its ambiguity and lack of precise knowledge towards each scenario.' Comparing two independent sources of estimates can surface uncertainties, e.g. using one qualitative technique and one quantitative technique, with expert judgement being used to validate the results where necessary.

The literature indicates that a balance needs to be struck between using the skills of an experienced estimator for theoretical predictions of time and costs and the reuse of previous production data. 'Since the direct predictions of the future may not be accurate, a decision maker can consider using some information from the past. The idea is to utilize the potential similarity between the patterns of the past and the patterns of the future (Kandel *et al*, 2001).' The research described in this thesis adopts an approach of integrating FBC, CBR and EJ in order to reduce response time, handle uncertainty and increase the accuracy and reliability of estimates.

There are similarities between FBC and the existing detailed (manual) estimating practice at the case study company. Both approaches are based upon the assumption that products comprise of associated features, and that the impact these features have on product costing is directly dependant on the number of features, and their complexity (Yang and Lin, 1997). Both manual estimating and feature-based costing processes require the ability to relate estimate requirements to existing knowledge on specific product shapes, features and finishes.

The interpretation of FBC applied to the case study company project can facilitate the codification of expert judgement and reuse it for future estimates. By creating a knowledge base of cost information (a central repository of engineering knowledge, accessible through a logical, structure interface) the product features specified, including those expressed in engineering drawings, can be transformed into a format which enables costing. 'Cost Estimating Relationships' (CERs) (Farineau *et al*, 2002) (Bajaj et al, 2003) are logic dependent and will be used to facilitate relational paths in the network. In order for this method to be effective at the case study company a complex specification of feature definitions is required, which is a limitation of FBC. 'With no universally accepted consensus on what a feature is, companies are faced with producing their own feature definitions and applying appropriate feature-based cost estimating relationships (Roy, 2003).'

Given that this research is targeted at the SME environment, a key objective is to evaluate the extent to which a low-cost decision support system can be used to guide the user through the initial feature defining processes in order to facilitate feature-based costing. The low production volumes, limited process capabilities and (relative) lack of complexity in products at the case study company, means the potential definitely exists to develop a novel hybrid FBC/CBR cost model.

2.2.1 Machined part estimating in the SME environment

The research described in this thesis is primarily based upon the project at the case study company, however the relevance of the research in the context of comparable SMEs machining organizations is also significant. For the purpose of the research, the preferred definition of an SME is shown in Table 3.

Criterion	*Micro firm*	*Small firm*	*Medium firm*
Maximum number of employees	9	49	249
Maximum annual turnover	-	7m Euros	40m Euros
Maximum annual balance sheet total	-	5m Euros	27m Euros
Maximum percentage owned by one, or jointly by several enterprise(s) not satisfying the same criteria	-	25%	25%
Note: To qualify as an SME, both the employee and the independence criteria must be satisfied, plus either the turnover or the balance sheet criteria.			

Table 3. EC definition of SMEs (DTI, 1999).

Both the criteria *turnover* and *number of employees* for the case study company meet the small firm classification. However, because the company is a wholly owned subsidiary of the Schmolz + Bickenbach Group they fail to satisfy the *independence* criteria, meaning they cannot strictly be termed an SME. Nevertheless it is important to stress (regardless of terminology / classification), the company experiences the same practical everyday problems which face many comparable SME machining companies:

- Competitive markets.
- Balancing production resources between frequent low margin orders and scarce, yet more desirable, higher margin orders.
- Satisfying production requirements through flexible utilisation of limited resources.
- Limited scope for investment.

For these reasons it is considered that the potential solutions to the problems acknowledged at the case study company are expected to be generically applicable in other (although relatively few) SMEs where the context is similar.

Research suggests that 'business unit effects' account for significantly more of the variance in company performance than 'industry effects' (Rumelt, 1991) (McGahan and Porter, 1997) (Hawawini *et al*, 2003) (Adner and Helfat, 2003), this supports the view that improving the estimating process at the case study company will be a strategic benefit. This resource-based view (RBV) of the firm can be used to explain these non-industry effects, i.e. superior performance of one firm over a competitor, or the key characteristics of companies within strategic groups. The RBV suggests the source of superior profitability is inside the case study company. It links their internal characteristics with performance. Resources that are simultaneously valuable, rare; imperfectly imitable and non-substitutable (VRIN resources) are likely to be the company's main source of sustainable competitive advantage (Barney, 1991). The concept of a firms resources being the basis of profitability (Grant, 1991) recognizes the link between knowledge resources, performance and competitive advantage.

For the case study company, 'resources' include all of the firms assets used to develop, manufacture and deliver forged steel product to their customers. Resources can be tangible (physical resources, human resources, organisational resources and financial resources) or intangible (brand, reputation, knowledge, culture). Management theorists who take the 'knowledge-based view' (KBV) (a management perspective which evolved from the RBV) of the firm argue that the true source of advantage is the knowledge that underlies company capabilities. 'Since the origin of all tangible resources lies outside the firm, it follows that competitive advantage is more likely to arise from the intangible firm-specific knowledge which enables it to add value to the incoming factors of production in a relatively unique way (Spender, 1996).' Grant (1996) describes the key assumptions of the KBV as being:

(i) individuals are the source of knowledge creation;
(ii) efficiency in knowledge production requires that individuals specialise in a particular area of knowledge; and
(iii) the essential task of the organisation is knowledge integration, i.e. to co-ordinate the efforts of specialists.

Sources of competitive advantage can be identified (depending on circumstances) by correctly analysing internal skills / capabilities and internal / external knowledge-based networks; in order to aspire to greater levels of organizational learning and flexibility. The process of managing organizational change and effectively introducing of new ways of working can strengthen the firm's longer-term competitive position. Jones (2003) views organizational flexibility to be the key source of competitive advantage for most SMEs.

Grant (2002) proposes a 'framework for analysing resources and capabilities' (Grant 2002), which has been used to identify potential sources of competitive advantage at the case study company, in respect to where to compete; how to gain advantage; what assets are required; what assets do we have and how to change? The model for this analysis is shown in Figure 13.

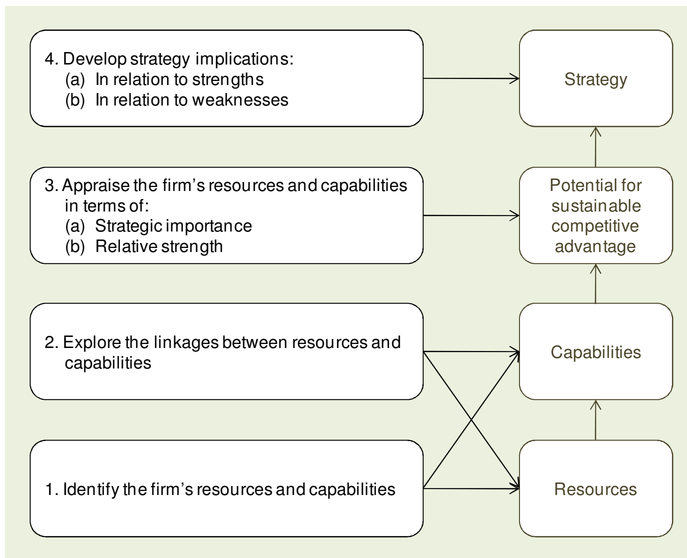


Figure 13. A framework for analyzing resources and capabilities (Grant, 2002)

The intention of the project at the case study company is to develop the company's capacity to integrate, co-ordinate and manage their internal estimating knowledge resources. 'The only thing that gives an organisation a competitive edge – the only thing that is sustainable – is what it knows, how it uses what it knows, and how fast it can know something new (Prusak, 1996).'

When conceptualising competitive advantage in small firms, Jones (2003) reflects on the importance of an effective change agent, external networks, flexibility and innovation, see Figure 14. Even though change must be a team effort, there will generally be one individual who acts as champion, taking on responsibility for building and motivating 'collective transformational leadership' (Day, 1994). 'Smaller firms cannot possibly have internal access to all the knowledge and skills required to remain competitive (Jones, 2003).' An SME's *absorptive capacity* is key to improving organizational competitiveness by ensuring that new information is rapidly disseminated to managers, technical staff, first-line supervisors and shop floor employees (Jones and Craven, 2001). One of the major advantages smaller firms have over their larger rivals is their ability to react more rapidly to changing customer requirements, therefore when introducing any new system of work it is essential that emphasis is placed on the importance of flexibility.

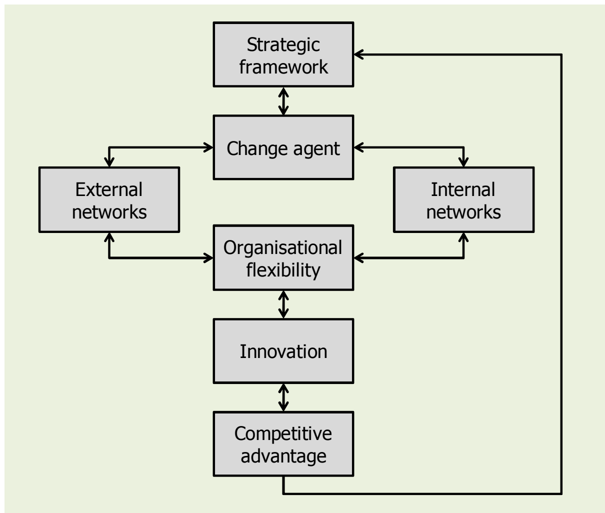


Figure 14. Conceptualising competitive advantage in small firms (Jones, 2003)

The case study company compete with *niche* market strategies (Porter, 1985), which are ‘differentiation focused’. A significant proportion of their ‘value added’ relates to machining operations, therefore accurate machined part cost estimates are an essential factor of being competitive. A *niche* firm such as the case study company focuses on quality and diversity but with high costs. Thus, reducing costs through innovation (without detrimentally effecting quality and diversity) should improve financial performance. The value chain, Figure 15, is used to disaggregate the case study company’s operations into strategically relevant activities.

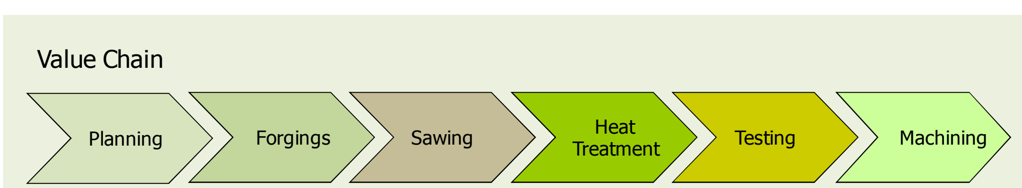


Figure 15. The case study company’s value chain (based in Porter, 1985)

A process of stakeholder consultation was carried out to take a balanced view of their expectations, those surveyed included the company's senior management and staff; systems consultants and customers (Schmolz + Bickenbach, 2008). Customers are most satisfied with:

- Knowledge of products (average rating 8.9 out of 10)
- Product quality (average rating 8.4 out of 10)
- Technical support (average rating 8.2 out of 10)

Customers are less satisfied with:

- Reliability of deliveries /length of lead times (average rating 6.9 out of 10)
- Price (average rating 6.9 out of 10)
- Improvement of the business (average rating 7.1 out of 10)

Industry perception of being both competitive and reliable was considered to be essential for nurturing customer relationships, as some customers had indicated that the company was perceived as being expensive and unreliable. Therefore the company should endeavour to produce estimates as accurately as possible, in order to improve their competitiveness. It became evident when considering the key stakeholder expectations, Figure 16, that a thorough and unambiguous understanding of the costs of production underpinned many of those expectations.

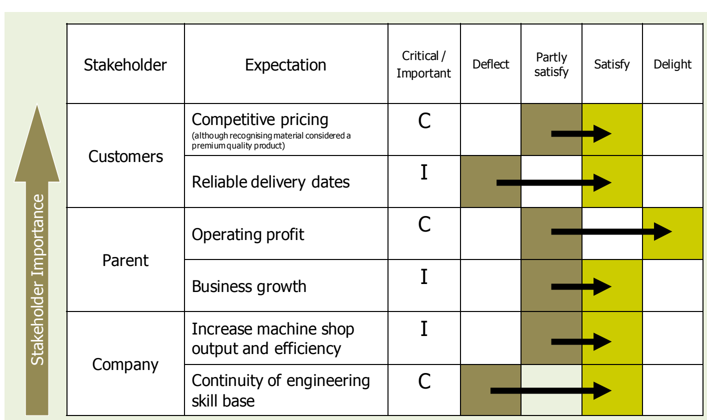


Figure 16. Key stakeholder expectations

Informal interviews with the key stakeholders helped to identify business objectives, critical success factors and two systems of interest. The connectivity between these issues is shown in the network diagram Figure 17.

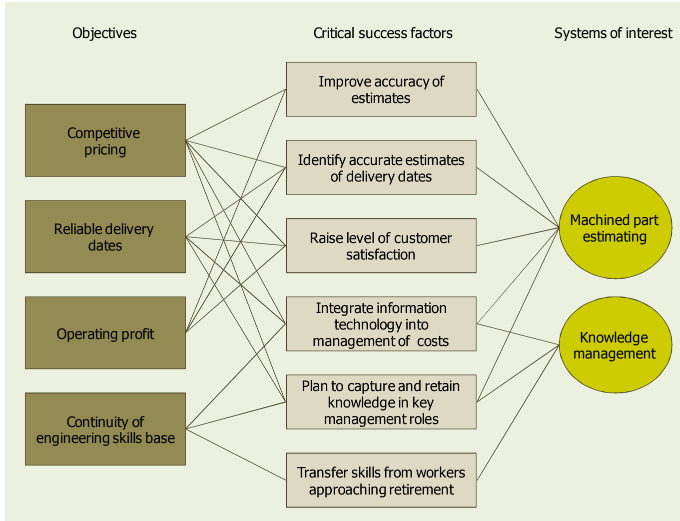


Figure 17. Critical business objectives, problems and areas for improvement

These issues map closely to Wickham's (2001) analysis which suggests four factors can potential lead to competitive advantage, see Table 4. Similarly, Man and Chan (2002) propose that competitiveness is concerned with factors which contribute to firms being competitive as well as with ways in which it can be achieved. They identify six areas of competency, Table 5, which together form what the authors' term the 'process dimension'.

Factor	*Potential competitive advantage*
Costs	Importance of price to customers, suppliers, distributors.
	Extent of demand elasticity
Knowledge	Stage of industry life-cycle
	Common or localised knowledge
	Tacit or codified knowledge
Relationships	Building links with customers, suppliers, distributors
	Position in network and relative power
Structure	Creating appropriate organisational structures
	Ability to respond to market signals

Table 4. Establishing competitive advantage (Wickham, 2001).

This research incorporates all of the factors detailed in Table 4 and the behaviour focus of each of these competency areas from Table 5, but with particular regard to *relationship*, *conceptual* and *organizing* competencies.

Competency area	*Behavioural focus*
Opportunity competencies	Recognise and develop market opportunities
Relationship competencies	Person-to-person, group-to-group interactions based on cooperation, communication and trust.
Conceptual competencies	Conceptual abilities related to decision-skills, information absorption, risk-taking and innovativeness
Organising competencies	Internal activities associated with human, physical, financial and technological resources
Strategic competencies	Setting, evaluating and implementing strategy
Commitment competencies	Entrepreneurial drive to develop the business.

Table 5. Competence and competitiveness (Man and Chan, 2002)

‘What becomes clear is that firms cannot expect to purchase sustained competitive advantages in open markets. Rather such advantages must be found in the VRIN resources already controlled by the firm (Barney, 1991)’; e.g. the organizational knowledge which supports the machining activities at the case study company. Tacit knowledge is often difficult to articulate but the case study company recognise the importance of managing this knowledge for future prosperity. This view is supported by the KBV, in that core competencies, intangible resources and tacit knowledge are all believed to provide sustainable competitive advantage. The company project aims to obtain the ability to retain and better utilise this knowledge.

Tongue and Tilley (2003) consider that ‘many smaller firms lack managerial and technical skills, which inhibits their effectiveness.’ This research aims to produce application software which improves the decision making process, facilitating a competitive advantage through excellence in estimating. ‘Improving the competitive advantage of SMEs is important to individual firms and the UK economy as a whole, as SMEs are important in terms of their overall share of GDP (Tongue and Tilley, 2003).’ Refering to Government White Papers (Cabinet Office, 1995; 1996), Tongue and Tilley (1996) acknowledge that ‘SMEs make important contributions to the UK economy in terms of technological progress, increased competitiveness, creating of new jobs and the economic revival of certain regions.’ ‘In the UK, SMEs are more important than larger companies in their contributions to business turnover and jobs (Curran, 1999).’

In many SMEs the potential exists for advances in technology and management practices; ‘because small firms lack managerial resources and functional specialists, many activities are poorly managed (Buratti and Penco, 2001).’ But it is vital for SMEs that a greater percentage of time is spend on developing relationships with external customers, rather than its 'internal customers', hence internal systems are less likely to be developed to their best potential. Often'small firms lack the time, resources, technology or expertise to research and develop new business ideas and innovations (Tongue and Tilley, 2003).' Effective use of information systems can lead to efficient use of both human and physical resources, enabling more time to be spent on adding value to the company.

The Federation of Small Businesses Study 2002 (Carter, 2002) was 'one of the largest non-governmental surveys of the small business sector', with 18,561 firms responding. The report findings included:

- 'The smaller firms, with turnover of less than £50,000, had the highest incidents of non-computer usage at 22%. This category also had the highest usage of single desktop or personal computers at 59% (Carter, 2002).'
- When questioned on the understanding of new technology 35.9% were satisfied and 8.9% very satisfied, however the study identified 'some variation in the adoption of new technologies corresponding to the age of the respondent. Respondents from the highest age category (over 65) were markedly less likely to have adopted any type of technology. (Carter, 2002).'

The author believed the study provided 'unequivocal evidence that there is an important and direct relationship between training and business performance (measured by growth and turnover) and that these respondents recognised that the most important factor in their success is their own business' capabilities, and they recognise the need for constant improvements (Carter, 2002).'

In a later survey and report on managing IT in small enterprises, attention is drawn to the following principal findings:

- '52% of respondents reported an expenditure of less than £5,000 on equipment and software in the previous 12 months (Stanworth, 2006).'
- '34% of respondents in firms with between 20 and 49 full time employees invested between £20,000 and £50,000 in ICT in the previous 12 months (Stanworth, 2006).'

- ‘17% of respondents in the manufacturing sectors had invested more than £20,000 in ICT during the previous 12 months (Stanworth, 2006).’
- ‘Manufacturing businesses were generally the most extensive ICT users (Stanworth, 2006).’
- ‘The acquisition of ICT skills – there was a strong tendency towards ‘self-teaching’ (85% of respondent firms) (Stanworth, 2006).’
- ‘46% of manufacturing respondents said that investment in ICT had helped them to develop new markets (Stanworth, 2006).’
- ‘Flexibility of employees having ICT skills – 66% of manufacturers indicated that they were satisfied with the flexibility of staff with ICT skills (Stanworth, 2006).’
- ‘47% believed that ‘ICTs have generally improved the quality of working life’, whilst only 18% felt that ‘ICTs have taken the people element away from working relationships’ (Stanworth, 2006).’

When analysing operational requirements, the case study company identified the need for flexibility in scheduling as many of their key customers often place ‘priority orders’ which demand short lead times. Fiegenbaum and Karmani’s (1991) analysis of secondary data confirmed output flexibility as a variable source of competitive advantage for smaller firms. This places increased emphasis on the issue of requiring accurate estimates for effective scheduling and accommodation of new orders already discussed in section 2.2.

In terms of machine part estimating, it is common for SME machine shops to persevere with manual calculation methods rather than to implement an information systems solution (Dimmock, 2007). This research suggests that is possible to develop a cost effective systems approach to estimating which will fall within the budget of an SME, given the levels of investments in IT reported by Stanworth (2006).

2.3 *Human factors in estimating and decision making*

The case study company face the challenge of replacing experienced estimators as they approach retirement. This raises particular concerns in respect to the wealth of knowledge, both tacit and explicit, which these estimators have accumulated through experience. 'Issues of particular practical importance include:

- Cognitive and social capabilities, workload, and cognitive effort
- Task complexity, both routine work and the limits of complexity that can be coped with
- Interference caused by taking responsibility for different types of tasks
- The use of decision support systems, their effectiveness, impact on trust and reliance, and circumstances where estimators override these systems
- The manner in which the outputs from the estimating unit are communicated to relevant personnel and functions
- Whether skill and expertise can be defined in relation to human estimators and how these attributes can be observed and analyzed
- The processes by which estimators are selected, formal and informal learning, and the effectiveness of training programs (MacCarthy *et al* 2001).'

Poor estimating performance will impact on both the productivity and competitiveness of an organisation. Whilst this research seeks to investigate the potential benefits which may result from the utilisation of an intelligent information system, it is important that a balanced view is taken of the realizable value such a system could deliver to an SME.

The knowledge-based view (KBV) of the firm considers that *knowledge* is the principal source of value in an organization and that individuals are a source of knowledge. 'Efficiency in knowledge production requires that individuals specialise in a particular area of knowledge; and the essential task of the organisation is knowledge integration, i.e. to co-ordinate the efforts of specialists (Grant, 1996).' The KBV perspective clearly identifies the important influence of human factors on effective knowledge management and *systems* development.

Swart and Kinnie's (2001) research into expanding knowledge-intensive SME's suggests that the main characteristic of the knowledge intensive firm is their growth pattern, in that they are usually born out of an innovative idea to fit a niche market need. These authors suggest that Human Resource Management is critical, and that human resource procedures should 'grow from within and become embedded in 'the way we do things'. Harrison (2000) shares this view of the value of the employee, stating that 'people hold the key to more productive and efficient organisations.' The way in which employees are developed at work has major effects upon quality, customer service, organisation flexibility and costs (Harrison, 2000).

Throughout the preliminary investigations into the case study company's working practices the word *flexibility* frequently occurred, both in terms of reacting to dynamic customer order priorities and the fluctuating levels of employee involvement. Employee flexibility is important to SMEs, where the core of workers typically 'have the security of 'permanent' contracts, and who have skills that are extremely important to the employer. In return, these core employees are expected to be functionally flexible by applying their skills across a wide range of tasks (Marchington and Wilkinson, 2002).' Flexibility can be both vertical and horizontal. Vertical flexibility refers to employees who take on tasks that are at a higher or lower skill level than that of the job they were recruited for. Horizontal flexibility refers to employees who undertake a wide range of tasks at the same broad skill level to that for which they were recruited. 'Each of these forms of functional flexibility is driven by employer needs for increased productivity and quality so as to survive in highly competitive product markets (Marchington and Wilkinson, 2002).' The vision for the decision support process described in this thesis, is one of facilitating both vertical and horizontal flexibility for those employees currently engaged in associated business functions. The 'useability' of the future estimating process should be sufficient so as to enable its use by sales staff at all levels, engineering managers and business administrators.

In a study on human scheduling practice, Crawford *et al* (2001) provides a model of roles and behaviour. The role of the estimator is compatable to that of the scheduler in many ways, not least in that the output from estimating leads to the input to scheduling. In SMEs it is often the case that these activities are actually the responsibility of one individual. Owing to this similarity Crawford's model is adapted for estimating for the puroses of this thesis, and shown in Figure 18. Definitions for the *tasks* and *roles* are as follows, again modified from Crawford's definitions for a scheduler:

- Formal task behavior: the behavior that the company has specified that 'estimating' personel should carry out.
- Housekeeping task behavior: the behavior that the estimators demonstrate to keep the data they need to carry out their job.
- Compensation task behavior: the behavior that the estimators demonstrate while attempting to compensate for some level of problem or failure in the overall system.
- Link & Net role: captures the interpersonal role behaviours of developing interpersonal networks, informal bargaining, friendship and favour networks and mediating.
- Hub & Filter role: captures the informational role of behaviours, acting as an implicit and explicit information hub, ensuring that information is accessible and visible, and filtering information to the shopfloor.
- Balance & Valve role: captures the decisional role behaviours of problem predicting and problem solving, interruptions handling, and deciding on the allocation of resources.

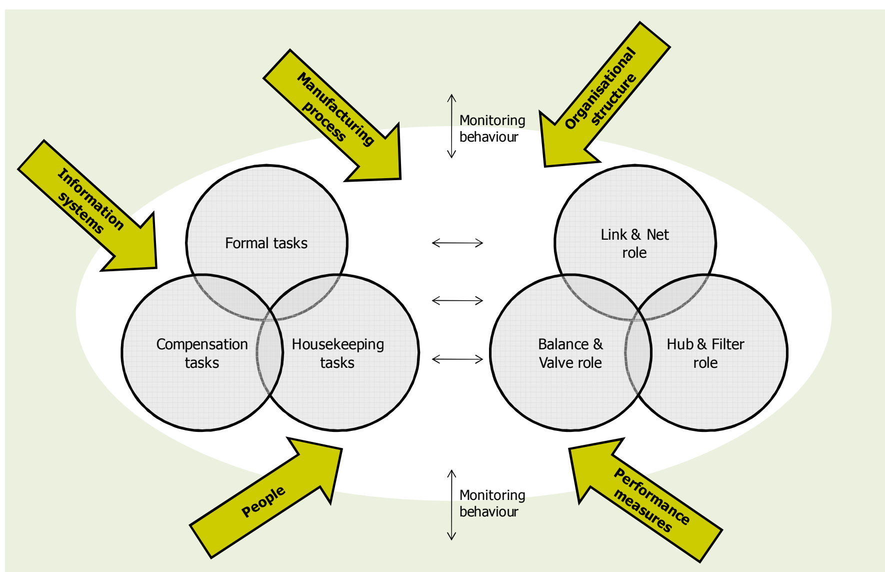


Figure 18. A model of human estimating practice (adapted from Crawford *et al*, 2001)

Decision making is a critical aspect of the proposed intervention at both strategic and operational levels. It was important to understand both the existing decision making process and other management perspectives on decision making and evaluating risk, before specifying potential solutions.

At the strategic level, decisions relate to the selection of appropriate techniques, methodologies and technologies employed in the re-engineering of the estimating process; and the evaluation of both benefits and risks resulting from those choices. At the operational level, both the rational and psychological perspectives (Tetlock, 1991) are explored to understand the cognitive processes of the decision makers. These perspectives on individual behaviour aid the evaluation of influential issues such as the use of heuristics; complexity (Fiske and Taylor, 1991) and 'bounded rationality' (Simon, 1975). Hence, many interrelated issues impact on the ability of an estimator to make effective decisions.

Sparrow (2000) suggests that uncertainty and the need for sense-making are key themes in modern management. Evolving environmental demands trigger changes in organisational structures: driving changes in strategy, structure and management (Bartlett and Ghosal, 1993). In such environments, greater uncertainty and complexity encourages searches for, and reliance on habitual and routine cues - 'tacit' knowledge, learnt in the context of work, described as 'theories-in-use' (Argyris and Schön, 1974). When individuals 'master' the organisational skills of reducing uncertainty, 'strategic contingencies theory' suggests this expertise enables them to exercise *power* (Crozier 1964) (Hickson et al, 2002). The view of resource dependence theorists, such has Pfeffer and Salancik (2002) is that power is a positive-sum game for those who control critical resources. Power is central to the strategy process in organisations, with decisions effecting resource allocation and the control of tasks, people and information (Pettigrew, 2002). In terms of decision making when allocating resources, better utility and opportunities for more intelligent organisation of work are provided through *empowerment*, *teamwork* and *collaboration* (Sewell, 2002). Both innovation and collaboration are driven by complexity and change, developing s*pecialisation* is a primary way in which knowledge is advanced (Loasby, 1999). However, Storey and Salaman (2005) describe the tension between existing organisational strengths and innovation arising from the deep, emotionally based attitudes of some managers.

Organisations depend on complex knowledge retained in 'organisational' memory, the net sum of employ experience and awareness. The *knowledge structures* of individuals, quality of information and provision of sufficient time in which to make judgements, are vital elements of effective decision making. When coping with a high volume of information there is a risk of 'punctuating' its flow excessively, impacting on subsequent sense-making. Weick (1995) suggests that as information load increases people take increasingly strong steps to manage it. Much of the information within organisations is problematic: either poor quality, ambiguous or quickly redundant. Making sense of problematic data not only wastes time but at a personal level it leads to feelings of inability to cope, inadequacy of knowledge and increased stress. Managing the quantity and quality of information processing is a key strategic management skill (Sparrow, 2000), providing environments which reduce *information overload* and the ensuing potential for risk is a critical challenge facing organisations.

The dominant management approach has dealt with problems rationally, however the process by which organisations make intelligent inferences about new information is not always rational. Individuals employ *knowledge structures* which act as mental templates, to represent their 'information world' so as to construct managerial and organisational knowledge.

Tetlock (1991) discusses three perspectives on human decision making, *rational*, *psychological* and *social* perspectives. The *rational-economic perspective* makes decisions in pursuit of maximum expected utility (Bazerman, 1998), considering the probably economic benefit / loss of decisions, 'utility theory'. Whist the assumption of rationality is beneficial in economics, De Bondt (1998) points to evidence that *individuals* behave differently. People are both *risk averse* and *risk-seeking* (Kahneman and Tversky, 1979) and individual behaviour is influenced by perception of risk. In order to make the effective decisions it is important to recognise the limits of human rationality. The use of heuristics (Nicholson, 2000) and intuition (grounded in our tacit knowledge and experience) offer an alternative process to rational decision making, providing awareness is maintained of relevant influences and biases. Fiske and Taylor (1991) suggest that either heuristics or complex cognitive strategies are selected as an aid to decision making depending on particular circumstances.

The case study company believe that the resources at their disposal, including human resources, reflect the 'four specific attributes – value, rarity, imperfect imitability and a lack of substitutes (Barney, 1991)', required for sustained competitive advantage. These attributes give the company a unique character which may lead to competitive advantage in their industry. This 'resource based view' of the firm is supported by Wernerfelt (1984) and Barney (1991) who suggests that firms can 'obtain sustained competitive advantage by implementing strategies that exploit their internal strengths, through responding to environmental opportunities, while neutralising external threats and avoiding internal weaknesses (Barney, 1991).'

It is important to recognise that it is the *estimating process* which is being developed, not just the information technology supporting that process. Hence, stakeholder engagement will have a critical impact on this research in terms of the ability to codify relevant knowledge. Human interaction is traditionally the preferred way to share knowledge, and sharing tacit knowledge requires verbal communication. 'Implementing knowledge management is not a technical exercise but a question of leading and managing change, involving as it does a broad range of responsibilities for those involved and a wide range of outcomes in terms of behaviour and business performance (Scarbrough *et al*, 1999).' Everyone has cognitive limits, thus in order to respond rapidly to the changes in the work environment, all organisational levels have to be much better informed and more adaptable.

2.4 Managing learning and knowledge in organisations

The workplace learning context focuses on the continual development of appropriate skills and knowledge required by organisations for them to survive and prosper. The pace of change affecting these organisations directly affects the speed at which the skills and knowledge of their employees require updating. Barnett (1999) examined the relationships between learning and work, suggesting that although they are different concepts, learning is inherent in work and work is inherent in learning. Under conditions of 'supercomplexity' ('the challenge of multiple, conflicting and ever-emerging frames of understanding and action') work demands learning and learning becomes more challenging.

The case study company employ experienced estimators but with key individuals approaching retirement the company recognizes the importance of effective workplace learning and the development of learning opportunities. This company have traditionally followed an apprenticeship model of learning to transfer knowledge and skills, an approach identified as typical within similar communities of practice (Dimmock, 2007). Learning from other people within the organisation is the major contributor to the performance of learning (Eraut *et al*, 2002).

The conventional approach to skill formation (the formal provision of education and training) owed much to the dominance of human capital theory (Ashton, 1998). Ashton suggests a change of emphasis towards less formal workplace learning, the *situated learning* perspective, arguing that skill formation needs to be continuous process in which learning at work is central.

Lave and Wenger, (1991, 2002) suggested that legitimate peripheral participation in communities of practice, rather than specific master-apprentice relationships, improves participation and learning. They stress the importance of opportunities for engagement in practice and the structuring of learning resource within the community of practice, suggesting that environmental issues have a greater significance on how apprentices learn (notably engagement with peers) rather than specific master-apprentice relationships. These authors observed that apprentices' understanding and knowledgeable skills develop as a consequence of their direct involvement in activities. They consider participation is crucial to learning the practice of the community and the process of developing into full practitioners; highlighting access by newcomers to the community of practice, opportunities for participation and the notion of transparency of knowledge artefacts as being 'key' to learning. The authors highlight the dilemma facing 'newcomers', compliance with accepted norms to become a full practitioner in the established community, or developing practice to establish their own identity – which is 'fundamental to the concept of legitimate peripheral participation (Lave & Wenger, 2002)'.

In his study of workplace learning Billet (2001) discusses the economic imperatives driving individuals' maintenance of their vocational practice throughout their working lives. Billet identifies that the quality of learning is contingent on the kinds of activities individuals engage in and the guidance they can access; proposing that, 'although able to regulate their participation, ultimately individuals' ability to maintain their vocational practice is constrained by the way workplaces afford opportunities for engagement and interactions (Billet, 2001).' 'The social and systemic dimensions of learning are the key determinants of how an organization successfully acquires, productively deploys, and develops its stock of skills' (Keep and Rainbird, 2002). However, in most organizations the practical implications of strengthening informal learning opportunities are not yet understood. Guile and Young (2002) discuss the importance of the role information and communication technologies will play in developing the skills and knowledge that are emerging as essential to a learning society, for both accessing information and communicating within distributed communities of practice.

The vision for METALmpe was to develop a 'dual purpose' system solution: (i) decision support for the immediate problem at the case study company (i.e. the need to improve the performance and process capabilities for the estimating function); and (ii) an application tool for supporting the future development of novice estimators. For this reason the system development described in Chapter 4, specifically adopts the approach of developing the application as an *enriched work representation* (Sumner et al, 1999) (Mulholland et al, 2001). This concept is discussed further in section 4.2. In order to develop an application which supports and enhances workplace learning (through the use of tools and documents which aid collaborative working and learning), it was important that research theories on adult learning.

Kolb and Fry (1975) conceptualise adult learning as a cyclical process, Figure 19. This experiential cycle (in which knowledge is created through the transformation of experience), focuses on the individual, reflecting on an experience which may produce new concepts, insights and understandings. The influence of rituals and routines can also be seen in Argyris and Schön's (1974) framework for thinking and reasoning, '*theory-in-use'*, which proposes that we learn from those around us '*the way that we do things around here'*.

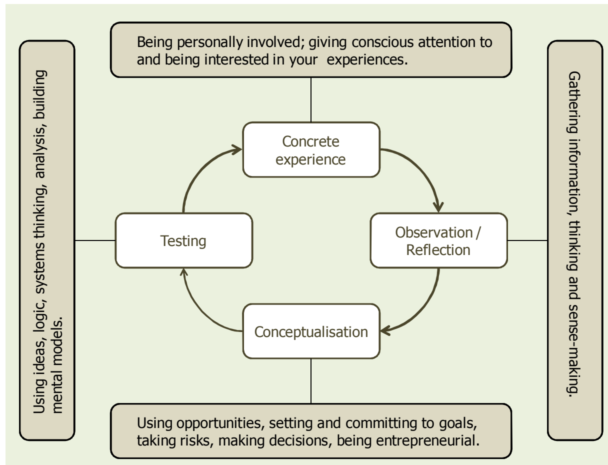


Figure 19. Experiential learning (adapted from Kolb and Fry,1975)

Theorists suggest that more than one approach, theory or concept may be appropriate in any organisation at any one time, however a recurrent theme is the central role of the learner (Rogers, 1980). Academics such as Chris Argyris (1999) stress that learning is not just about '*what*' is the intended outcome, but also the '*how and why'*. Understanding the learning process helps individuals to become more effective and efficient learners. There are implications for learners in that although a learning goal may be clear, perhaps the best route (strategy and tactics) is not so clear. Integrating practice, learning and theory can help you to make a difference for individuals and organisations (Open, 2005).

Problems in professional life are typically complex and are often not best addressed by over-simplified problem solving models - '*technical rationality'* (Schön, 1983). Reflective practice plays an important role in managing such complex problems, assisting practitioners to understand how management practice, learning and theory interact. Schön (1983) first introduced the notion of the reflective practitioner, describing the process of effective learning and development as stemming from re-examination and re-interpretation of experience. Our individual personalities mean it is important to develop individual approaches to reflection. The value of reflective practice is it enables the practitioner to continually develop their understanding, skills and competence.

Experience on its own does not guarantee learning, reflecting on that experience however can enable us to acquire deeper insight. Schön (2003) sees clear differences between 'knowing-in-action' (second nature), 'reflection-in-action' (thinking on your feet) and 'reflection-on-action' (evaluating your performance). Schön argues that it is 'reflection-on-action' that enables you gain in terms of personal and professional growth. 'Reflection-in-action' is seen as being crucial in building expertise and problem solving but is dependant on preparation, and preparation itself draws on reflection-on-action. Reflective practice enables us to take generic management theories and apply them to our own particular set of circumstances, influencing our practice through mixing theoretical models and recognised knowledge with experience and shared values / goals. By consistently and systemically thinking about our knowledge limits we examine our metacognitive knowledge (Krathwohl, 2002) and gain a more complete picture of the state of our knowledge and competence.

An alternative approach for workplace learning is represented by the knowledge management perspective. Knowledge management focuses on the *outcomes* of the learning process rather that the process of learning. In today's highly developed economy, knowledge is increasingly seen as an organisations most valuable intangible asset, with the potential to create differentiation in the marketplace. It is knowledge and its effective application that lead to new learning, create innovations, improve organisational processes, and help organisations achieve superior performance, thereby leading to further learning and continuing the cycle. Knowledge management is closely associated with developments in information management, and approaches to managing knowledge can be summarised as 'the triple challenge of:

(i) managing explicit information and processes;
(ii) managing people and the environment in which they work; and
(iii) bringing these together so that tacit knowledge is exchanged more naturally and systematically and is thus more widely available to key personnel in the organisation (Open, 2005c).'

There are many definitions of knowledge management, however in the context of this research an appropriate definition is provided by the European Standard: 'Planned and ongoing management of activities and processes for leveraging knowledge to enhance competitiveness through better use and creation of individual and collective knowledge resources (CEN 2004).'

Knowledge-based theorists (Penrose, 1959; Kay, 1993; Spender, 1996; Grant, 1996), consider knowledge the principle source of value in an organization; effective knowledge management is seen as a key strategic capability. Watkins and Callehan (1998) describe learning as 'the process that makes the creation and use of knowledge meaningful'; however Strassman (Knowledge Inc., 1996) suggests the majority of firms perform poorly in this activity. Knowledge management initiatives are valued as a meaningful economic resource (Drucker, 1993), reflecting their emphasis on contribution to profitability / efficiency.

Core themes to knowledge management are:

(i) Knowledge is viewed as an 'asset' which should be actively managed;
(ii) knowledge should be captured and re-used; and
(iii) creation of new knowledge should be promoted through changes to the structures and cultures of organisations.

Polanyi (1969) regarded all knowledge as either tacit or rooted in tacit knowledge, 'the idea of a strictly explicit knowledge is indeed self-contradictory; deprived of their tacit coefficients, all spoken words, all formulae, all maps and graphs, are strictly meaningless.' The personal judgement of a human being is necessary to attempt to interpret information in a comprehensible manner (Open, 2005a). Organisational practice is shaped by context-specific interpretation of informal and formal rules. Apprentices who become competent practitioners master the capacity to act and think in the manner of an insider: they enter the 'inner circle' of expertise. For Polanyi (1983), the 'tacit knowing' that lies behind imagination, hunches, intuition, skilled judgement, etc, cannot be specified or 'commodified'. Accomplished practitioners can recognise competent practice, even if they are not conscious of what they are recognising. Qualities such as skilled judgements and intuition depend on dwelling in the particulars of a particular activity; 'indwelling' (Open, 2005a) enables a human being to become familiar with the details of a particular context, although we may not be conscious of what we have learned.'

Nonaka and Takeuchi (1995) 'set the standard for the emergent field with a rich mixture of concepts and field data' (Easterby-Smith and Lyles, 2003), treating Polanyi's (1983) concept of 'tacit knowing' in a manner that makes it accessible to managers – an asset that could be managed. Nonaka and Takeuchi's (1995) concept of tacit-explicit knowledge conversion tackles the problem of 'finding a way to express the inexpressible'; 'for tacit knowledge to be communicated and shared within the organisation, it has to be converted into words or numbers that anyone can understand.' The challenge as seen by Nonaka and Takeuchi (1995) is converting partly formed information (schemata, mental models, perceptions, etc) into a different type of information: the words or numbers that anybody can understand, which the authors call 'explicit knowledge'. For Nonaka and Takeuchi knowledge creation is a spiral process that starts at an individual level and spirals out to enrol a wider community of practice. This 'intelligent cooperation of colleagues' (Nonaka and Takeuchi, 1995) is represented in the SECI model (Figure 20) which involves four modes of knowledge conversion. *Socialisation* is a process of sharing experiences and thereby creating tacit knowledge such as shared mental models and technical skills. *Externalisation* is a process of articulating tacit knowledge into explicit concepts. It is a knowledge-creation process which uses metaphors, analogies, concepts, hypotheses, or models in order that tacit knowledge can become explicit. *Combination* is a process of systemizing concepts into a knowledge system. This mode of knowledge conversion involves combining different bodies of explicit knowledge. *Internalization* is a process of embodying explicit knowledge into tacit knowledge.

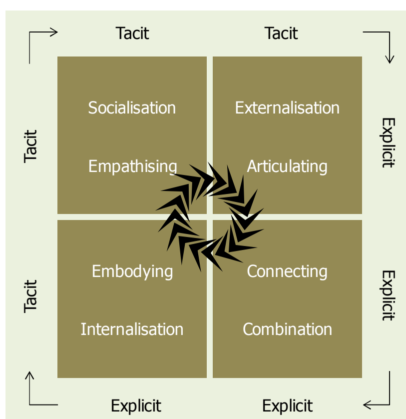


Figure 20. The SECI Model (Nonaka, 1994)

Nonaka and Takeuchi (1995) propose a middle-up-down process for knowledge creation, Table 6. 'The middle-up-down management model is by far the most comprehensive in terms of who gets involved; the most all-inclusive in terms of what knowledge is created; the broadest in terms of where knowledge is stored; and the most flexible in terms of how knowledge is created (Nonaka and Takeuchi, 1995).'

Who	Agent of knowledge creation	Team (with middle managers as knowledge engineers)
	Top management role	Catalyst
	Middle management role	Team leader
What	Accumulated knowledge	Explicit and tacit
	Knowledge conversion	Sprial conversion (SECI model)
Where	Knowledge storage	Organisational knowledge base
How	Organisation	Hierarchy and task force
	Communication	Dialogue and use of metaphor/analogy
	Tolerance for ambiguity	Create and amplify chaos / fluctuation
	Weakness	Human exhaustion Cost of redundancy

Table 6. Middle-up-down management process for knowledge creation (Nonaka and Takeuchi, 1995)

Knowledge management initiatives aim to 'capture' what individuals know by converting know-how into explicit knowledge, the information that would enable any suitably qualified person to do the job. When organisations such as those at the case study company are performing relatively fixed functions in a stable environment, their past experiences can prove to be a reliable guide to the future. The capacity to learn from experience and to communicate that what has been learnt is important in contributing to organisational learning. Cook and Brown (1999) reinterpret and strengthen Nonaka and Takeuchi's claims about 'knowledge creation', relating the concepts of explicit and tacit knowledge to 'knowing how to *do things* in practice.' Cook and Brown insist that 'it is not possible under any circumstances for tacit knowledge to become explicit' and that knowledge possessed by individuals is distinct from knowledge possessed by groups. The authors suggest there are four types of knowledge 'tools', all of which have equal standing, which have to be put to work in practice (the concept of 'knowing in action' Figure 21).

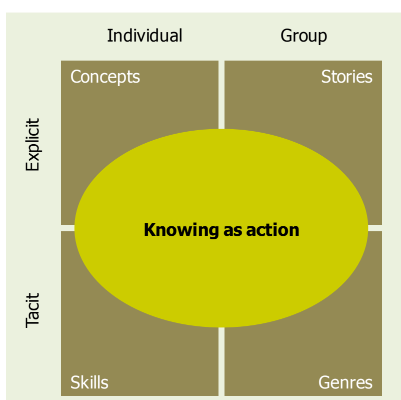


Figure 21. Mapping the knowledge tools (Cook and Brown, 1999)

Another perspective on managing knowledge is presented by Firestone and McElroy (2003) who support a fallibilist variety of knowledge management. This variant of second generation knowledge management, termed 'The New Knowledge Management' by McElroy (2003) is differentiated from all other second generation thinking in that it is anti-justificationist. 'Not only does it deny the appeal to authority as a basis for truth, it denies the very possibility of certainity about truth in the first place. That is, it says we as humans are fallible and can never know the truth with certainity (*fallibilism*: Popper, 1972). If there can be no truth with certainity, only proximity to it at best, any part of our knowledge may be wrong – even top managers' knowledge.' Popper (1972) suggested that all knowledge should be continuously subjected to test and evaluations, to rational and continuous criticism.

When considering decision support in the project at the case study company, this thesis takes the view that what is needed is an operating environment in which all organizational knowledge relating to cost estimating is continuously subjected to tests and evaluations. This principle of continuously evaluation is influential in developing the new approach to estimating, as is the concept of capturing newly evolving estimating and process performance knowledge within a repository that exists independently of expert estimators and manufacturing managers.

In knowledge management literature the term 'technology' is assumed to mean digital media and networks: software and hardware that comprise today's ICTs. In this literature review the focus is on technologies for communities of practice; and the core concepts of knowledge codification and representation. Of particular interest are questions arising from discussions with stakeholders at the case study company:

- Is the company really going to fall so far behind the competition if knowledge technologies are not adopted?
- To what extent are existing technologies upgradable?
- What evidence is available that a technological solution will work?
- We are already overloaded with information, will adopting new technologies ease this burden, or make it worse?
- How is the lifespan for a knowledge management system? Will it be a lot of work, without much of a future?

There are two key concepts of knowledge specifically related to ICT: representation and interpretation (Open, 2005c). *Representation* is the way in which information is made manipulable and shareable. To create a representation, we must codify information. *Interpretation* is the process of assessing information with respect to a goal. A consequence of this view of knowledge is that information may be interpreted in many different ways – its significance depends on the reader. An implication of this view is that, while information technologies deliver data structured using different representations, knowledge technologies are distinguished by their support for interpreting those representations.

A further significant concept is that of communities of practice (Lave and Wenger, 1991; Wenger, 1998). The 'concept of practice includes both the explicit and the tacit. It includes what is said and what is left unsaid; what is represented and what is assumed. It includes language, tools, documents, images, symbols, well-define roles, specified criteria, codified procedures, regulations, and contracts that various practices make explicit for a variety of purposes. But is also includes all the implicit relations, tacit conventions, subtle cues, untold rules of thumb, recognised intuitions, specific perceptions, well-tuned sensitivities, embodied understandings, underlying assumptions, and shared world views. Most of these may never be articulated, yet they are unmistakeable signs of membership in communities of practice and are crucial to the success of the enterprise (Wenger, 1998)'. Communities of practice shape when, how and why knowledge is: acquired, shared, validated, transformed and stored. In the context of designing knowledge technologies, it should be clear that the views and perceptions of the community of practice cannot be ignored. A further significant concept is 'situatedness', which refers to the view that the context in which knowledge is developed and deployed is fundamental – 'knowledge is a product of the activity, context and culture in which it is developed and used (Brown *et al*, 1989)'.

A central argument for knowledge management is the importance of making tacit knowledge explicit, and then codified; how knowledge gets transformed from the mind of an individual to reside eventually on a computer. Stahl (1993) presents an analysis of the transformation of knowledge from tacit to explicit to formally codified representations in a computer-interpretable form, emphasising the centrality of interpretation situated in the workplace, Figure 22. 'Hermeneutic presence' refers to tacit knowledge that underpins individual and collective understanding; it shapes our world, and we cannot step completely outside this perception. 'Symbolic representation' enables us to treat information and ideas as separate from ourselves – once codified, they can be manipulated and analysed. (Open, 2005b).

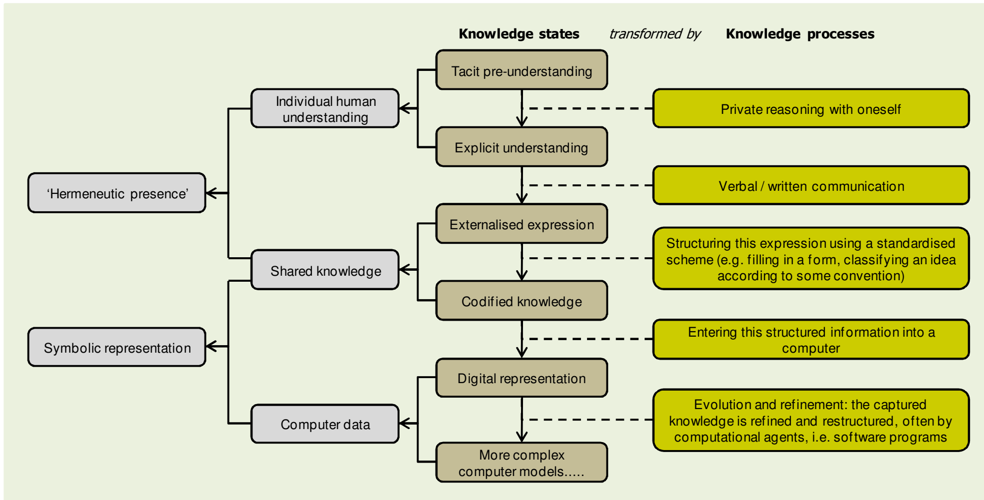


Figure 22. Transformation of knowledge from tacit 'pre-understanding' to explicit, computer based models; 'Hermeneutic presence' and symbolic representation (adapted from Stahl, 1993).

The whole dynamic system of people and technologies is conceived as constituting an organisation-wide resource that will enable it to become a more intelligent, learning organism; a rich collective of knowledge processes. A useful 'design space' for organisational memory has been proposed by van Heijst *et al* (1998), Figure 23. A design space articulates two or more dimensions that highlight important differences between designs. These authors also suggest example technologies.

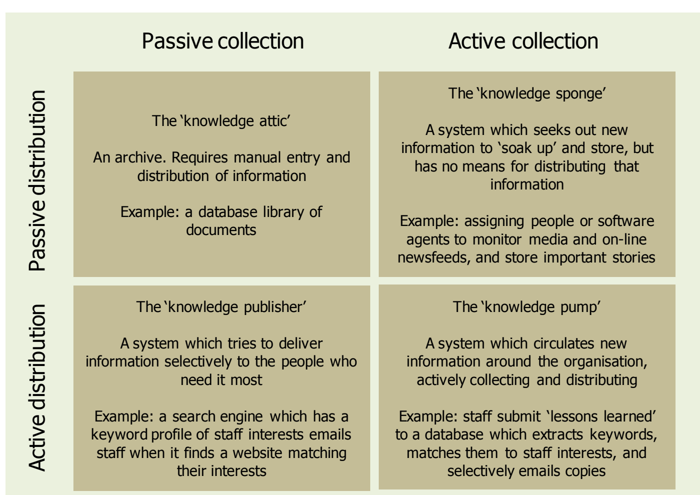


Figure 23. A 'design space' for organisational memory systems (van Heijst *et al*, 1998)

The ‘holy grail’ is a technology which promotes the integration of information and experience in order to build new layers of meaning and higher levels of understanding, but this may only ever be possible in very tightly restricted fields (van Heijst *et al*, 1998). Commercial technology packages promise much in terms of ‘plug and go’ solutions, but the complexity of integrating COTS applications into the workflow in a particular context can obstruct progress. Bespoke solutions, although less readily available, mean that the technology meets the needs of the community of practice – ‘it is invariably harder to change work practice than software (Open, 2005c).’

Communities of practice are technical and social networks which ‘set the context in which new knowledge arises in daily work, and determine how it is shared and interpreted, what counts as important knowledge and how people become recognised as members of that community (Brown and Duguid, 1998).’ Some technology implications of focusing on the community of practice as the unit of analysis are:

- Technologies should permit multiple degrees of formality in communication.
- Technologies should permit peripheral participation in online forums.

The emphasis is on augmenting communication by mediating and hence structuring it electronically, and/or by adding functionality to digital artefacts to allow their meaning to be negotiated explicitly. Knowledge-based systems have the ability to analyse specific kinds of information in order to take action, these systems are described in greater detail in section 2.6. However, a point of interest here is how a knowledge-based system can help the user structure information. The approach of *incremental formalisation* (Shipman and McCall, 1994) can assist in building the *ontology* itself by suggesting new classes and structures. ‘In the field of artificial intelligence the term ‘ontology’ has been appropriated to mean a ‘reusable terminological scheme’: a scheme for providing a rigorous description of the concepts, attributes and interrelationships deemed relevant to describe a particular aspect of the world. ‘An ontology is an abstract knowledge model, which if created in digital form, software tools can assist in checking its internal consistency, and convert it into a knowledge-based system for a particular application to a problem (Open, 2005b).' A critical factor that will determine whether ontologically enriched technologies are adopted is the usability of the system.

- How much understanding of the ontology is required to use it effectively?
- Can new entries be added to the knowledge base at the right moment?

It can be seen that the value of knowledge management is not generically applicable, it depends on the context and complexity of the knowledge created within a community of practice and the extent to which that knowledge is usefully applied. Within small companies the opportunities for innovation and distribution of knowledge are often so restricted, that the notion of knowledge management is less relevant. In a study of knowledge management in small businesses, Matlay (2000) concluded that 'although learning can occur in the majority of small businesses in the sample, only a minority of these manage new knowledge strategically to sustain and advance their competitive advantage'. These smaller companies tend to rely on the skills and experience of a small core of employees and demonstrate fewer opportunities to create new knowledge and filter out inappropriate knowledge, compared to larger and /or more complex organisations. In an another study of lifelong learning from a small firm's perspective, Martin (2002) found senior management lacked awareness of the concept of lifelong learning and failed to appreciate its potential benefits at an organisational level. This was coupled with a resistance to embracing learning for all staff, instead *preferred* employees had been 'the main participants of formalised firm learning and had taken learning outside work for personal development.'

Rowley (2000) recognises a relationship between knowledge and power, and the strategic implications this holds for culture change in organisations. Knowledge management is often viewed as predominately benefiting employers, enabling organisations to reduce their dependence on human expertise (relocating knowledge from the individual into organisational systems). This can affect employee's views on knowledge management, with a perceived belief that they will become more expendable. Employees are more likely to 'buy-in' to the notion of the 'learning organisation' with its suggestion of benefits for all, rather than become enthused by knowledge management initiatives. For effective learning to become a central theme in organisational life it must be part of the company paradigm and be entwined in the culture and values of the organisation.

At the case study company the issue of the *power* (Crozier, 1964) (Hickson et al, 2002) (Pfeffer and Salancik, 2002) (Pettigrew, 2002) held by the estimators was a less critical issue. These individuals were time-served, trusted employees, who were keen to see the company succeed into the future past their impending retirements. Whilst they were initially dismissive of the possibility that an intelligent system could provide significant decision support in machined part estimating (within the context of this organisation), there was never really much doubt that they would be complicit in the knowledge elicitation process. However, the risk of their non-compliance was recognised in the stakeholder analysis, detailed in Appendix C.

It has to be considered that the circumstances at the case study company would not typically exist in other settings, and therefore alternative tactics / incentives may be required in the management of the knowledge elicitation process. A thorough investigation of employee motivation was not part of the scope for the research which is the subject of this thesis. However, having researched to a lesser extent the likelihood that IT innovations would be adopted in SMEs, it is the opinion of this author that small-sized companies would be inclined to 'buy-in' to the notion that KM can bring benefits to all.

Organisations have to recognise that everyone has cognitive limits, and where necessary implement processes for managing knowledge and organisational learning to strengthen their strategic assets. In organisations where the management of knowledge is closely linked with their value chain, it is important that learning is encouraged within the organisation. This ensures key activities are not wholly dependent on an individual as such dependence is a risk.

2.5 Implications for developing information systems

Contemporary management theories refer to efficient information sharing as being the key to the success of an organisation. In most progressive companies, information sharing takes place, at least partially, via an information system. 'An information system can be defined as a set of inter-related components that capture, transmit, store, retrieve, manipulate and display information to support decision making and control in an organisation (Laudon and Laudon, 2001).'

It is vital to think about a systemic solution to the project and the research needs to consider: the boundaries, components, internal organisation, behaviour, emergent properties, levels of complexity and the connectivity through the system. The importance of human interaction in systems development and knowledge management is widely recognised, specifically in respect to: limitations of hard system methodologies; understanding and transfer of tacit knowledge; and the inherent difficulty in developing intelligent information systems to mimic human intelligence and expertise.

There is a particular hierarchy of information systems Figure 24, which are of interest in this thesis, which branch from the distinct heading of *strategic information systems*. Some of the business benefits attributed to strategic information systems include: reduced costs, eliminated delays, improved reliability, improved customer service and reduced transaction times.

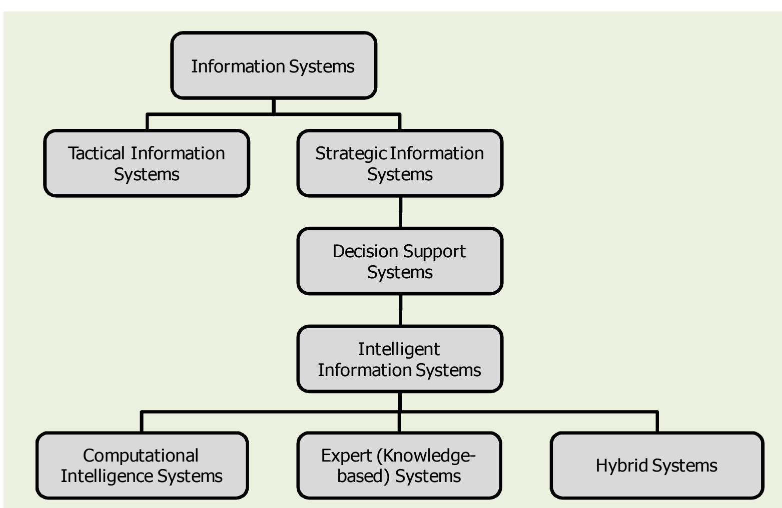


Figure 24. Hierarchy of information systems

Decision support systems are a type of strategic information systems, which can apply in any functional area of the business, providing information and data manipulation tools to help decision making. The framework shown in Figure 25 shows the positioning of Decision Support Systems in relation to more commonly used Management Information Systems and Database Management Systems. An intelligent information system is a type of decision support system, which provides flexible information processing capability for handling real-life ambiguous situations. Intelligent information systems exploit the tolerance for imprecision, uncertainty and appropriate reasoning, and are popular in systems that encapsulate human expertise (Tiwari, 2005).

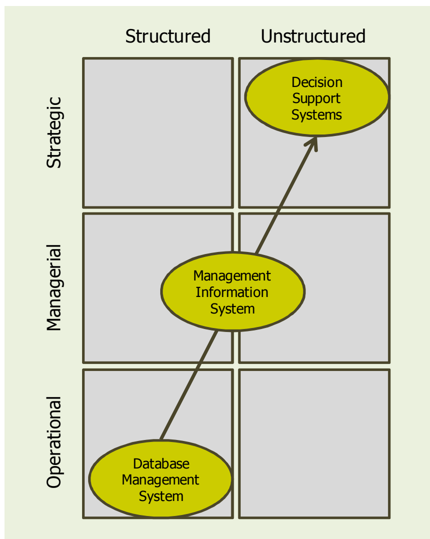


Figure 25. The Gorry Morton Framework
(Cited by Johnstone, 2005)

Research in artificial intelligence has resulted in tools which aim to mimic human mental activity, some of which have potential applications in cost estimating. Marvin Minsky (1975) defined artificial intelligence as 'the field of study that is attempting to build systems which if attempted by people would be considered intelligent.'

These tools can be roughly divided among knowledge-based (expert) systems, computational intelligence and hybrid systems (Hopgood, 2001), and are collectively referred to as *intelligent systems,* Figure 26. Intelligent systems can offer benefits in knowledge retention; knowledge distribution; training; competitive edge and cost reduction.

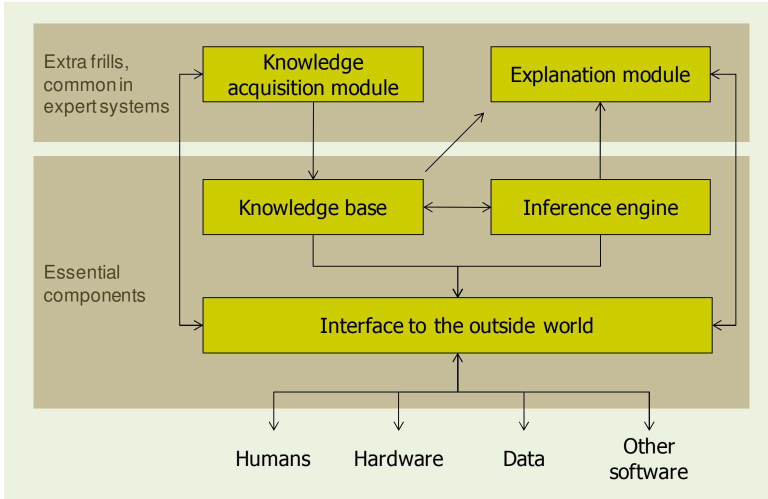


Figure 26. The main components of a knowledge based system (Hopgood, 2001).

Expert systems are intelligent computer programs that use knowledge and inference procedures to solve problems that are difficult enough to require significant human expertise for their solution (Feigenbaum, 1982). Their purpose is to replicate knowledge and skills of a human expert, using this knowledge to solve similar problems with significantly less human expert participation. Expert systems do not replace experts, but they make their knowledge and experience more widely available and permit non-experts to work better (Shehab, 2005). The advantages of using a computer rather relying on human expertise are: human expertise is perishable, not always consistent, difficult to transfer and expensive. However, an expert system cannot automate all processes, and the advantage of human expertise is that: humans are creative, flexible and possess common sense (Darlington, 2000).

The 'knowledge' within such systems can be in the form of data, rules, facts or heuristics - the rule-of-thumb or simplifications that allow its users to draw the conclusions without being certain. The human mental process is too complex to be represented in an algorithm, however most experts are capable of expressing their knowledge in the form of rules for problem solving.

The main characteristics of expert systems are:

1. 'They simulate human reasoning about the problem domain, rather than simulating the domain itself
2. They perform reasoning over representations of human knowledge, in addition to doing numerical calculations or data retrieval. They have

corresponding distinct modules referred to as the inference engine and the knowledge base.

3. Problems tend to be solved using heuristics or approximate methods or probabilistic methods which, unlike algorithmic solutions, are not guaranteed to result in a correct or optimal solution.
4. They usually have to prove explanations and justifications of their solutions or recommendations in order to convince the user that the reasoning is correct (Shehab, 2005).'

Advantages of expert systems include: increased output and productivity, increased quality and reliability, improved customer service, complex problem solving and decisions making, training capabilities.

The development of technology and software solutions must fulfill many requirements and sophisticated mechanisms of social-technical systems (Jones and Lindstaedt, 2008; Koper *et al*, 2005). Expert-driven software engineering is increasing seen as not being sufficient for the complexity and dynamics of socio-technical systems (Mödritscher and Wild, 2009). Concepts such as *opportunistic design* and *end-user development* are becoming increasing relevant, and are embraced by this work. End-user development aims at empowering users to design their software applications for their purposes (Fisher *et al*, 2004). Further still, opportunistic design requires even more in terms of technical, personal and social competencies of end-users (Stahl, 2008). The concept of *technology appropriation* (Overdijk and van Diggelen, 2006) implies a process of social construction in which the actions and thoughts of the technology user are shaped through the use of the technology, while at the same time the meaning and effects of the technology are shaped through the users actions. This perspective suggests that a technology gets its form and meaning from the mutual influence and dependency between users and technology.

This thesis describes a solution for managing cost estimating processes through a feature-driven case-based approach to machined-part estimating. The process is specifically developed for use in SMEs where there is little current use of computer-based estimating. The purpose of this methodology is to provide an integrated and systemic approach that would enable the development of knowledge resources.

Progress has been made in addressing these problems through the use of decision support systems (Souchoroukov *et al*, 2002; Kingsman and de Souza, 1997;

Bertens, 1997). Whilst it is often difficult to reliably predict manufacturing times (owing to complexity of business processes and variance in individual productivity), using information technology to help extract information from empirical data can shorten the time taken to produce estimates significantly. When developing a decision support system, it is important that sufficient emphasis is focussed on the business processes and not solely the development of an information system. This thesis describes a methodology which aims to capture and disseminate estimating knowledge, which will be of valuable daily benefit to the next generation of estimators at the case study company.

The initial emphasis of the research concentrated on the potential use of hypermedia, feature-based costing and case-based reasoning in the development of a task support system. A key aspect of this early research was the evaluation of whether hypermedia technology could to create a novel user interface, which would enable step-by-step process instructions to facilitate estimating by non-experts. Lowe and Hall (1999) define hypermedia as ‘an application that uses associative relationships among information contained within multiple media for the purpose of facilitating access to, and manipulation of, the information encapsulated by the data’.

Hypermedia technology enables non-sequential information access, so that the user defines the sequence in which information is read. ‘Hypermedia ostensibly mimics the way the brain stores and retrieves information and its aim is to permit fast and easy access to vast quantities of information by establishing multidimensional links among related items (Gygi, 1991).’ This process is suggested to be better at imparting information to human beings than traditional sequential text information (Togher, 2001).

Hypermedia technology is an extension of the earlier proposed electronic repository systems conceptualised in the 1960s (Nelson, 1965), inspired by Dr Vannevar Bush’s pioneering research work in the 1940s (Bush, 1945). It is a linking concept, concerned with linking pieces of information and assembling them into a web of interrelated nodes. ‘Hypermedia enables the user to decide the path to take when presented with a number of options, and to control the how long a piece of information is displayed before moving on (or back) again (Nielsen, 1990)’. ‘Interactivity defines hypermedia’ (and speed of response is important) in order for the user to control the experience (Togher, 2001). Togher (2001) suggests some of the advantages of hypermedia include ease of navigation through information space;

electronic storage of large quantities of organisational information with rapid retrieval; instantaneously accessible via computer and ease of authoring & updates. Nielsen (1990) suggests advantage will be gained from using hypermedia in situations when:

- There is a large body of information organised into numerous fragments
- The fragments relate to each other
- The user needs only a small fraction of information at a time
- The user will be near the computer

The term *Industrial hypermedia* generally refers to hypermedia applications in manufacturing and process industries. The concept of *industrial strength hypermedia* was proposed by Malcolm *et al* (1991), who argued that an industrial strength hypermedia system had to 'evolve beyond the stand alone applications to become a technology that integrates various resources across an engineering enterprise.' Tjahjono (2003) suggests the reasons that hypermedia technology is suited to industrial task support applications are: fast, non-linear access to simultaneous presentations of text, pictures and other multimedia items; ease of user navigation; information association; embedded support system; improved comprehension; multimedia can break the language barrier and easy authoring. Examples of industrial hypermedia applications include:

- Web based manufacturing support (Cheng, Pan and Hamiliton, 2001).
- Electronic performance support (EPSSs) (Ockerman *et al*, 1999).
- Adaptive product manuals (Pham and Setchi, 2000).
- Document management (Tjahjono, 1998), (Ockerman *et al*, 1999).
- Interactive task support, (Greenough, 1999), (Kasvi *et al*, 1996), (Rea *et al*, 1998), (Brusilovsky and Cooper, 1999).
- Training (*Owen et al, 1993*), (Kasvi et al, 2000).

However, having conducted a review of this potential technology in respect to managing both tacit and explicit knowledge in the domain of machined part cost estimating, it was decided that developing a true hypermedia application would not deliver an appropriate solution to the situation at the case study company. Whilst hypermedia would have certainly addressed issues of knowledge management and organisational learning, it would have not have integrated cost estimating techniques such as parametric estimating and analogy-based reasoning, unlike an *intelligent* *system* solution (Tiwari, 2005). Therefore it was difficult to justify the extent to which the accuracy of estimate would be improved. Further consideration was given to the likely return on investment (ROI): constraints of time, development and infrastructure costs, and the potential for adopting the hypermedia technology elsewhere in the group, all of which were negatively received. Instead, key stakeholders expressed a preference for a solution which placed more emphasis on decision support; which subsequently directed the research towards a method of estimating which integrates aspects of feature-based costing and case-based reasoning.

At present many of the case study company's estimates are made in the absence of complete information about the decision consequences. What is required is a set of 'expert rules, based on intuition and experience' (Kandel *et al*, 2001) which can assist the decision making process. 'Since the direct predictions of the future may not be accurate, a decision maker can consider using some information from the past. The idea is to utilise the potential similarity between the patterns of the past and the patterns of the future.' This research proposes the development of a knowledge based system which predicts decision consequences, using expert rules. It sets out to establish the extent that an information system can tackle the same problems as human activity could. There are three distinct approaches to acquiring the relevant knowledge for a particular domain:

- the knowledge is teased out of a domain expert
- the builder of the knowledge-based system is a domain expert
- the system learns automatically from examples

Knowledge acquisition (Milton, 2003) includes the elicitation, collection, analysis, modelling and validation of knowledge for knowledge management projects. Some import issues in knowledge acquisition include:

- Most knowledge is in the heads of experts
- Experts have vast amounts of knowledge
- Experts have a lot of tacit knowledge
- Experts are very busy and valuable people
- Each expert does not know everything
- Knowledge has a 'shelf life'.

The tools and techniques used in this research for knowledge acquisition were interviews; process mapping; concept mapping; observation and commentating, Figure 27 shows where these tools can be appropriately applied.

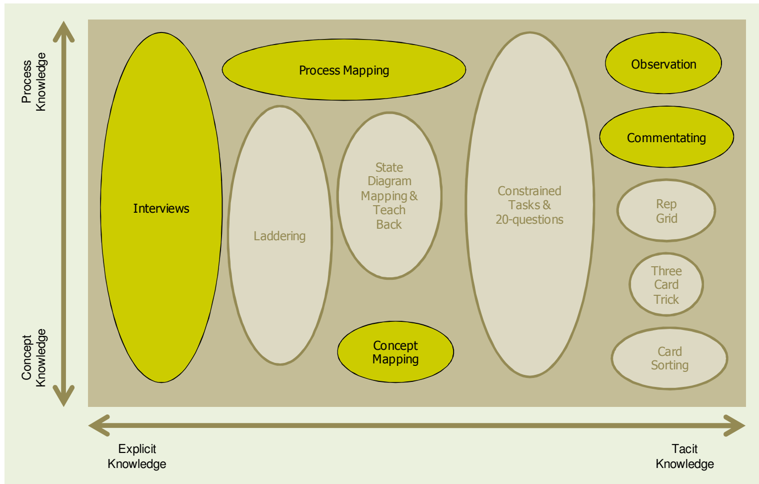


Figure 27. Comparison of KA techniques (adapted from Milton, K., 2003)

In terms of organisational advantages, expert systems can offers benefits in knowledge retention; knowledge distribution; training; competitive edge and cost reduction. Expert systems process knowledge rather than information. This knowledge is frequently represented in the form of *rules*; which store the heuristics that guide the human expert. The basic structure for an intelligent information system is shown in Figure 28.

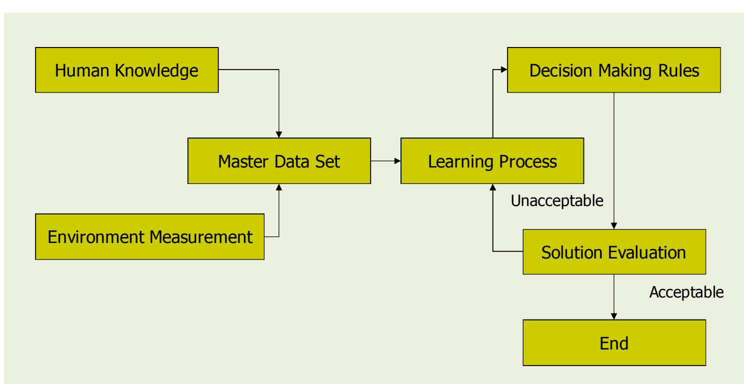


Figure 28. A basic structure for Intelligent Information Systems (Tiwari, 2005)

Actions are executed when the conditions of the rules are satisfied. The rules created in this way are collectively known as the *knowledge base* (Darlington, 2000). The other essential component of expert systems is the *inference engine*, which selects a rule for testing and then checks if the conditions for that rule are true. When the conditions of the rule are found to be true, the conclusion of the rule is true. The conclusion of the rule will be added to the knowledge base or may be displayed via the user interface for information.

The cost estimating technique which most closely meets the requirements of the case study company's quotation process is *feature-based costing*. The logic behind FBC is to identify features associated with a product, and estimate the cost of the product based on its individual characteristics. This process matches the approach to *detailed estimating* currently undertaken by the expert estimators. Furthermore, by deciding to implement the technique at the lowest level of decomposition (i.e. definition of individual attributes of a product), the feature-code structure can:

(i) specify the feature definition,
(ii) establish cost estimating relationships,
(iii) enable a further process to be applied, that of the intelligent system methodology *case-based reasoning* (CBR).

This use of a second estimating technique (CBR) means that analogical reasoning can also be applied to the estimating problem. Comparing two independant sources of estimates can surface uncertainities (Parekh *et al*, 2009), i.e. a qualitative technique (CBR) and a quantitative technique (FBC), with the intervention of a estimator being used to validate the results where necessary. The applicability of FBC to the later stages of the product lifecycle i.e. full scale development and production (and similarly, detailed cost estimation), is discussed by Rush and Roy (2000).

The benefit from introducing analogy-based reasoning into the solution arise from:

> 'When confronted with a new problem, for which the solution is not known, humans generally search for similar problems that they have been able to solve in the past (Rich and Knight, 1991).'

General theories of analogical problem solving describe frameworks for understanding the processes that an expert using this type of reasoning would exhibit. Case-based reasoning is best focused on situations where the source of the analogy is drawn from the same domain as the problem its seeks to solve, in such situations the mapping new cases and past cases is often straight-forward because a common set of features is shared, which will be the case in machined part estimating.

CBR is a successful artificial intelligence methodology currently employed in a variety of commercial software. CBR works by selecting a case from a stored database of past cases that best resemble the characteristics of the problem currently under investigation. CBR is a relatively recent concept, with the original research conducted in the early 1980s as first described conceptually by Schank (1982). Cunningham (1998) suggest case based reasoning can be effective in situations where experience, rather than theory, is the primary source of knowledge; where solutions are reusable, rather than unique to each situation or where the objective is the best available solution rather than a guaranteed exact solution. 'When confronted with a new problem, for which the solution is not known, humans generally search for similar problems that they have been able to solve in the past (McKenzie, 1995).' CBR is a methodology for introducing intelligence into the analogy approach. There are two fundamental concepts for CBR (Tseng et al, 2005). 'One is that similar problems will have similar solutions. The other is that the same problems will often occur.'

CBR provides a cognitive model of how people solve problems, by adapting solutions that were used to solve old problems (Kolodner, 1993) (Riesbeck and Schnak, 1989). CBR provides a "hierarchical case memory structure and context-based indexing method for retrieval and reuse of previous production data and their costs" (Perera and Watson, 1998). Cases are selected from a stored database of past cases that best resemble the characteristics of the problem currently under investigation. Information held in the retrieved case is then reused to provide an initial solution to the problem. When it does not fully satisfy the specification required the retrieved case is revised using domain rules, heuristics and/or human intervention. The revised case is then evaluated to assess suitability and retained or discarded. However, whilst CBR may provide the estimator with fast access to information, the quality of this information is highly dependent on effective linkages to similar past cases.

With guidance from analogical and case-based theories of problem solving, a framework for expert reasoning is shown in Figure 29. The basic steps of the CBR approach are thus:

Step 1: *Index assignment*. Case representation and storage: organisation of the information describing the problems and their solutions. Classify cases in the database through different features that serve as indexes.

Step 2: *Case retrieval in the database.* Searches the case library for the case(s) that best match the problem (target case). For a new problem, enter the index values for its features and compare cases to look for the one that has the highest similarity.

Step 3: *Old case adaption.* Revises the retrieved case(s) to fit the current problem context. Adaption methods vary depending the system context (Leake, 1996), (Hanney and Keane,1997), (Jarmulak et al (2001) and (Watson, 1997).

Step 4: *New case evaluation*. Evaluate the adjusted case to ensure its feasibility.

Step 5: *Case accumulation and storage*. The storage of new cases and the update of existing cases in the database to achieve the self-learning function. Fenves et al (2000) state that the more cases contained in the case base, the better the performance of the system. Saving the case of new problem solution in the database will reach the purpose of knowledge regeneration for future re-use. (Tseng et al, 2005).

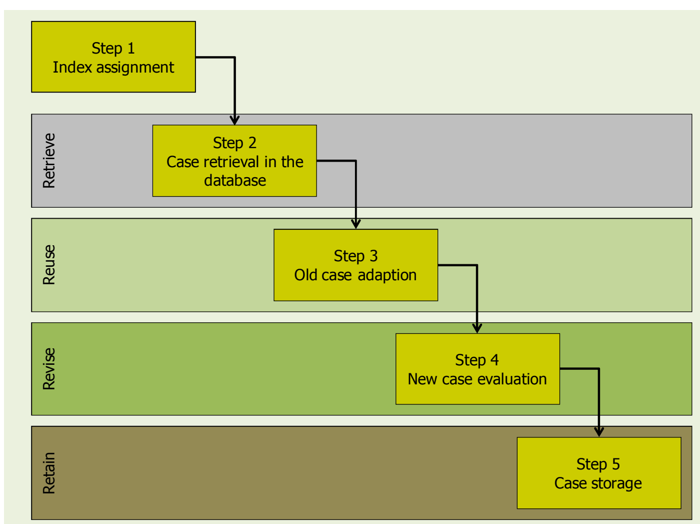


Figure 29. The CBR Cycle (adapted from: Perera,1998; and Tseng, 2005).

There are a number of applications within the CBR market and some examples are shown below, however there are relatively few instances of its application being directly integrated into manufacturing processes. Examples include:

- Help desk applications (Göker & Roth-Berghofer, 1999).
- Scheduling and process planning (Chang et al, 2000) (Schmidt, 1998)
- Machine design (Vong, Leung & Wang, 2002)

- Architecture design (Heylighen & Neuckermans, 2001)
- Customer relationship management (Choy, Lee & Lo, 2003) (Changchien & Lin, 2005) (Chiu, 2002)
- Fault diagnosis (Liao, Zang & Mount, 2000) (Yang, Han & Kim, 2004)
- Knowledge management (Lau et al, 2003) (Wang & Hsu, 2004)
- Software Estimation (Mukhopadhyay et al, 1992)
- Maintenance Support (Auriol, 1999)
- Benefits evaluation (Lin, Sayed & Deleur, 2003)
- Project planning (Lee et al, 1998)
- Workflow model management (Madhusudan, Zarshall, & Marshall, 2004)
- Environmental systems (Hector et al, 2004)
- Steel bridge engineering (Waheed & Adeli, 2005)

Commercial CBR tools are generally characterised by a sophisticated case representation and memory structure, integrating advanced indexing and retrieval mechanisms. A CBR system derives its power from its ability to retrieve relevant cases quickly and accurately from its case base (Arditi 1999). Whereas their case adaption mechanisms tend to be less sophisticated, owing mainly to individual applications requiring very diverse forms of domain knowledge.

Applying the CBR approach to the estimating process poses two problems. First, how do we characterise the engineering *features* of the machined part as *cases*? Second, how do we identify similar cases for retrieval? Assessing similarity is a problem, to which there are a variety of approaches including a number of preference heuristics proposed by Kolodner (1993):

- *Nearest Neighbor Algorithms*. These are the most popular and are based upon straightforward distance measurement or the sum of the squares of the differences for each variable. In either case each variable must be first standardized (so that it has an equal influence) and then weighted according to the degree of importance attached to a feature.
- *Manually guided induction*. Here an expert manually identifies key features, although this reduces some of the advantages of using a CBR system in that an expert is required.

- *Template retrieval*. This function in a similar fashion to query by example database interfaces, that is the user supplies values for ranges, and all cases that match are retrieved.
- *Goal directed preference*. Select cases that have the same goal as the current case.
- *Specificity preference*. Select cases that match features exactly over those that match generally.
- *Frequency preference*. Select cases that are most frequently retrieved.
- *Recency preference*. Choose recently matched cases over those that have not been matched for a period of time.
- *Fuzzy similarity*. Where concepts such as at-least-as-similar and just-noticeable-difference are employed.

The approach described in this thesis organises cases hierarchically through *shared feature networks*. In defining the machine parts features, which become the case, the user is conducting a form of *manually guided induction*. Initially, the new case is matched against the contents of each node in the network at the highest level, then its descendant levels, until the best-matching node is returned. However the proposed method also makes use of *specificity preference*, which is definable when creating new ‘operations’ in the software application. This explained in further detail in Chapter 4.

Partitioning the data makes retrieval more efficient than a serial search, but keeping the network optimal as further cases are added can be problematic, therefore it is important that the system is designed to help maintain the networks effectively. This is an important consideration, as how the case definitions are constructed and stored directly relates to how the product features are defined for Feature-based Costing. Chapter 4 of this thesis describes how METALmpe enables product features to be defined to facilitate both FBC and CBR, in a process which also supports and enhances organisational learning around its *enriched work representation*s (Mulholland *et al*, 2001). Work representations are *tools* and documents embedded in work activities which are used to support collaborative working and learning, these are *enriched* by tightly coupling the system with its context.

When developing a decision support system, it is important that sufficient emphasis is focussed on the business processes and not solely the development of an information system. This is particularly relevant in small firms, which often lack managerial resources and functional specialists, leading to poorly managed activities (Buratti and Penco, 2001). It has been argued that whilst enhancing human resources, ICT has only been used for relatively low-level exchanges of knowledge (Scarbrough et al, 1999); and that information systems have not always been effective in capturing the knowledge that decision-makers use daily (Davenport, 1994). This thesis describes a decision support system which aims to capture and disseminate estimating knowledge, which will be of valuable daily benefit to the next generation of estimators at the case study company.

2.6 Research summary

2.6.1 Clarification of the aim for the research

The restricted context in which the research is set is:

> *Small scale production of medium and large-sized machined steel forgings; produced using manually controlled, conventionally operated, machine tool equipment.*

(i) The research aim is to validate the concept of a feature-driven case-based machined part estimating cost model; based on a hybrid feature-based costing / case-based reasoning technique specifically tailored to meet the needs of specialist engineering SMEs.

(ii) The commercial aim is development of an estimating system capable of providing intelligent decision support for the case study company; including the project deliverable 'METALmpe' - application software which creates a tangible asset and contributes to improved operational efficiency and competitiveness.

The objectives are to contribute to the effectiveness of an organization by:

- Shortening the time taken to produce estimates and quotations.
- Improving the reproducibility and dependability for calculations of process time and cost.
- Capturing evolving organisational knowledge; to inform future decision making and reduce reliance on individual 'experts'.
- Creating a learning platform which will support and enhance workplace learning.

2.6.2 Research questions

1. Through novel use of the hybrid feature-based costing / case-based reasoning cost model, can METALmpe produce estimates of production times which are accurate (-5% to +10%) when compared with the actual times taken? Accuracy levels greater than (-5% to +12%) would be seen as performance improvement over the existing process of manually compiled estimates.

2. Is the viability of METALmpe justifiable in terms of cost for SMEs? Assuming a typical annual investment in ICTs for SMEs of 1% of turnover.

3. Can the METALmpe process method configure networks of feature definitions, cost estimating relationships and algorithms which enable:
   (i) Codification of cost engineering knowledge,
   (ii) Capture of evolving estimating and production knowledge.

   Thus, reducing future dependence on the expert estimator?

4. What benefits can be gained from the development of bespoke application software for the feature-driven case-based cost model? In terms of:
   - Shortening the time taken to produce estimates and quotations.
   - Creating a learning platform which will support and enhance workplace learning.

5. To what extent can the method and software application be shown to be generically applicable?

2.6.3 Contribution to Knowledge

In July 2003, the Decision Engineering Group in Enterprise Integration at Cranfield University published a report titled 'Cost Engineering: Why, What and How? (Roy, 2003)'. *Decision Engineering* was described as an 'emerging discipline which focuses on developing tools and techniques for informed decision making by utilizing data and information available (facts) and distributed organizational knowledge.' During the early stages of the research described in this thesis, the DEG report provided an insight to the state-of-the-art in cost estimating, particularly in respect to Professor Roy's views on the future of cost engineering (Roy, 2003). The most notable of these observations were:

- 'Another area of future growth and research in cost engineering is to capture and reuse human expertise or knowledge during the development of a cost estimate.'
- 'Current commercial software needs to go a long way to develop this capability in an intelligent manner, so that the additional workload on the cost estimators is reduced.'
- 'There is a need to develop low cost engineering software for Small and Medium scale Enterprises (SMEs). This is particularly relevant for European SMEs, where there is a distinct lack of commercial software for this sector.'

This thesis describes how this 'baton' (a metaphor for the above observations) was carried forward in the project at the case study company, and why a *feature-driven case-based approach* to machined part estimating provides a strategic solution to the research problem within the context of a SME.

Based upon the following concepts of 'originality' proposed by Phillips (1992): '*being cross-disciplinary and using different methodologies*' and '*adding to knowledge in a way that hasn't been used before*'; this thesis presents the case that the practical method for feature-driven case-based machined part estimating demonstrates an original contribution to knowledge, see Chapter 6.

2.7 Chapter summary

The essence of the commercial project is the development of a process for the management of estimating and process performance knowledge, which the literature reviewed suggests could lead to a valuable strategic asset to a small or medium sized company. The suggestion is that by improving the ability of an organisation to respond more effectively to customer enquiries in terms of: speed of response, accuracy and reliability; the supplier will be able to get much closer to their customers and operate with increasing flexibility.

The knowledge structures of individuals, quality of information and provision of sufficient time in which to make judgements, are vital elements of effective decision making (Weick, 1995; Daniels, 1999; Sparrow, 2000). The development of information systems and decision support systems have been shown to benefit companies seeking to control their organizational processes (Olaopa, 2003; Shehab, 2005) and reduce the likelihood of overburdening individuals with information, which might otherwise impair their decision making ability.

The feature-driven case-based estimating technique described in this thesis and the application software METALmpe (which is a deliverable of the commercial project) evolves out of the following principles:

- The need for continuous evaluation
- The necessity to capture newly evolving knowledge
- The belief that technology can transform tacit and explicit knowledge into a tangible asset
- The support of workplace learning

The importance of expertise, knowledge and the ability to innovate is recognised by the literature, and the project aims to deliver innovative application software which enables effective cost estimating. This would be viewed as a key strategic capability, contributing to competitive advantage. Linking decision support with organisational learning encourages development of a company skilled at creating, acquiring and transferring knowledge and at modifying its behaviour to reflect new knowledge and insights. Prahalad and Hamel (1990) argue that ‘in the long run, competitiveness depends on an organisation’s ability to develop a core of competence around a key skill or set of interrelated skills’. Continuing growth in innovative ICT enables improvements in the cross-boundary interdependence between organisations: customers, suppliers, partners etc. Organisations are better able to collaborate from remote locations (with both internal and external customers), leading to changes in organisational structure and interactions. If successful, METALmpe will break down some of the traditional barriers to entry into the estimating community of practice:

- making it easier for non-experts to produce estimates and quotations (without constantly relying on expert estimator input),
- enabling estimates to compiled from any remote location over the internet,
- providing the necessary continuity and support which will ensure the future ability to provide low-volume, speciality machined parts as a core competence.

3 Methodology

3.1 Introduction to the methodology

Chapter 2 established the practical and theoretical problems faced by the research and described the many interlocking academic, management and technology disciplines, which would influence the solution to the following research questions:

1. Through novel use of the hybrid feature-based costing / case-based reasoning cost model, can METALmpe produce estimates of production times which are accurate (-5% to +10%) when compared with the actual times taken?
2. Is the viability of METALmpe justifiable in terms of cost for SMEs?
3. Can the METALmpe process method configure networks of feature definitions, cost estimating relationships and algorithms which enable:
   (i) Codification of cost engineering knowledge,
   (ii) Capture of evolving estimating and production knowledge.
   Thus, reducing future dependence on the expert estimator?
4. What benefits can be gained from the development of bespoke application software for the feature-driven case-based cost model? In terms of:
   (i) Shortening the time taken to produce estimates and quotations.
   (ii) Creating a learning platform which will support and enhance workplace learning.
5. To what extent can the method and software application be shown to be generically applicable?

The research methodology required cross-boundary co-operation and co-ordination to ensure effective application. The decision support system development, which is discussed further in Chapter 4, required information technology innovations which necessitated inter-organisational collaboration (Taylor *et al*, 2000) and research & development alliances between the case study company, Zenzero Solutions and Cranfield University. Of the seven dimensions of knowledge strategy (Open, 2005c), the emphasis for this project concentrated on four areas from which knowledge can be exploited to achieve demonstrable business benefit, shown in Figure 30.

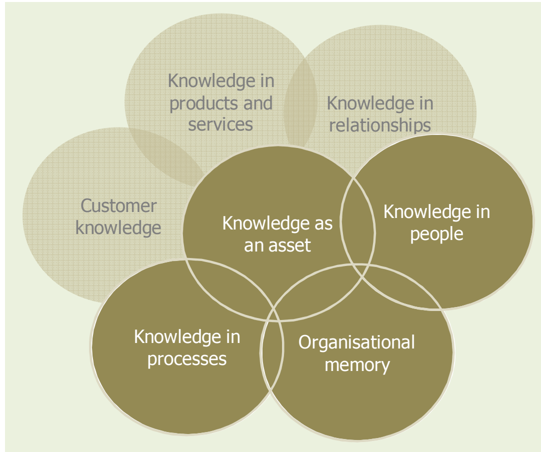


Figure 30. The four dimensions of knowledge strategy influencing the project methodology (Open, 2005c).

Chapter 3 defines the research methodology, the tactics adopted in its implementation and why it was considered appropriate. Justification for each of the four elements of research methodology applied during this work (approach, type, category and investigative techniques) follows in section 3.2, and the *types* of research applied are indicated in Figure 31.

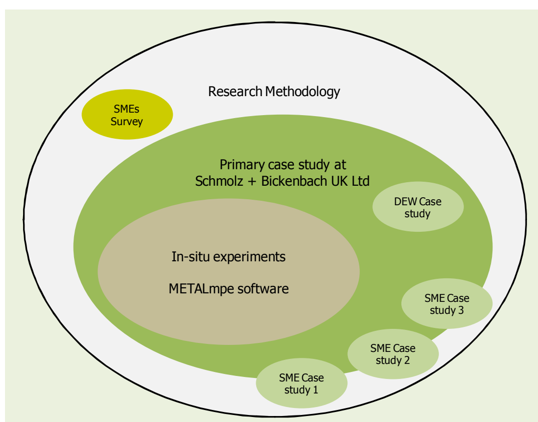


Figure 31. Choice of research types

The development of a technological solution required a detailed understanding of interdisciplinary and cross-boundary nature of the problem. Literature from the field of *systems practice* provided the methods by which a clear understanding of the problem situation could be ascertained, and *systems thinking* concepts provided insight for the conceptual design of the decision support process. The research procedures described in section 3.3 take into account the influence of the research engineer in the *system of inquiry* and *the situation of interest* (Figure 32a). The experience of the research engineer in the project at the case study company is also represented in Figure 32. The metaphor of the *juggler* (BECM) used in Figure 32b symbolizes **B**eing a practitioner, **E**ngaging with a 'real world' situation, **C**ontextualizing a particular approach and **M**anaging their involvement with the situation. In order to make a difference in any intervention, there needs to be an appreciation of the iterative process of interaction between theory, practice and learning. Experiential learning is central to the effective development of systems practice, with the model of reflective practice playing a key role in the appreciation of 'self' and interaction with stakeholders.

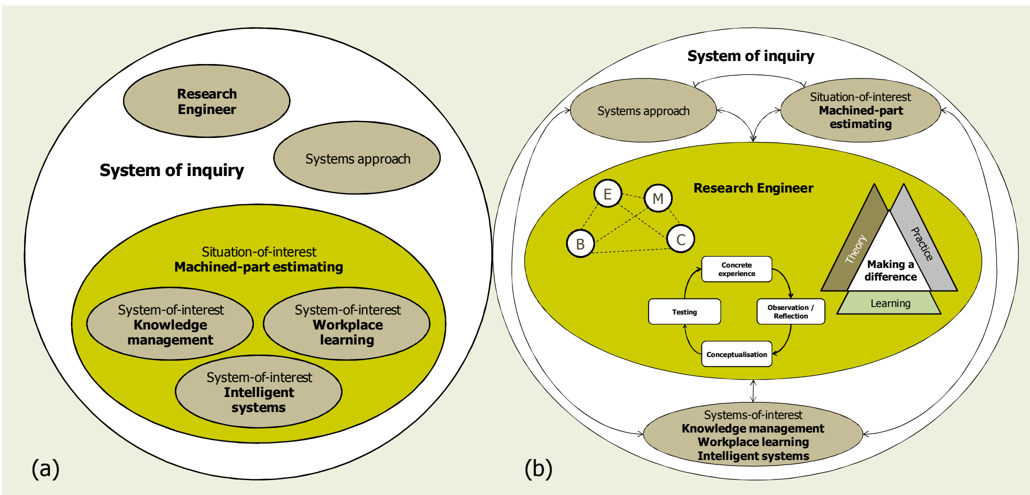


Figure 32. (a) The 'system of inquiry' and (b) the research engineer in the system of inquiry

3.2 Justification of the methodology

The research aimed to provide practical solutions to problem situation at the case study company through the implementation of a system-based approach to machined part estimating. This required a clear understanding of the existing situation:

(i) the perceived problems and opportunities for improvement,

(ii) alternative methods of cost estimating required investigation,

(iii) the availability of technologies to support the estimating function.

The nature of the research problem necessitated joined up thinking and a combination of various systems methods were identified (in a model of planned change, Figure 4, Chapter 1) in order to facilitate delivery of an effective solution. The problem was amenable to quantification and the measure of what would constitute success could be identified, but the steps required to achieve success were initially unclear (Open University, 2000).

The research approach adopted was that of empirical, inductive research. The initial stages of the research evaluated whether the implementation of a decision support process could benefit the organisation or if alternative approaches to estimating should be considered further. Once a model of planned change was established (Figure 4, Chapter 1), an investigation proceeded to establish the possibilities for developing a flexible hybrid FBC/CBR cost model capable of providing intelligent decision support in the context of an SME engineering company.

The choice of type and category of research were influenced by the requirement to evaluate:

(i) approaches to managing the knowledge of an expert estimator,

(ii) commercially available software applications,

(iii) the benefits of a bespoke application development.

These influences lent towards a triangulation of research ‘types’: survey, experiment and case study. Gorman and Clayton (1997) suggest triangulation increases the scope, depth and accuracy of a study.

A major influence on the direction taken in respect to systems development was the case study company’s existing bespoke ERP system: METAL (Material and Engineering Transaction Application) developed by Zenzero Solutions Ltd. In addition to the research aims and objectives (section 2.6), specific directives from the project sponsor (Hadley, 2005) were:

(i) 'Any new software must seamlessly integrate with METAL.'

(ii) 'Ideally we only want one provider of IT systems support.'

(iii) 'Data entry requirements must be keep to a minimum, and double-entry should be avoided.'

(iv) 'Changes to standard operating procedures should be kept to a minimum.'

Commercially available estimating software was reviewed and observations made on the potential effectiveness of these applications for improving machined part estimating at the case study company. 'Commercial off-the-shelf' (COTS) solutions scanned were:

- Match-it – www.make247.co.uk
- Kapes – www.kapes.com
- True H and Price H – www.pricesystems.com
- SEER - www.golarath.com

However, given the aforementioned constraints and the cost of implementing COTS packages (e.g. Kapes: typically £6,000+ per seat license, plus implementation and training); the potential benefits from the functionality of the COTS packages were not sufficient to merit further consideration. Zenzero Solutions were already the preferred (and trusted) IT solution provider, and a decision to develop a bespoke estimating module for the METAL suite was subsequently approved.

An exemplar case study formed a substantial part of the research. The case study proved invaluable in establishing the context and perspective of the research, whilst providing the main measure of the effectiveness of potential solutions. Verification testing was an integral part of the case study (re-processing actual company records), and featured prominently in the overall evaluation of the research. The essence of the case study was to evaluate the proposed solution under normal operating conditions. Importantly the case study provided an indicator as to the effects on estimator performance between the existing and proposed methods. The most notably measurements being: the effect on a novice estimators' ability to produce sufficiently accurate estimates; and the comparison in results between the existing *detailed estimating* process and the METALmpe approach (to provide a measure of accuracy for each).

To ensure the case study was methodologically rigorous; strategies were adopted (Gibbert *et al*, 2008) which (in the positivist tradition) emphasize the quality measures *internal validity*, *construct validity*, *external validity* and *reliability*, Figure 33.

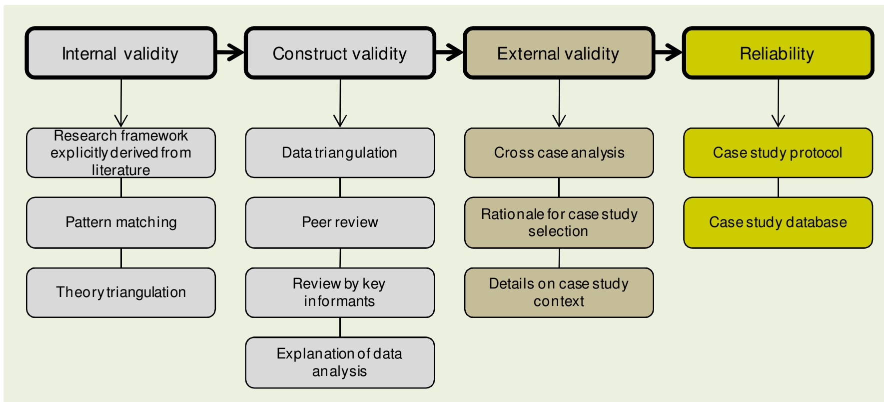


Figure 33. Model of a rigorous case study (adapted from Gibbert *et al*, 2008)

Internal validity refers to whether the researcher provides compelling casual argument and logical reasoning that defends the research conclusions. *Construct validity* refers to the quality of the conceptualization of the concept and the extent to which the procedure leads to an accurate observation of reality. *External validity* refers to whether theories account for phenomena in settings other than the case study in which they are studied, through a process of analytical generalisation. *Reliability* refers to the transparency and reproducibility of the study, enabling subsequent research to arrive at the same insights.

In order to conduct a thorough investigation other methods were used in the research. Ethnography, an approach of participant observation which is considered to be effective in studies of small groups, was used to understand the ways that individuals at the case study company operate and communicate; aiming for 'a rich detailed description of observed events, which can be used to explain the social processes which are involved' (Open, 2001). This study was conducted in the *diagnosis* stage of the research to gain an in-depth understanding of the estimating procedures and elicit information which helped determine the software requirements.

Survey methods were used in both the *diagnosis* and *planning and negotiating interventions* stages during the specification of requirements. The primary research included semi-structured face-to-face interviews with key employees at the case study company; the output of these interviews was then subject to qualitative analysis (Open, 2001). Subsequently, a questionnaire was distributed to engineering SMEs in the West Midlands, to investigate the potential use of information technologies for machined-part estimating.

These research methods suited the small scale and focussed qualitative and quantitative evidence available 'where the focus was on the detail of the commonsense character of specific everyday practices to provide an explanation of what was occurring (Open, 2001).'

The case study facilitated the development of a bespoke software application, based on a feature-driven case-based cost model. The methodology described in this chapter and the procedures defined in section 3.3 were designed to test the validity of the cost model and the effectiveness of the METALmpe application in respect to the research questions.

3.3 Research procedures

3.3.1 Literature review

The research commenced with a literature review (Table 7) to understand the drivers of the move towards using intelligent systems for machined part cost estimating. Subsequently, the research aimed to understand how the concept of advanced cost models has become associated with, and necessary to, improved estimating practise. The research established relevant links between estimating practises, knowledge management and workplace learning, Figure 34, and focussed on developing a specific area of interest with was mutually beneficial.

Typical databases used	*Key words*	*Relevant timeframe*
Science Direct	Cost estimating techniques	1995 onwards
EBSCO	Feature-based costing	2000 onwards
ProQuest	Case-based reasoning	2000 onwards
Web of Knowledge	Intelligent systems	1995 onwards
Emerald	Knowledge management	NA
SearchHub	Lifelong learning	NA

Table 7. Search process for literature review

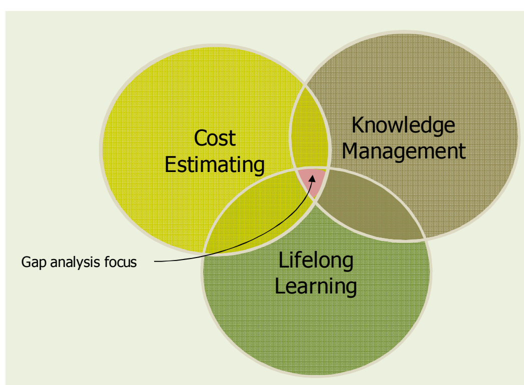


Figure 34. Focus of the literature review

3.3.2 Deploying research tactics

In order to conduct a thorough investigation in the diagnosis phase of the project, a triangulation of methods were used in the qualitative research: Ethnography, survey and case-study.

(i) Ethnography:

This approach of participant observation was used to understand the ways that individuals at the case study company operate and communicate. The ethnographic process provided an evaluation of the culture and structure of the organisation (Hart, 1998) (Crawford et al, 1999).

Systems thinking techniques provided insight to the *system-of-inquiry,* with the soft systems method (SS-method) (Checkland and Scholes, 1990) being applied as a interpretive 'process' method. This was useful in determining the existing *situations-of-interest*, and what it might be effective (worthwhile) to do about them.

The learning system deployed in this diagnosis phase of the research facilitated the production of a positioning paper on '*a systems approach to machined part estimating'* (Dimmock, 2007), which was presented at the 24th International Manufacturing Conference at the Waterford Institute of Technology, Ireland.

(ii) Survey:

The first stage of this primary research at the case study company involved semi-structured face-to-face interviews with three key employees, the Managing Director, Machine Shop Estimator and the Systems Manager. The output of these interviews was then subject to qualitative analysis (Open, 2001). This surfaced issues associated with business objectives; critical success factors and identified two systems of interest, Figure 15.

Subsequently, a questionnaire was distributed to 83 engineering machine shop SMEs in the West Midlands. The survey evaluated the extent to which IT was utilised for machined part estimating for SMEs (Appendix A). Questionnaires 'can identify people willing to be interviewed and can be used effectively with case studies, helping to put them into a wider context (Sheffield University, 2003).'

(iii) Case-study:

The investigation of company requirements was *descriptive* and permitted an explanatory account of the predicted outcomes from adopting systems approaches, it featured both:

- *Formative Evaluation:* 'to make improvements to a specific programme, policy or set of activities at a specific time and place, and with a specific group', and
- *Ethnomethodogy:* 'to describe the ways in which people make the sense they do in and through the ways they communicate (Hart, 1998).'

During requirements elicitation a model of the existing cost estimating process was generated using IDEF0 functional modelling (detail in Appendix B), which traced all the inputs, controls, mechanisms and outputs which contribute to the costing of machined parts.

The case study specifically addressed the application of knowledge management techniques to capture and retain machined-part estimating knowledge. The significant knowledge management issue was codification (the transfer of knowledge from tacit to explicit) within the proposed system. These knowledge intensive tasks were identified and relevant knowledge captured, through the use of a technique known as Knowledge = Expert – Novice (KEN) (Bailey *et al*, 2000), Figure 35. Within this approach the novice (research engineer) used the data and tools of the cost-estimating experts to produce an estimate. As difficulties arose, the novice called on the experts for the solution. As the novice works through the required activities and tasks, the knowledge management requirements are documented.

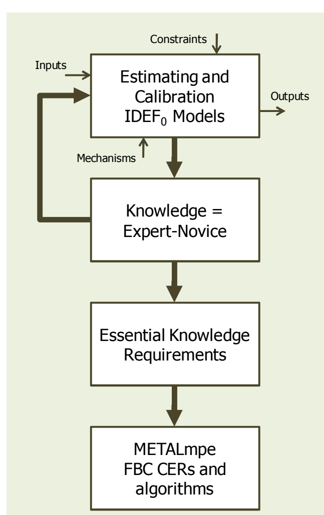


Figure 35. Knowledge capture (adapted from Rush and Roy, 2001a)

Issues of particular interest to the project at the case study company, which needed clarification and agreement between all stakeholders, were:

(i) What is machined part estimating / a estimator?
(ii) What influences estimating practice and performance?
(iii) How do engineering estimators actually estimate?
(iv) What makes a good estimate?
(v) What support is needed to match estimating task needs?

3.3.3 Verification and validation of the METALmpe solution at the case study company

The evaluation phase of the model of planned change was designed to verify and validate the METALmpe application software and the underpinning estimating method. The purpose of the evaluations was to establish whether the project had produced a satisfactory solution to the problem faced by the case study company, the extent to which this solution was also applicable to other similar organisations, and whether the research conducted stood up to peer review.

Past company records at the case study company were used to populate specific METALmpe 'features definitions' with historic performance data from 2004 through to 2007 inclusive, in order that the effectiveness of CBR could be evaluated. The company records consulted provided information on: the estimates of time and costs in the product realisation process; the production route used; and actual production performance. Information relating to the *process* of costing products (specifically in terms of the calculations of times for machining operations) was of primary importance. Similarly, emphasis was placed on establishing the costs for other value-adding processes, such as heat treatment and non-destructive testing.

Verification tests (Tables 8 and 9) were conducted at the case study company which tested the accuracy of both feature-based and case-based estimates compared with actual performance data and the original expert estimates. The samples were selected to ensure they tested the full range of estimating functionality required by the case study company. The products sampled in Table 8 (Appendix L) were a new product range in 2009, and although the machining was limited to milling only, all estimating options could be tested:

- Expert = detailed estimates produced by the expert estimator
- FBC = estimated by feature-driven algorithms
- CBR_{pa} = estimated by parameter adjustment on nearest matching cases
- CBR = estimated based on data from exact matching cases

Appendix	Actual product sample	Sample size	Estimating technique to be evaluated			
			Expert	FBC	CBR_{pa}	CBR
I	970165	5	•	•	•	•
	980066	20	•	•	•	•
	970505	15	•	•	•	•
	980197	10	•	•	•	•
	970244	15	•	•	•	•
	970249	10	•	•	•	•
	970502	10	•	•	•	•

Table 8. Verification test criteria: AISI 8630 MOD oil tool forgings milled six faces

The products sampled in Table 9 (Appendix M) were an established product range, requiring numerous machining activities, thus enabling analysis at both 'product' level and 'operation' level.

Appendix	Actual product sample	Sample size	Estimating technique to be evaluated			
			Expert	FBC	CBR_{pa}	CBR
J	3″ SEC Body	20	•	-	-	•
	3″ DEC Body	71	•	-	-	•
	3″ TEC Body	75	•	-	-	•
	3″ SEC Body	52	•	-	-	•
	3″ DEC Body	60	•	-	-	•
	3″ TEC Body	79	•	-	-	•
	3″ SEC Body	20	•	-	-	•
	3″ DEC Body	20	•	-	-	•
	3″ TEC Body	18	•	-	-	•

Table 9. Verification test criteria: AISI 8630 MOD rough machined blow out preventor forgings

Following training workshops with METALmpe the participants (two novice estimators, one expert estimator and the project sponsor) were surveyed to assess their perception of the validity of the system. The criteria and questions were based upon Johnson and Scholes (2003) 'generic testing criteria': *suitability*, *feasibility* and *acceptability*. The three key success criteria were used to evaluate:

- Suitability (would it work?)
    - Deals with the overall rationale.

- Does it make economic sense?
- Would it be suitable in terms of environment and capabilities?

- Feasibility (can it be made to work?)
  - Are the resources required to implement METALmpe available: funding, people, time and information?
- Acceptability (will they work it?)
  - Deals with the performance expectations of stakeholders.
  - What benefits can the stakeholders expect (financial and non-financial)?
  - What is the probability and consequence of failure?
  - What is the likely reaction of stakeholders?

The key emphasis for this peer review and subsequent member/respondent validation (Bloor, 1997) was the qualitative validation of:

(i) the system configuration,
(ii) the process by which expert knowledge is codified,
(iii) the mechanisms by which new estimates are generated, and
(iv) how current production knowledge is captured.

A final assessment of the benefits delivered by the research was conducted and conclusions made after the project had closed. The final assessment included:

- Measures of
  - Monetary benefits
  - Tangible benefits
- Overall project impact
- Key learning for future projects

Comprehensive project records (both hardcopy and electronic databases) were established and maintained for all aspects of the design and evaluation processes, these are appropriately reference and archived. This archive will be securely stored, making retrieval easy for future tests of reproducibility if necessary.

3.3.4 Evaluating the external validity of the METALmpe solution

Four external case studies (Appendices H, I, J and K) were conducted in order to assess the external validity of the estimating method, these included both SMEs and one large scale machining facility. Key decision makers from each organisation reviewed the application software in conjunction with a workbook (Figure 36), which provided both guidance on the use of METALmpe, and background information on the concepts behind the decision support process.

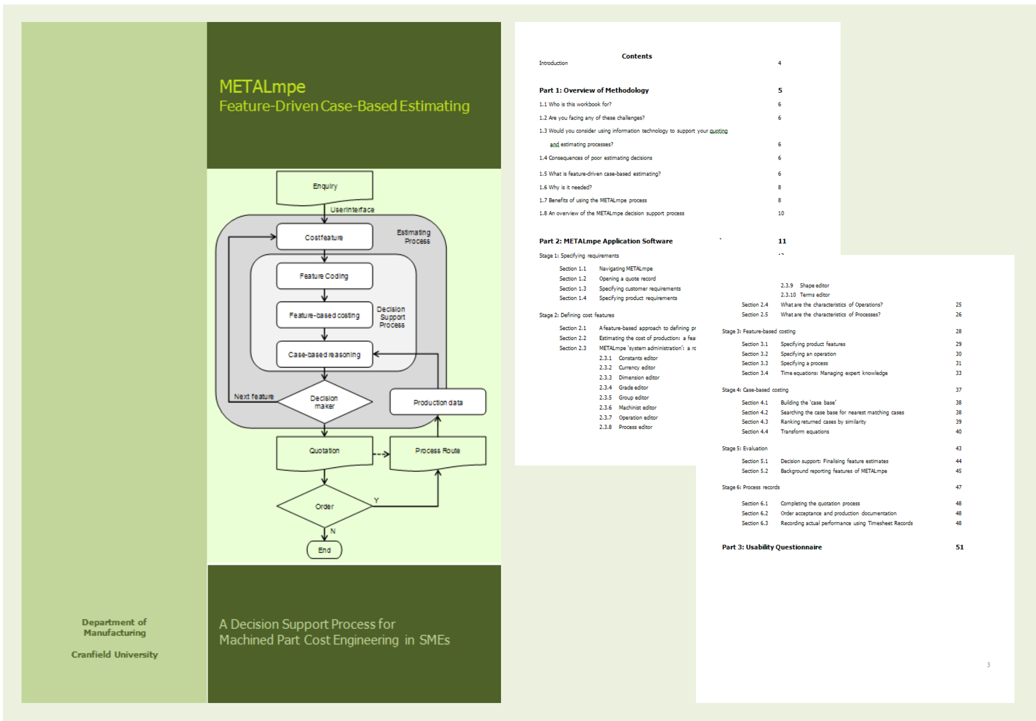


Figure 36. METALmpe workbook

In addition to the case studies, a research paper describing the 'feature-driven, case-based method of machined part estimating' was submitted for peer review to the Proceedings of the Institution of Mechanical Engineers, Part B, Journal of Engineering Manufacture (Dimmock and Greenough, 2010).

3.4 Chapter summary

This chapter described the procedures implemented to ensure the research reported in this thesis was methodologically rigorous. Robust validation procedures had to consider the many different perspectives and interests of the multiple stakeholders in the project; and emphasized the quality measures: internal validity; construct validity; external validity and reliability.

The case study was designed to produce a robust cost model, which could also be applied in other similar settings. This required a detailed and accurate understanding of the technical aspects of *intelligent* estimating systems and the impact that a systems approach to estimating would have on business performance at the case study company, hence the research methodology shown in Figure 37.

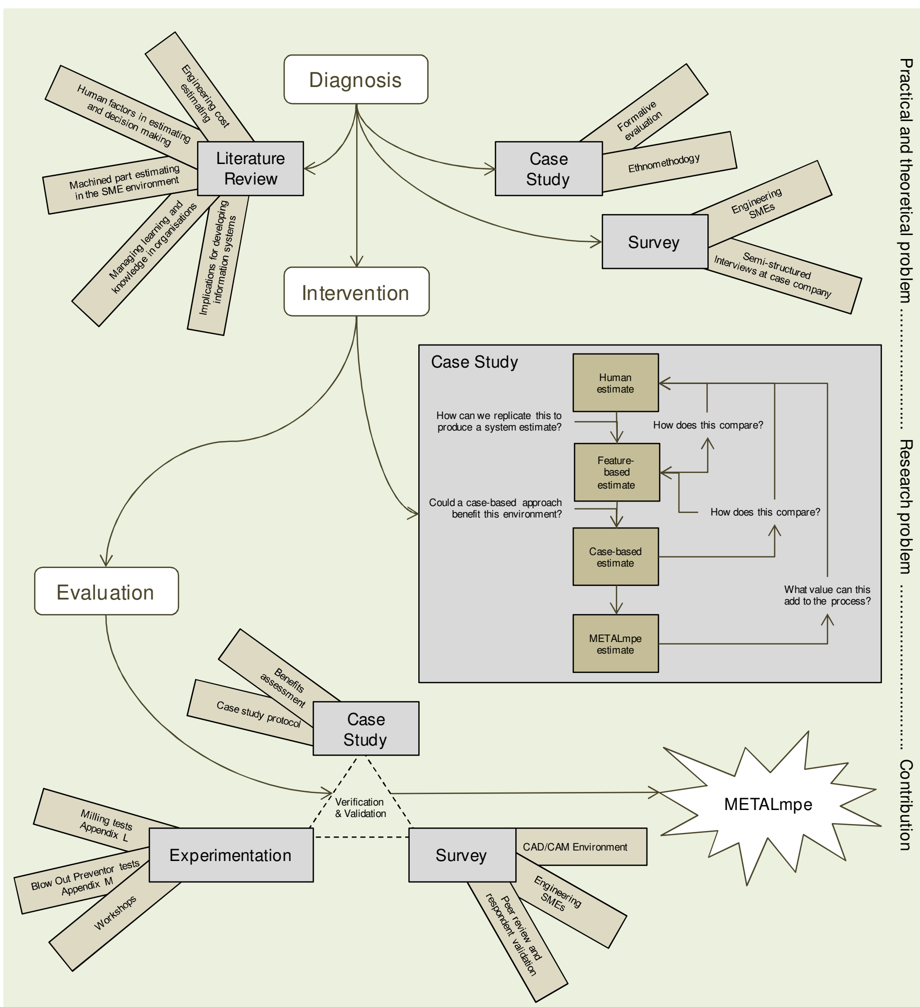


Figure 37. The research methodology.

In the following chapter, the author describes the process controls applied across the decision support system development. Issues relating to the software project management and knowledge elicitation and codification are discussed. An overview is provided of the METALmpe decision support process, and an explanation of estimating practise using METALmpe is provided.

Chapter 4 Decision support system development

4.1 Introduction

This chapter describes the application development for the METALmpe decision support system, with section 4.2 covering the management of the software engineering project. Detailed estimating knowledge elicited from the existing processes and the expert estimators is examined, as is the process by which it is codified within METALmpe. This chapter illustrates METALmpe process functionality, demonstrating its application at the case study company.

A significant knowledge management issue is codification (the transfer of knowledge from tacit to explicit) in the feature-based costing segment of the METALmpe cost model, which is discussed in section 4.2.1. The specification for the feature-defining mechanism (by which features are defined, cost estimating relationships established and estimating knowledge codified) was carefully negotiated between the research engineer, estimators and software engineer.

People are seen to own knowledge, create value, and retain organisational memory – and they can leave, which has a very detrimental short-term effect on operations. The pace of change in organisations requires continuous regeneration of their organisational knowledge base and the social and systemic dimensions of learning are the key determinants of how an organization successfully *learns*. This chapter describes a practical method for strengthening the learning opportunities in the estimating function at the case study company. The application of double-loop learning in METALmpe (Argyris and Schön, 1974) is shown in Figure 38. The principle of continuous evaluation is influential in developing a new approach to estimating, alongside the necessity to capture newly evolving estimating and process performance knowledge. The concept is to create more effective information through the transformation of experience and reduce workload through reuse of information. A further objective is to reduce data entry – simultaneously generating estimates, quotes and process routes from the initial user inputs, with sufficient accuracy to ensure the profitability of manufacturing and provide effective production instructions.

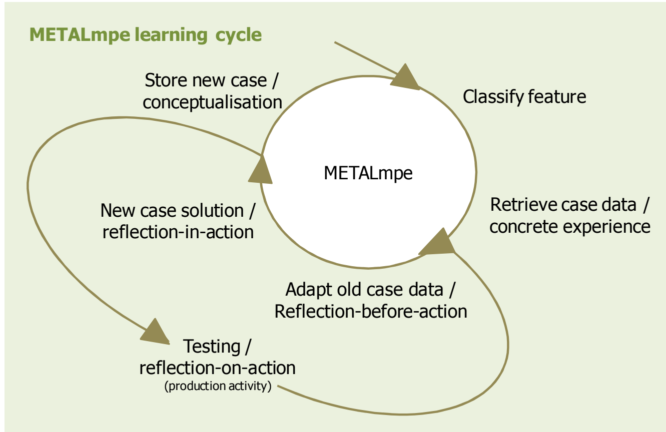


Figure 38. The application of double-loop learning in METALmpe

An agenda for the application development effort at the case study company was established, see Table 10.

Stage	Theory/Approach	Data collection	Information representation
Diagnosis	Organization analysis SS-Method Situated actions Ethnography Survey	Archives Interviews Interaction/observation Performance observation Questionnaire	Function analysis Process mapping Benefits dependency framework
	Internal validity	Pattern matching Theory triangulation	Research framework
Planning and negotiating interventions	HS-Method Knowledge elicitation Process analysis Benefits dependency Organisation analysis	Behaviour observation Interviews Archives Interviews XPat knowledge capture Stakeholder analysis Interaction/observation Abstracted experiments Return-on-investment	Task analysis IDEF0 Requirements specification Benefits dependency network Benefits cash-flow model Risk analysis
	Construct validity	Data triangulation Peer review Stakeholder review	Archival data Interview data Observation data Transcripts
Taking action	Software engineering Business transformation End-user development	Stakeholder analysis	Software requirements specification Benefits realisation plan
Evaluation	Benefits monitoring and assessment HCI usability	Stakeholder analysis Monetary benefits Tangible benefits Intangible benefits Interview Expert walkthrough In-situ experiments	Project report Quality rating
	External validity	Cross case analysis Rationale for selection Case study context	Multiple case studies Peer reviewed publication
	Reliability	Case study database	Case protocol

Table 10. Agenda for the application development effort the case study company

4.2 Managing the software engineering project

The case study company are experienced in ‘inter-organisational activity’ through their 15 year relationship with Zenzero Solutions Ltd for outsourced ICT provision. This was relevant when planning the inter-organisational collaboration (Taylor *et al*, 2000) between the case study company, Zenzero Solutions and Cranfield University. A trusting relationship (Huxham and Vangen, 2005) had developed between the companies, *managing trust in practice* is significant when managing across boundaries, Figure 39.

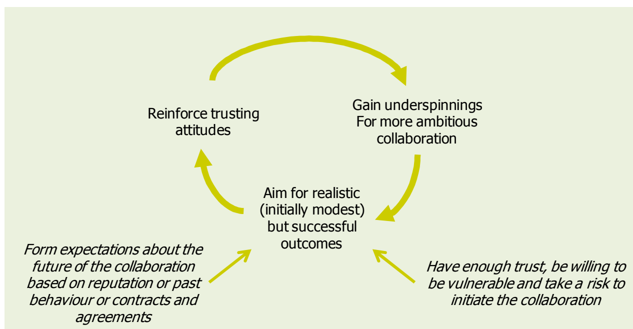


Figure 39. The trust building loop (Huxham and Vangen, 2005)

A process of stakeholder consultation was carried out; those surveyed included senior management and staff, consultants and customers. Stakeholder analysis provided input for project management: identifying potential areas of resistance and assessing commitment, and helping the co-ordination of change management activities. Ackerman and Eden (2003) provided a useful model for identifying stakeholder influence, applying this specifically to the research (see Figure 40) aided the approach to stakeholder management. Throughout the developing stages of the intervention, an iterative process of consultancy took place involving the stakeholders. Regularly this involved small focus groups, but the main method of eliciting stakeholder needs (and monitoring their perception of progress) occurred informal one-to-one meetings. A project steering group reviewed the output of stakeholder analysis and agreed that the decision support system would need to satisfy the following project objectives:

- Shortening the time taken to produce estimates and quotations.

- Improving the reproducibility and dependability for calculations of process time and cost.
- Capturing evolving organisational knowledge; to inform future decision making and reduce reliance on individual 'experts'.
- Creating a learning platform which will support and enhance workplace learning.

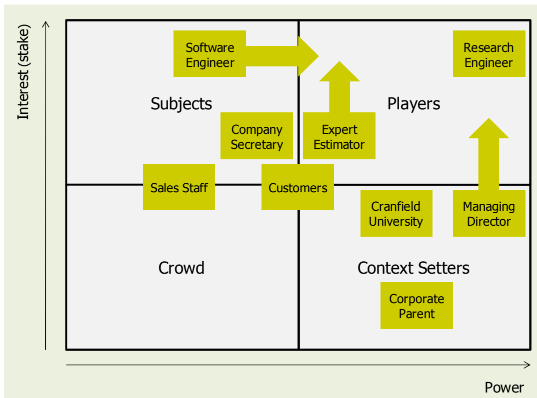


Figure 40. Stakeholder analysis

This project steering group (comprising the research engineer, project sponsor, estimators and a software consultant) identified the significant issues, processes and IT opportunities that require solutions. The project was reviewed by this 'cross-boundary' steering group against generic testing criteria: suitability, feasibility and acceptability (Johnson & Scholes, 2003). The project sponsor agreed to approve the full-scale development of METALmpe, with the expectation of benefits which would contribute to the achievement of key stakeholder expectations, Figure 41.

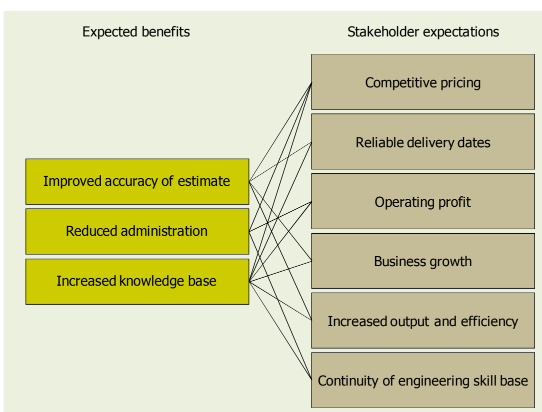


Figure 41. Linking expected benefits to stakeholder expectations

The opinions of all stakeholders were compiled to produce a 'force field analysis' (Lewin, 1952), analysing the case study company's readiness to change, for which detail is provided in Appendix C (accompanied by risk analysis). This analysis identified a number of forces that are strongly related to human acceptance or resistance to the proposed changes and forces that would not be manageable directly from within the case study company.

A *contribution schedule* was produced (Table 11), which calculated a budget for the METALmpe software development project. The projected duration for the work was to be 13 months, with the 'budgeted cost of work scheduled' at £29,080.00. This produced a curve for 'earned-value' monitoring of project progress, shown in Figure 42.

	Activity	Responsible	Involved	Cost £
1	Requirements elicitation	Research Engineer	Expert Estimator	1,400
2	Software Requirements Specification (SRS)	Research Engineer	Expert Estimator	1,400
3	Phase 1 software development	Research Engineer	Software Engineer	6,400
4	Phase 1 testing	Research Engineer	Software Engineer	2,400
5	Review of software engineering	Research Engineer	Software Engineer	1,040
6	Review of methodology	Research Engineer	Project Leader	1,040
7	Benefits monitoring	Research Engineer	Project Leader	400
8	Analysis of case study	Research Engineer	Systems Admin.	1,600
9	SRS revision	Research Engineer	Expert Estimator	1,400
10	Review of Case study	Project Sponsor	Research Engineer	2,400
11	Phase 2 software development	Research Engineer	Software Engineer	4,800
12	Integration testing	Research Engineer	Software Engineer	3,200
13	Verification testing	Research Engineer	Novice Estimator	1,600

Table 11. Contribution Schedule

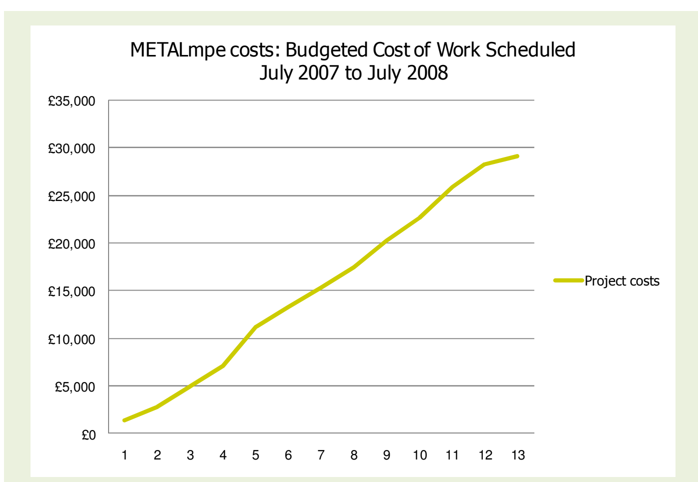


Figure 42. METALmpe project: Budgeted cost of work scheduled

The curve is almost linear, therefore does not conform to the typical 'S' curve. The main reason being that almost all of the resource utilized is 'labour' rather than 'materials'. The project makes use of existing hardware, so the majority of the costs are attributed to bespoke software engineering. Whilst the contribution of each participant was variable throughout the project duration, typically two individuals would be contributing to the project at any given time.

A critical aspect in the development of the decision support system was the knowledge capture exercise, which continued at different levels throughout the initiative. Functional models of the estimating process (Appendix B) were produced using IDEF notation (FIPS, 1993) to help illustrate connectivity through the process. These models emerged from the knowledge gathered in an exercise using the 'eXpert Process Knowledge Analysis Tool' (XPat) (Roy, 2005), which provides a framework for capturing knowledge, see Appendix B. 'The task of knowledge elicitation is extremely cumbersome and requires understanding of what type of knowledge needs to be elicited from an expert and how best to structure the knowledge for reuse in the future (Roy, 2005).' Modelling system complexity can be beneficial as it provides a simplified, visual aid for something which cannot be readily observed.

For the knowledge elicitation stage described in section 4.2.1, an increasing understanding of the cognitive processes and theoretical calculations used by the 'expert estimator' was gained using the KEN approach (Bailey *et al*, 2000). This information was documented in 'hard copy', within the software requirements specification.

The importance of human interaction in systems development and knowledge management is absolutely critical, specifically in respect to limitations of hard system methodologies (such as IDEF0); understanding and transfer of tacit knowledge; and the inherent difficulty in developing intelligent information systems to mimic human intelligence and expertise. Integrating human factors into the system development was important to ensure user acceptance of METALmpe. Therefore the technique of *end-user development* (a participative form of user involvement) was adopted in the software engineering processes. This approach involved the case study company staff in the detailed decision-making regarding system design, specification of operating requirements, HCI design and METALmpe deliverables. *End-user development* (Fisher *et al*, 2004) aims to empower users to influence the design their software applications for their own purposes. Lieberman et al, (2006) state that end-user development changes systems from being 'easy to use' to being 'easy to develop' in order to increase their responsiveness towards the diversity of users, i.e. people with different skills, knowledge, cultural background, etc., as well as towards the dynamics of work and learning practices.

The vision for METALmpe was ambitious, not only was it intended as a cost model for improving the estimating process, a further intention was to use it as a tool for developing the next generation of estimators at the case study company. The concept of *enriched work representations* (Sumner *et al*, 1999) influenced the software development of METALmpe in order to facilitate collaborative working and learning. *Enriched work representations* (Sumner *et al*, 1999) (Mulholland *et al*, 2001) are an approach to supporting and enhancing organisational learning through the use of tools and documents which aid collaborative working and learning, which are enriched through associations with formal knowledge models and informal discourse. A work representation is a 'tool of knowledge work rather than just paperwork', which should support knowledge intensive activity. The work representation should structure, coordinate and record the work, capturing ongoing problem solving activity as well as final solutions (Mulholland *et al*, 2001).' *Enriching* a work representation means that is tightly coupled with its context; a solution becomes a far more valuable asset if it is contextualised with the process by which it is created.

The iterative nature of the system development process and the degree to which end-user development shaped the decision support system, contributed to the *appropriation* of the technology. *Technology appropriation* (Overdijk and van Diggelen, 2006) implies a process of social construction in which the actions and thoughts of the technology user are shaped through the use of the technology, while at the same time the meaning and effects of the technology are shaped through the users' actions. Carroll *et al* (2002) define appropriation as a process in which a technology is explored, evaluated and adopted or rejected by users. According to their view, users make use of certain capabilities of a technology, and reject others, in order to satisfy their own needs.

Figure 43 shows an overview of typical *application design effort*, which provided an aide memoire for the project planning and encompassed the following stages of the METALmpe application development process: designing the technical system; coding and testing software; and testing the technical system.

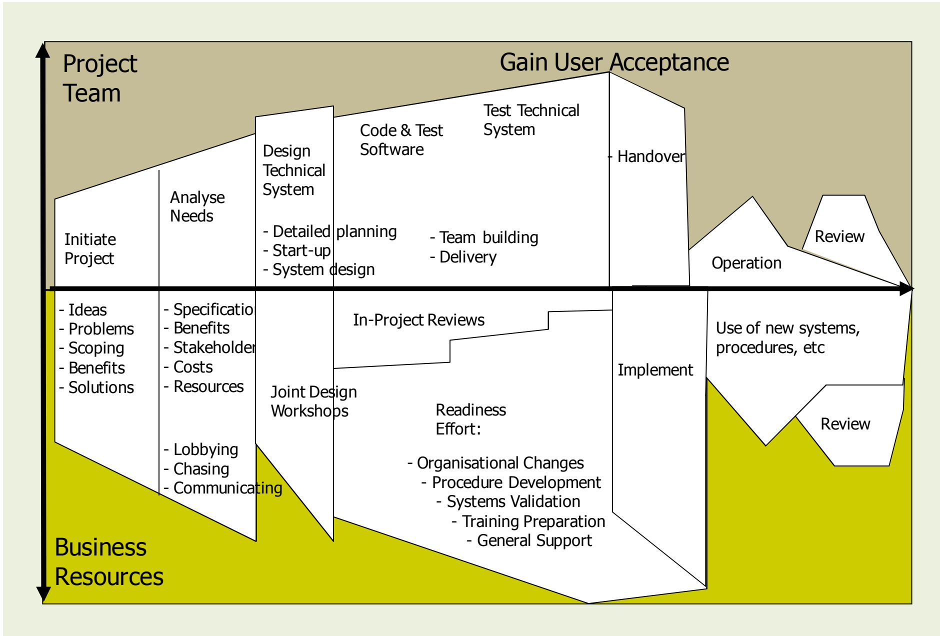


Figure 43. Application development effort (Lambert, 2005)

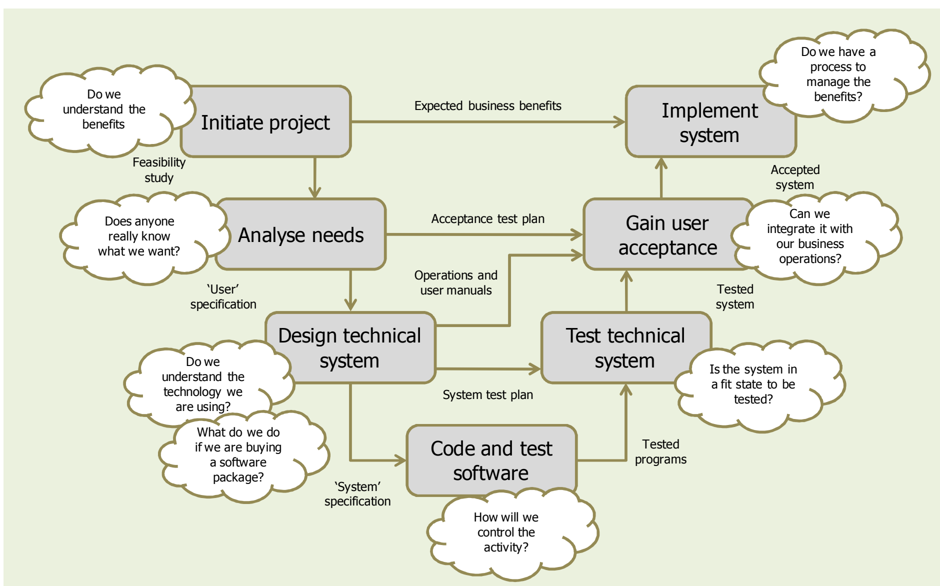


Figure 44. 'V' model of systems development used in METALmpe project (adapted from Lambert, 2005)

Figure 44 shows the traditional 'V' model of systems development, which was used as a framework for the software engineering in this project. An initial user requirement specification was prepared (indicating the potential to use both feature-based costing and case-based reasoning methods) which was used to rapidly develop a 'rough cut' prototype application. The prototype was used in a preliminary evaluation of the efficacy of the proposed model for knowledge management and information system development. This iterative process of software engineering and stakeholder assessment throughout this rapid application development evolved into a full system/software requirements specification and test definition. The prototype system enabled benefits monitoring and assessment to ensure the deployment of further resources in full-scale application development was justified. The defining feature of this phase of the research was the iterative nature of the system development and the evolution of the software functionality, shown in Figure 45.

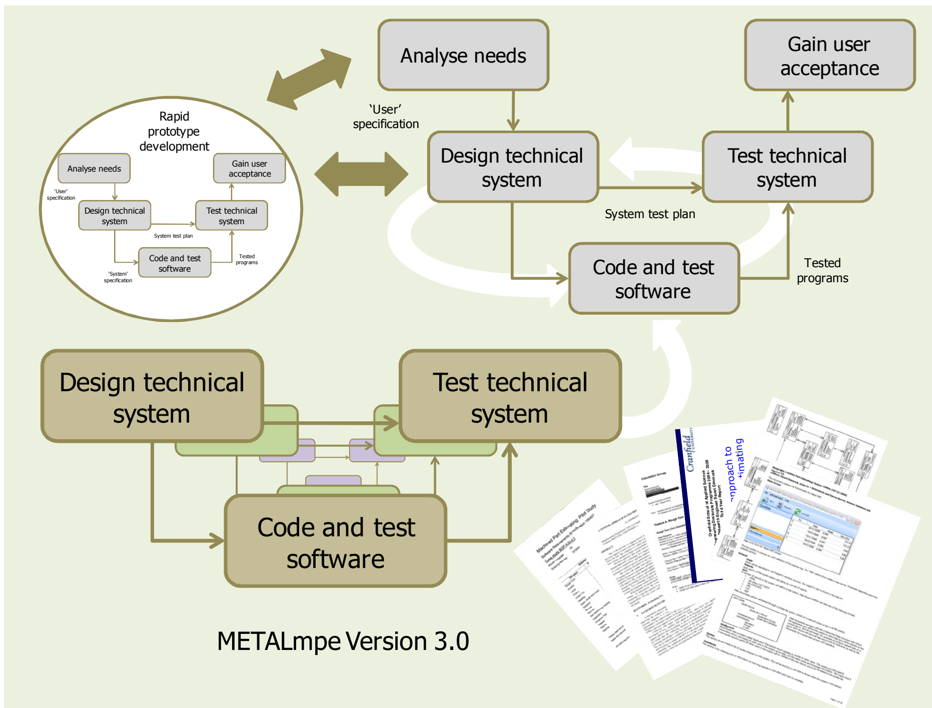


Figure 45. Multiple iterations of the software requirements specification

When developing a decision support system, it is important that sufficient emphasis is focussed on the business processes and not solely the development of an information system. The use of benefits evaluation techniques (Lambert, 2005) (Hotchkiss, 2006) (Appendix D), which were interwoven into the project agenda (Table 10), ensured that focus is maintained on the quantified benefits and visionary purpose for the research at the case study company. A benefits dependency network (Figure 46) was produced in order to identify the perceived commercial benefits to the case study company. It serves to illustrate (from right to left) the activities and development stages which are expected to facilitate delivery of the project objectives, illustrating the different aspects of the initiative, their connectivity and dependence.

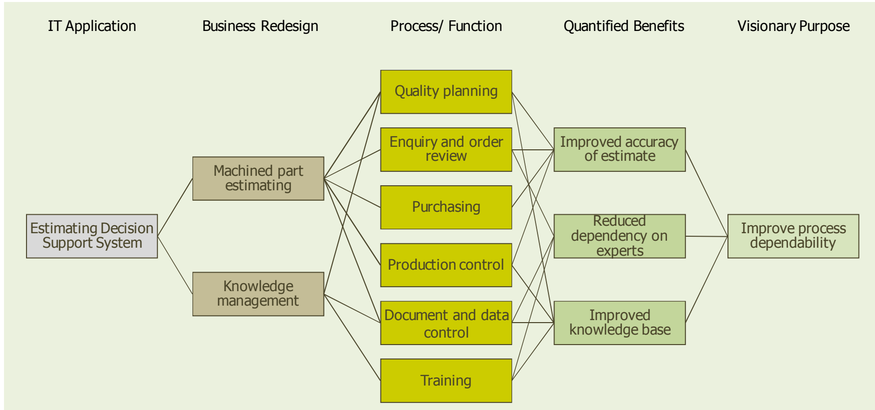


Figure 46. The benefits dependency network for the project

METALmpe is innovative software which provides an effective solution to machine part estimating for SMEs. The software is developed in Microsoft Visual Studio.net v.2.0 and will run on any operating system capable of running Microsoft.NET2.0 and Microsoft SQL Server 2005. The system deliverables include machined-part estimates, customer quotations and production route cards. The final database structure for the version of METALmpe deployed at the case study company (application version 3.0), is represented in Figure 47 (database version 7).

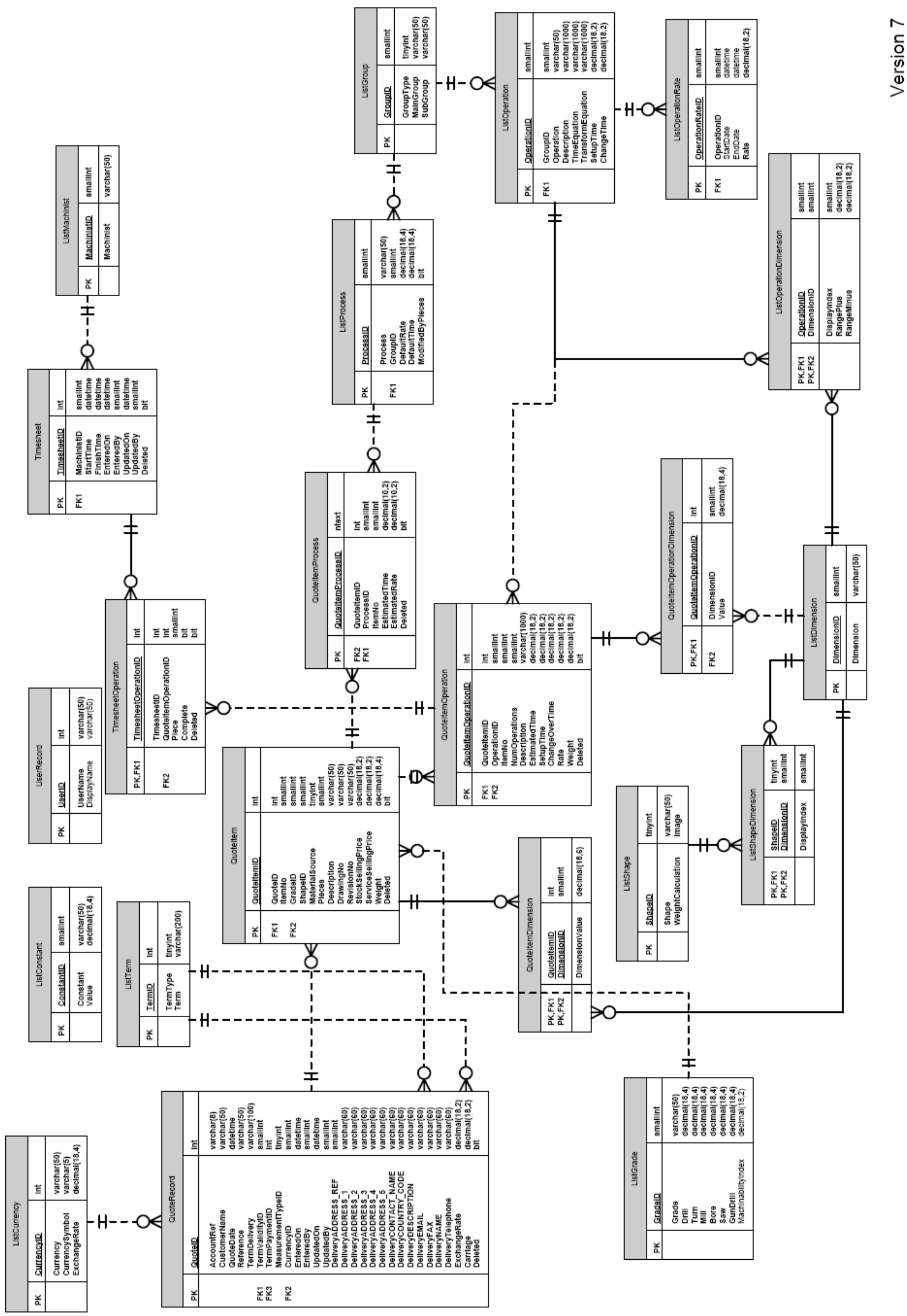


Figure 47. METALmpe database

4.2.1 *Knowledge elicitation and codification: conversion from manual estimating calculations to METALmpe algorithms*

One of the major considerations when planning the intervention to improve the machine part estimating process was how the company could manage the specific knowledge of the human estimator. The METALmpe approach is to provide a framework which enables algorithms to be established which (almost) exactly mimic the calculation processes followed when producing manually calculated estimates. The process of designing the feature-based costing aspect of METALmpe therefore required very close collaboration between the expert estimator, research engineer and the software engineer, Figure 48.

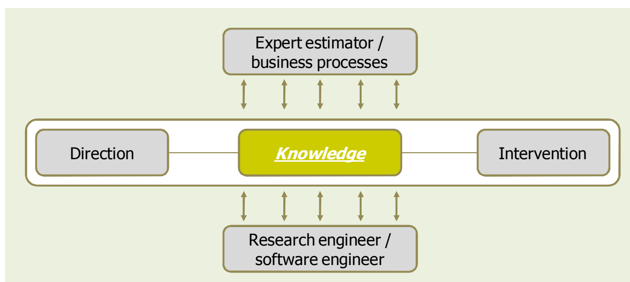


Figure 48. Simplified model of the exchange of project information

Although the knowledge management activity was on a relatively small scale (i.e. concentrated on estimating processes only), the concepts, theories and practice of the knowledge management disciplines were influential in the design of the system.

Through participant observation of the estimating practice, it was possible to elicit all of the calculations used by the case study company in the estimating of machining operations and the costing of value-adding processes; these are detailed in Appendix F and Appendix G. Involving end-users in the conceptual design stage and software engineering processes proved to be highly effective. A summary description of the elicitation process follows, illustrating the steps to codifying estimating knowledge:

(i) Familiarisation with current process

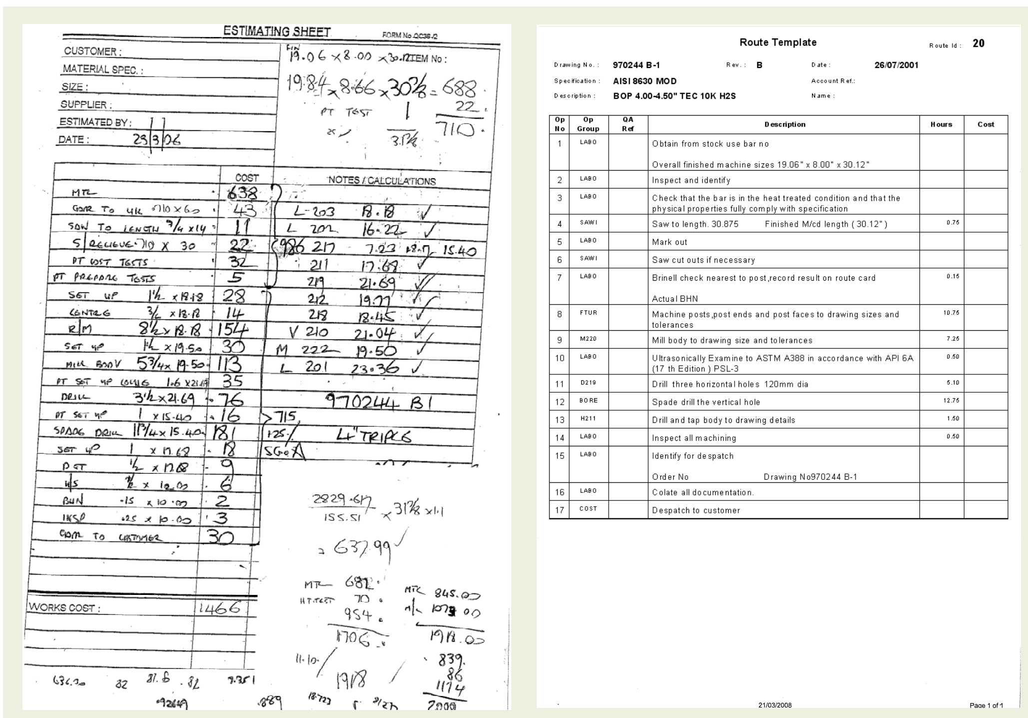
(ii) Extract formulae and heuristics used in manual calculations

(iii) Formulate algorithms to estimate activity times for each product feature

(iv) Create a feature definition in METALmpe, as either an ‘operation’ or a ‘process’.

(v) Enter and test the algorithm using the ‘calculation algorithm builder’ function in METALmpe.

When following the ‘manual’ estimating approach previously adopted, the expert estimator would interpret customer requirements specified on engineering drawings and accompanying material / product specifications; progressively completing an estimating sheet (Figure 49).



Route Template — Route Id : 20

Drawing No. : 970244 B-1 Rev. : B Date : 26/07/2001
Specification : AISI 8630 MOD Account Ref.:
Description : BOP 4.00-4.50" TEC 10K H2S Name :

Op No	Op Group	QA Ref	Description	Hours	Cost
1	LABO		Obtain from stock use bar no Overall finished machine sizes 19.06" x 8.00" x 30.12"		
2	LABO		Inspect and identify		
3	LABO		Check that the bar is in the heat treated condition and that the physical properties fully comply with specification		
4	SAWI		Saw to length. 30.875 Finished M/cd length (30.12")	0.75	
5	LABO		Mark out		
6	SAWI		Saw cut outs if necessary		
7	LABO		Brinell check nearest to post,record result on route card Actual BHN	0.15	
8	FTUR		Machine posts,post ends and post faces to drawing sizes and tolerances	10.75	
9	M220		Mill body to drawing size and tolerances	7.25	
10	LABO		Ultrasonically Examine to ASTM A388 in accordance with API 6A (17 th Edition) PSL-3	0.50	
11	D219		Drill three horizontal holes 120mm dia	5.10	
12	BORE		Spade drill the vertical hole	12.75	
13	H211		Drill and tap body to drawing details	1.50	
14	LABO		Inspect all machining	0.50	
15	LABO		Identify for despatch Order No Drawing No970244 B-1		
16	LABO		Colate all documentation.		
17	COST		Despatch to customer		

21/03/2008 Page 1 of 1

Figure 49. Estimating sheet for recording expert calculations and ‘route template’

The format of the information recorded on the estimating sheet made interpretation by anyone other than the estimator difficult. Furthermore to make use of this information for production purposes, the estimator would then enter the process route and estimated hours into a ‘route template’ (Figure 49); which would subsequently be used by the production operators. This ‘manual population’ of data was an inefficient step of the existing process and an opportunity for METALmpe to reduce data entry time.

Operation 8 on the route template, describes the operation by which diameter posts are machined on a rectangular forging, shown below in Figure 50. This activity is classified as an ‘operation’ within the METALmpe decision support process and defined by the operation code:

Group type: ‘Operation’

Main group: ‘Lathe turn – rough machined’

Sub-group: ‘Diameter from rectangle’

Figure 50. Typical example of operation group ‘LatheTurn_ RoughMachined _DiameterFromRectangle’

The estimating processes were transcribed in conjunction with the expert estimator, an extract from these handwritten records is shown in Figure 51, which relates to the machined feature in Figure 50. This information was then revised into a more ordered format by the research engineer, Figure 52.

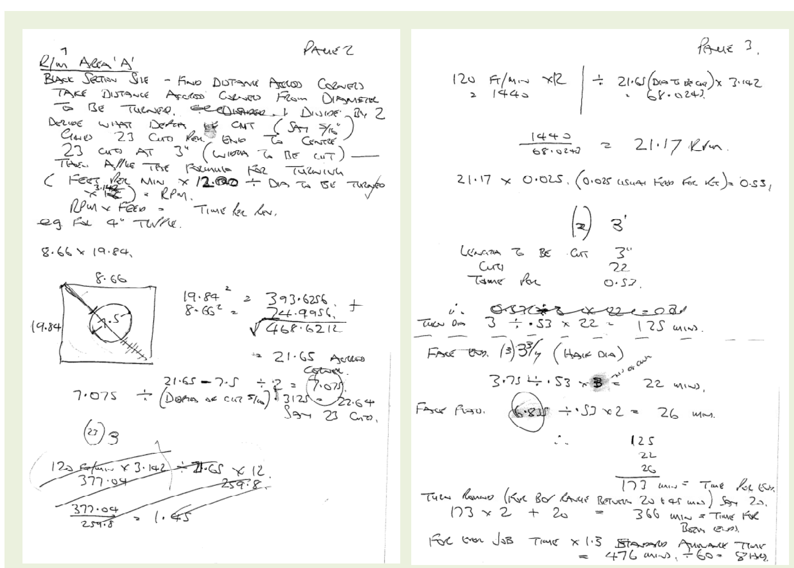


Figure 51. Detailed working for the calculation of turning a diameter post on a rectangular forging, provided by the expert estimator during the knowledge elicitation process

Op Ref	Process	Description
8	Rough Turn Feature A	Machining Select 'Feature type' by hyperlink *to be* [in this instance – turn dia post from rectangular stock] Calculate √ Height (“)^2 + Width(“)^2 = distance across corners *or diameter to be cut* Distance across corners – diameter (“) / 2 (fixed) / 0.3125 (depth of cut 5/16”) = Number of cuts (round up to whole number). Apply the formula for turning: Feet per minute [preselected dependant on material grade] x 12.00 / Diameter to be cut x 3.142 = RPM, RPM x Feed [usually 0.025 for rough turning]=Time per Rev. Length of diameter (“) / Time per Rev x Number of cuts [above] = X minutes Face end: Half-diameter / Time per Rev x 3[number of cuts - constant] = Y mins Face flats: Distance across corners – diameter (“) / 2 (fixed) / Time per Rev x 2[constant] = Z mins Calculate total time: X + Y + Z = T mins (time to machine 1 end feature)' T x (no. of features) + change over time (no.features – 1 x [number of minutes from preselected matrix] = total number of minutes per piece Compensate for relaxation allowance: Time x 1.3 [preselected relaxation factor] / 60 = hrs per piece [rounded up to nearest 0.25hr]

Figure 52. Research engineer's initial interpretation of formula for the calculation of turning a diameter post on a rectangular forging.

The calculations were then codified using USPExpress functions (e.g. trigonometrical) and operators (e.g. arithmetic) ready to be entered into METALmpe. USPExpress is an 'enterprise-level *expression parsing tool*' (Unisoft, 2010), where '^' is the arithmetic operator *power*; 'CEIL' is a function which returns the smallest integer greater than or equal to its numerical argument; and 'SQRT' returns the square root of a number:

i. Diameter to be cut = SQRT (Height^2+Width^2)

ii. Number of cuts = (Diameter to be cut – diameter) / 2 / Depth of cut

iii. Round up number of cuts to nearest whole number = CEIL(Diameter to be cut – Diameter / 2 / Depth of cut)

v. Number of cuts = CEIL((SQRT(Height^2 = Width^2) – Diameter) / 2 / Depth of Cut)

vi. RPM = Feet per minute * 12 / Diameter to be cut * 3.142) or (Feet per minute * 12) / ((SQRT(Height^2 + Width^2)) * 3.142)

vii. Time per Rev = RPM * Feed or (feet per minute * 12) / ((SQRT(Height^2 + Width^2))

viii. Time in hours = ((Turn Length / Time per Rev * Number of Cuts) / 60)

The complete algorithm, is constructed as follows:

TurnLength/((TurnFPM*12/(SQRT(Height^2+Width^2)*3.142)*
Feed)*(CEIL((SQRT(Height^2+Width^2)Diameter)/2/DepthofCut))

Subsequently, the algorithm is constructed in METALmpe using the 'calculation screen' shown in Figure 53, described in section 4.4.

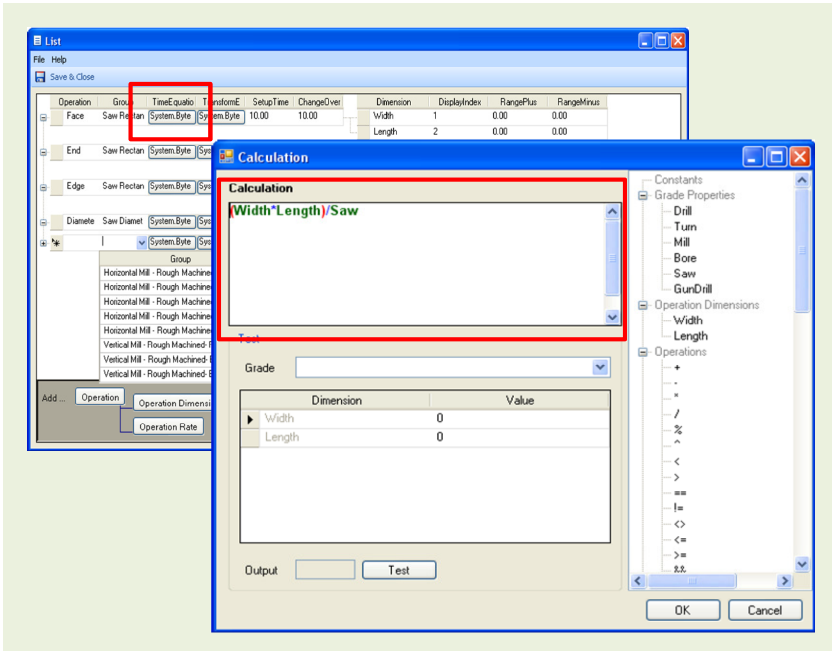
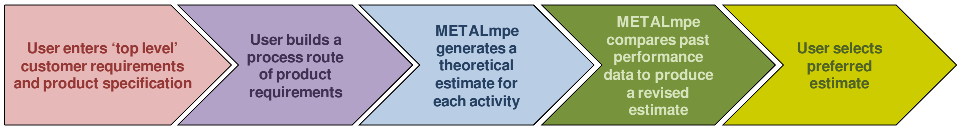


Figure 53. METALmpe - calculation screen: Time Equation algorithms

4.3 An overview of the METALmpe decision support process

The *estimating* activities comprise of 5 user friendly steps (Figure 54):



1 User defines the customer's product requirements and identifies manufacturing operations or processes required.

2 The application guides the user to construct the feature / case classification(s) for specific operations and processes.

3 The cost for each feature is calculated using decision rules representing codified knowledge from the human estimator.

4 Each new feature / case classification is compared with previous cases to predict costs using case-based reasoning.

5 User (decision maker) selects which prediction (CBR/FBC) to apply to the estimate, then repeats cycle 1 to 5 for remaining operations and processes.

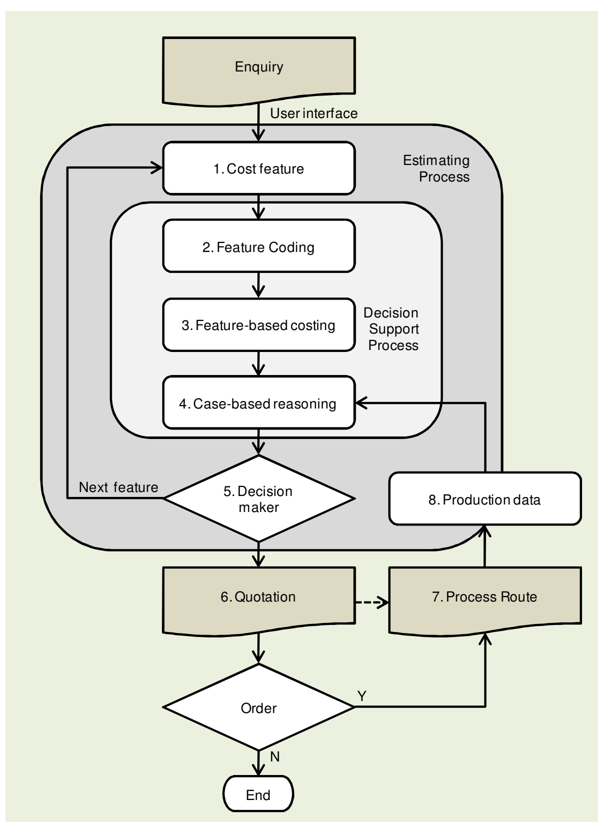


Figure 54. METALmpe decision support architecture

Post-estimation activities:

6 User completes estimate and produces a quotation.

7 Upon receipt of order the quotation is re-used to generate subsequent documentation.

8 On completion of production activities the feature / case classification is up-dated with actual production data for subsequent re-use.

An estimate is generated using the METALmpe application which requires the user to enter specific customer details, requirements and specifications. For each product, further levels of decomposition take place where the cost estimating of the product commences. Specific material requirements are entered, current stock can be searched to find the nearest available size, and a cost price for the starting material entered. Once the material has been specified, the estimator begins the process of defining the product features and the value-adding activities such as heat treatment and machining. The interface enables novice estimators to navigate their way through the task of defining the features of the machined part, using a series of drop-down option tabs. These actions drive the *feature-based costing* component of the system.

Once a time equation is entered it enables an operation time estimate to be generated, acting on the user inputs: (i) material specification and starting size; (ii) selected operation and (iii) specific feature dimensions.

The next stage of the METALmpe process is case-based costing, which does not require any further user input. Following the feature-based and case-based costing processes, the METALmpe interface displays a listing of nearest matching past cases and times derived by both CBR and FBC. At this point the user can intervene, selecting their preferred choice from either of the calculated times or alternatively they may decide upon an intuitive time.

During initial use of METALmpe, 'operations' and 'processes' need to be defined and algorithms for calculating operation times established (these steps are explained in detail in section 4.4), however once the coding structure is in place the standard quoting process become a simple activity, see Figure 55. A process flow diagram (Figure 56), illustrates the estimating processes which are (in varying degrees) required by the estimator in order to respond to a request for quotation (RFQ) from a customer. Figure N.1 (Appendix N) maps the processes in Figure 56 to the relevant sections of this chapter.

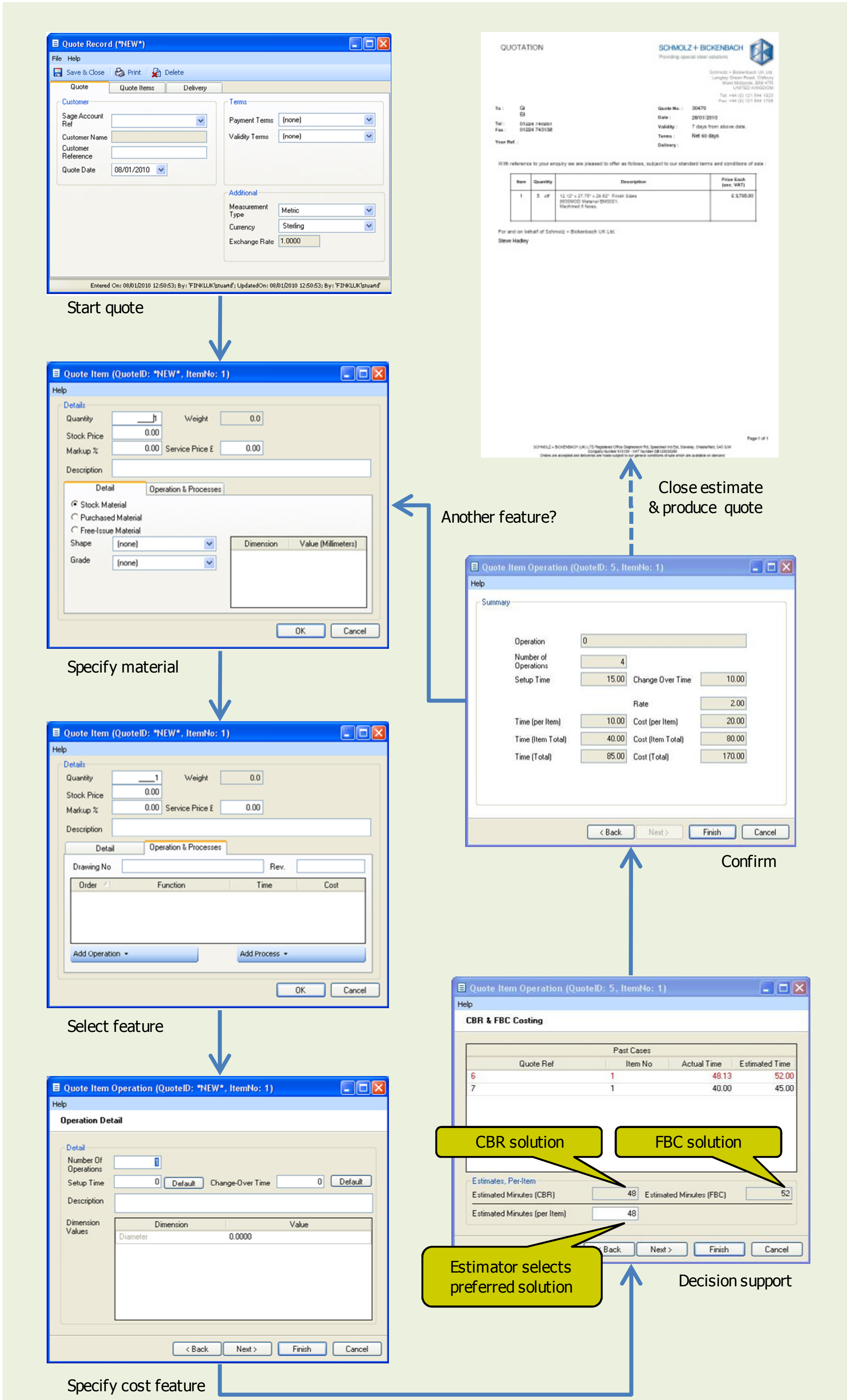


Figure 55. Standard METALmpe estimating process for products where existing feature codes apply

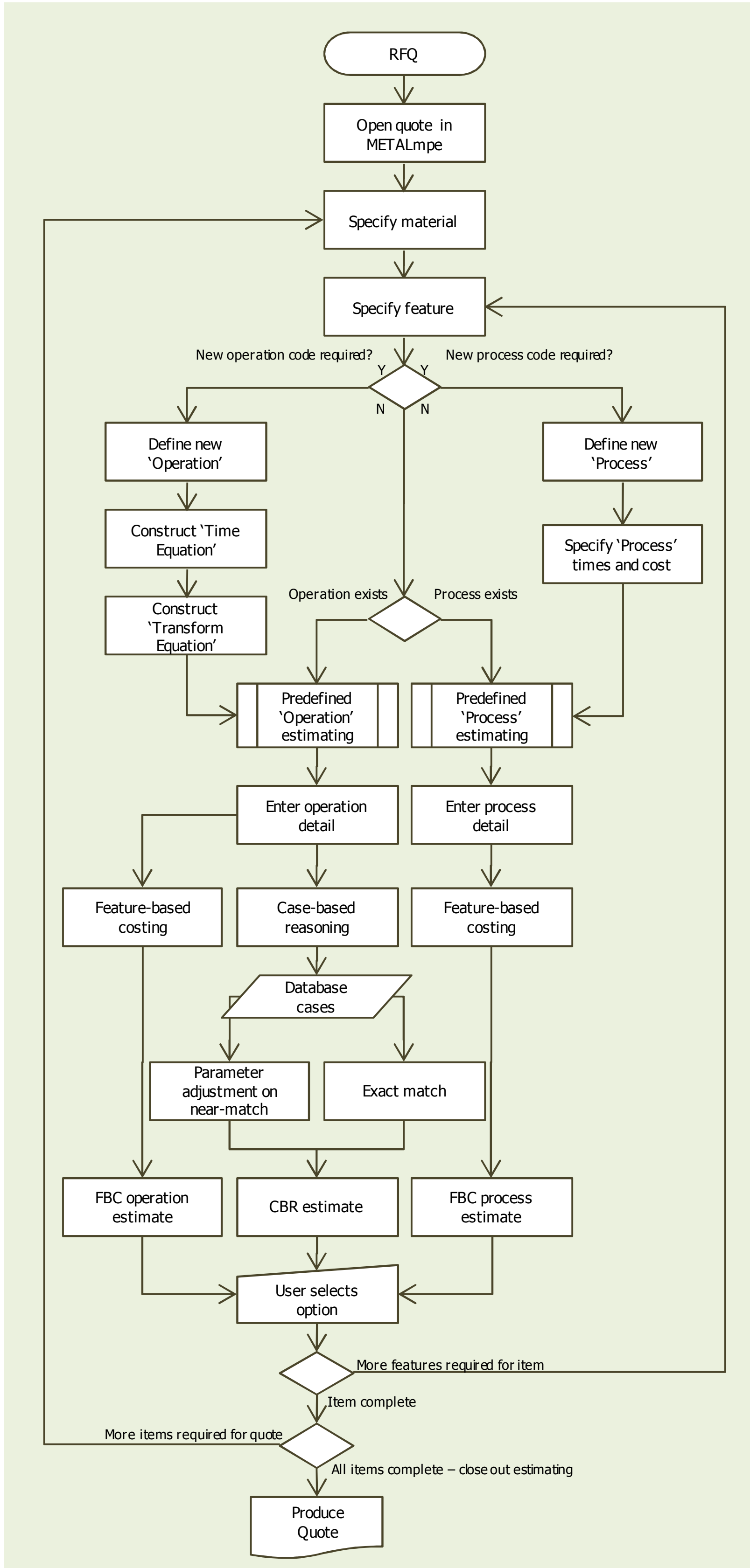


Figure 56. Process flow diagram for METALmpe estimating processes

In defining the new 'operations' and 'processes' shown in Figure 56, and the subsequent steps 'construct time equation', 'construct transform equation' and 'specify process times and cost' (as required); the system user is establishing cost estimating relationships (CERs), see Figure 57.

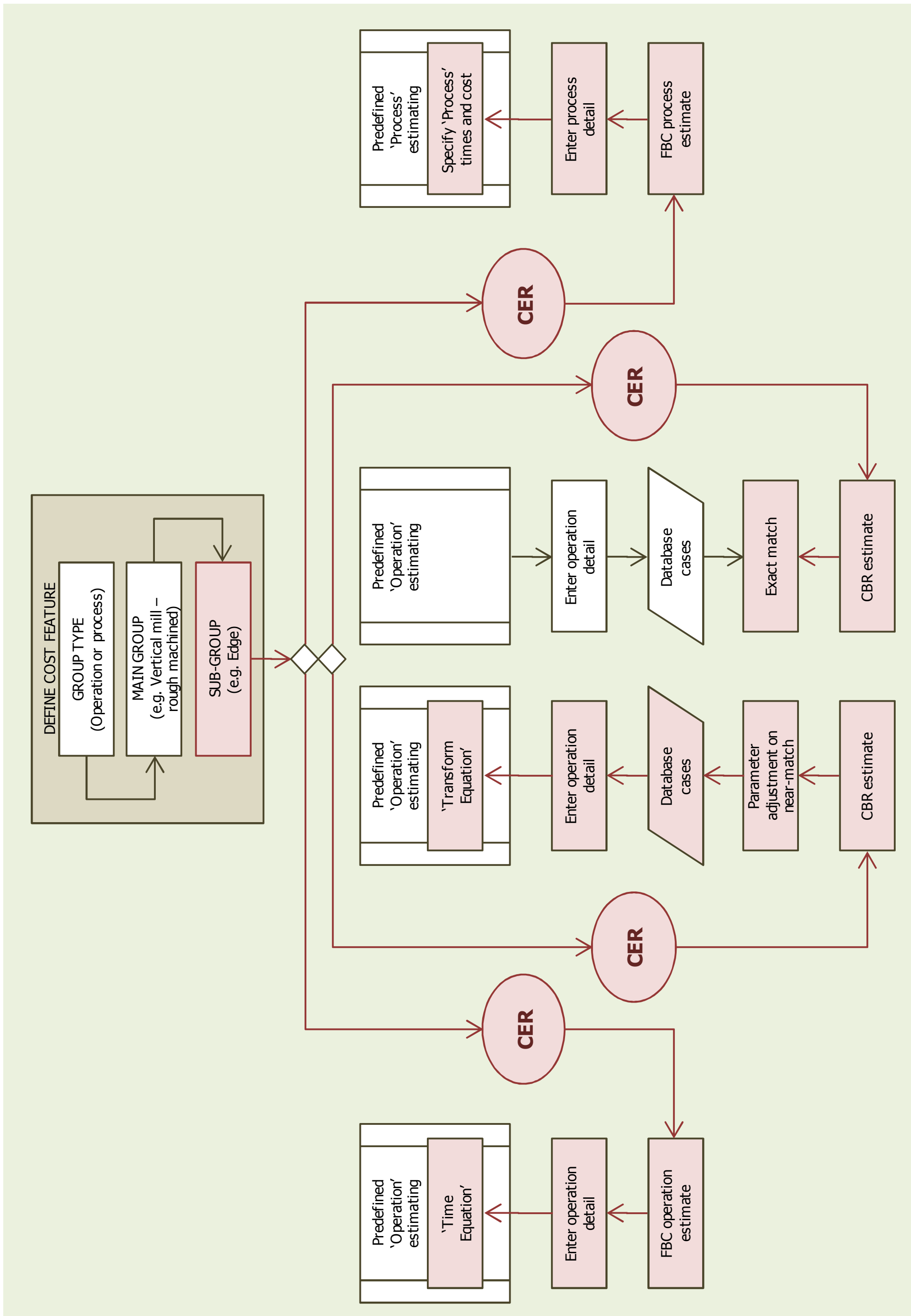
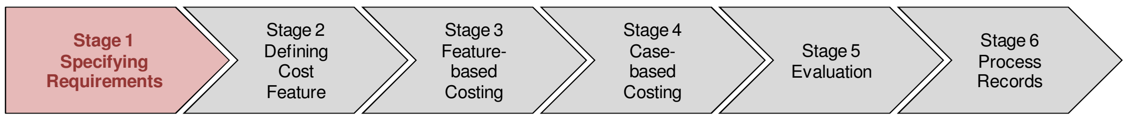


Figure 57. Cost estimating relationships (CERs) in METALmpe estimating processes

4.4 Process guide to the METALmpe application

4.4.1 Stage 1 Specifying Requirements



The overall objective for this stage is to open a quote in METALmpe and ensure that the top level customer requirements are defined. These include specifying account details, product specification, product drawings, quantities and material requirements, Figure 58.

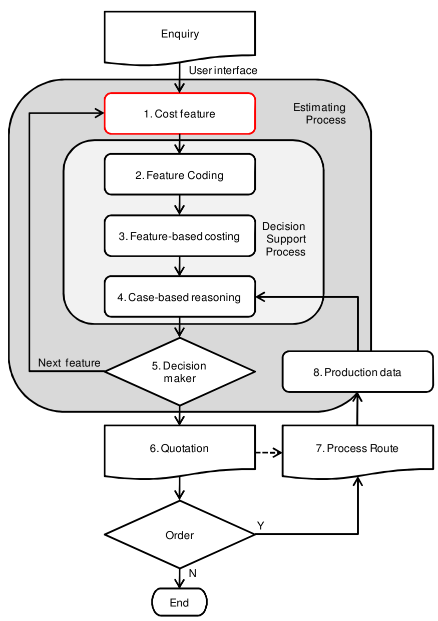


Figure 58. Stage 1: Specifying requirements

4.4.1.1 Navigating METALmpe

Users are identified by the logged in Windows account, the logged in user is shown in the title bar. The top toolbar is common to every selection from the explorer bar. The ‘new’ option creates either a new *quote* or *timesheet*, depending upon the selected section. The quotes section shows a historic list of quotes entered into the system. This is the first screen that is shown when the system is started. The timesheets section is for collecting production data on how long operations and other jobs took to complete. Each section of the quote system defines its own set of reports.

Company documents (e.g. standard operating procedures) can be deployed into a hierarchal folder structure that mimics the application and allows the system to show documents relevant to the current 'level', and all sub levels of the application.

4.4.1.2 Opening a quote record

The main quote record screen (Figure 59, Table 12) stores the 'top level' details necessary to begin a quote. A quote record comprises three tab pages. The first details administrative properties of the quote such as the account reference. The second page identifies the route used to service a quote, and deals with estimating costs. The final page records delivery details. The quote record stores all details relevant to a quote and is designed to empower novice users to produce detailed quotes though a combination of feature-based and case-based costing.

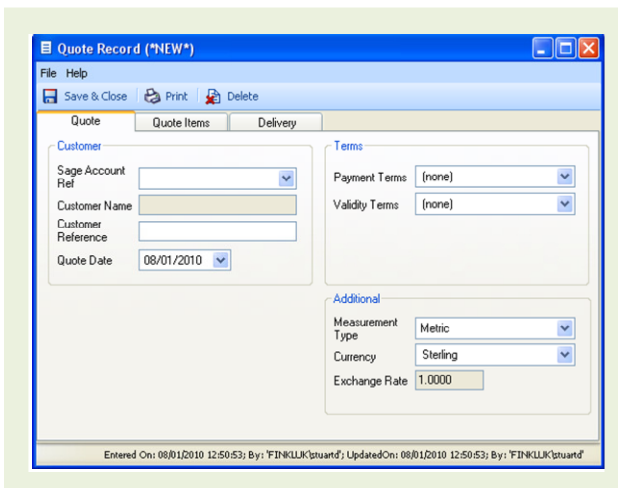


Figure 59. Quote record screen

Field	Input
Account Ref	The customer account reference. This value is a drop down list of values retrieved from Sage Accounts. Note: Once a quote has been saved the account reference and contact are fixed and cannot be edited.
Customer Reference	Customer reference is a value supplied by the customer.
Quote Date	The date of the quote. Please note that the date entered determines the rate per minute when calculating the operation cost.
Measurement Type	Metric Quote allows for the user to enter information in different measurement systems. The initial system will be restricted to either Metric or Imperial. Please note that all values will be stored in metric. Any input that is not in Metric will be converted on input and display. Rounding errors are avoided when converting from imperial to metric by storing all data to six decimal places. (Input and display in the system is only allowed to four decimal places). If imperial is selected all measurement values will be displayed in inches.
Payment Terms	A list of payment terms.
Validity Terms	A list of validity terms
Entered On	Identifies the date the quote was first entered
Entered By	Identifies who created the quote originally
Updated On	The date of the last quote update
Updated By	The user who last updated the quote

Table 12. Interface fields: Quote record screen

4.4.1.3 Specifying customer requirements

The 'quote items' page shows the detail of all parts included in the quote (Figure 60, Table 13). Each quote define a series of items and for each item, a series of processes or operations can be performed. This screen is primarily a visual aid, in order to view the details of a quote item the user is required to double click on the relevant row.

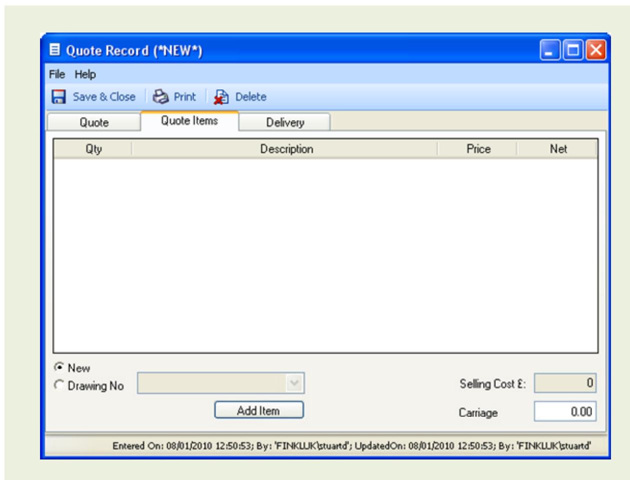


Figure 60. Quote items screen

Field	Input
Add Item	This adds a new item to the quote. This will automatically receive the next sequential Item No, and will open up a Quote Item Record. The user can add an item that is either creating a new quote, or create a clone of the quote based on a selected drawing number.
Pieces	The required number of duplicates. The terminology 'piece' is consistent with the timesheet collection feature of the system.
Description	User entered description defines the quote item.
Selling Cost	Cost for all pieces. This includes a mark-up on operation time and materials.
Carriage	This is the total carriage cost for the quote.

Table 13. Interface fields: Quote items screen

The delivery page of a quote record allows the user to enter arbitrary terms into a free input textbox, and to select a delivery address. The user can choose to select a customer's address from SAGE, based on the Sage Account Ref on the quote page. Delivery address and delivery Contact details are stored in the local database when read from SAGE, however these values are not editable.

4.4.1.4 Specifying product requirements

A *quote item* allows the user to provide the detail required to estimate the cost of that an item. The title bar of the quote item will enable the users to determine the particular identifier of the item they are reviewing. A quote item is split into two tabs, the first records basic details of the quote item, whilst the second list all the operations and processes necessary to complete a quote item and hence its costing (Figure 61, Table 14). This second tab constructs process instructions known as the 'production route'.

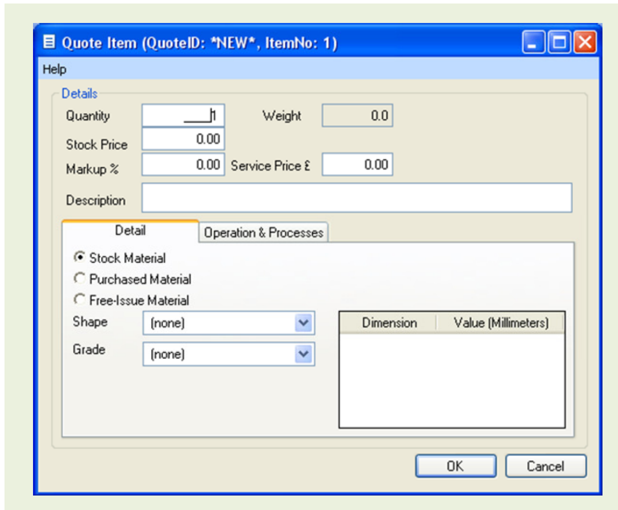
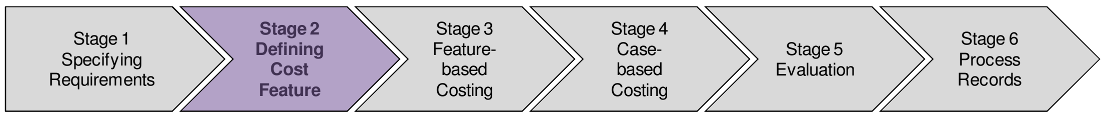


Figure 61. Material detail screen

Field	Input
Quantity	The number of times the quote item is to be produced.
Weight	The weight is calculated based upon the dimension values and the shape weight calculation.
Stock Price	Stock Price is only enabled for Stock and Purchased Material. The value is the cost to the customer, and should include a profit on purchasing the material.
Mark-up	This is the mark-up % applied to the service cost.
Service Price	The cost to produce this quote.
Description	A user entered description that describes the quote item.
Detail	The material page records basic material details.
Stock Material	Stock material identifies that (for the selected quote item) the material is sourced from the inventory. When this option is selected the cost option will be enabled, allowing the user to enter this cost of this stock item.
Purchased Material	Selecting this option indicates that the material must be specially purchased for this quote. Again, when this option is selected the cost option is enabled.
Free-Issue material	This option indicates that the customer supplies the material. This incurs no cost, and thus the cost is set to zero and the field is not editable.
Shape	This is the material shape. This will inform the list of dimensions that can be chosen.
Grade	The grade of the material used in the quote item.

Table 14. Interface fields: Material screen

4.4.2 Stage 2 Defining Cost Features



The overall objective for this stage is to define the separate cost features of each item being quoted, Figure 62. The process for defining features is very flexible and follows the principle of shared feature networks, where each level of feature definition adds complexity to the feature code and differentiates it further from other similar features. Cost features can be defined as either an operation or a process. Operations are most simply defined as being internal costs which are 'time variable', whereas processes are typically a fixed time / cost. The cost structures and algorithms defined within the operations and processes represent the codified knowledge elicited from manual estimating practice.

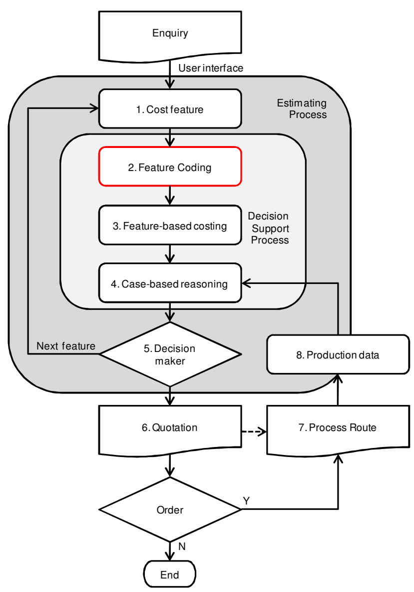


Figure 62. Stage 2: Defining cost features

4.4.2.1 A feature-based approach to defining product requirements

FBC determines product cost by assigning costs to specific features of the product based on their attributes, size, shape and the number of operations or processes required to produce the feature. All kinds of features must be taken into consideration, from physical features such as shape or materials, to process features such as special operations. The METALmpe estimating process calculates the total product cost by compiling cost estimates of associated individual features of the product. This requires the ability to relate estimate requirements to existing knowledge on specific product attributes, shapes, dimensions and finishes. The more features, the more manufacturing and planning is required. Omitting or underestimating a feature could dramatically impact on the margin between sales value and the actual cost of producing that part. The most significant difficulty with FBC is defining and categorising each feature within a coding structure that enables cost estimating relationships to be established.

4.4.2.2 Estimating the cost of production: a feature-based approach

In METALmpe, once a feature code and cost estimating relationship (CER) are generated, it can be easily identified and reused. CERs link the current estimating problem to algorithms stored in METALmpe repository of codified estimator knowledge (Figure 57), which are then used to calculate the theoretical cost of a specific feature.

In producing the quote the estimator defines a process route comprising both ‘operations’ and ‘processes’ which define the steps required to convert the initial base material into a finished product. A process is different from an operation in that the former does not modify the dimensions of a piece of material (in any appreciable way) e.g. heat treatment, whilst however adding value to the finished part.

Both operations and processes are selected from an options list with pre-defined case descriptions (group type, main group and sub-group) which open a record for this feature in the new quote, or new case descriptions can be created if necessary. Each separate *feature* of the machined part creates a ‘case’ to be stored in the database. The *case* is defined (and partitioned in the database) for easy retrieval by firstly, selecting the feature group from the drop-down menus, then secondly by the specified material grade, operation dimensions or process parameters.

Once the ‘group’ is selected METALmpe prompts the user to enter the variables required for processing a calculation. Specific cost algorithms elicited from a human estimator are codified within the application. METALmpe facilitates building up algorithms through a series of fields which can be dragged onto the screen, including user defined constants, mathematical operations, mathematical functions and mathematical constants.

4.4.2.3 METALmpe 'system administration': a rough guide

There are a number of administration records in METALmpe, all of which provide the ability to add and delete new list items, Figure 63. When closing this form the system checks for any modifications, and if the record has not already been saved the user is prompted to determine if changes should be saved.

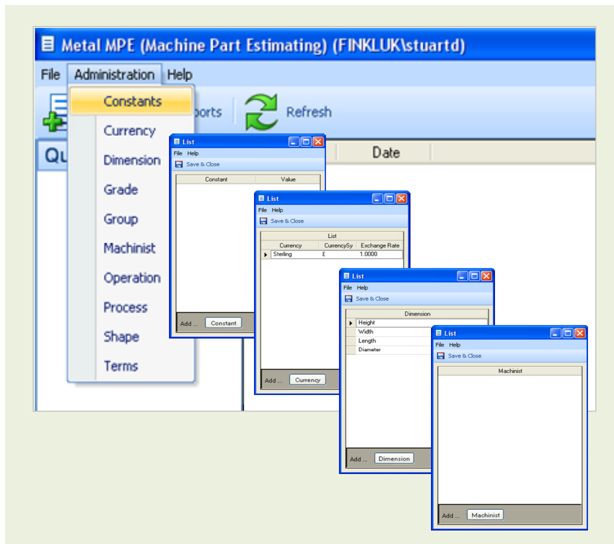


Figure 63. Administration editing screens

- *Constants editor*

  Constants in the system are defined values used in calculations.

- *Currency editor*

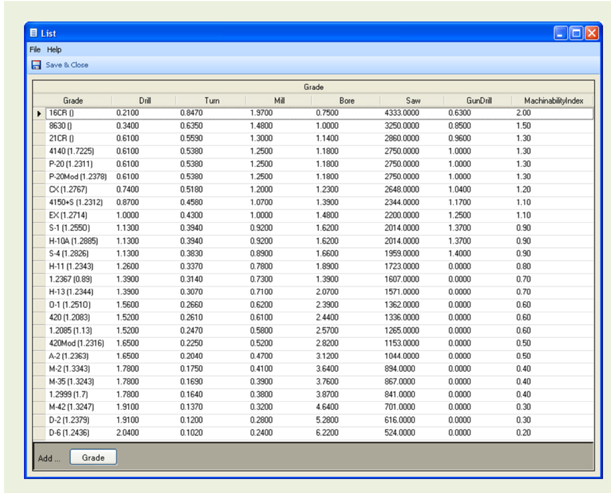
  METALmpe is developed so quotations can be presented in alternative currencies to Sterling. The currency editor enables new currencies to be added, along with their symbols and exchange rates. The exchange rates of existing currencies can also be manually amended.

- *Dimension editor*

  A simple list of dimensions, all stored in millimetres e.g. Height, Width, DepthofCut, Length etc.

- *Grade editor*

  The grade administration screen, Figure 64, allows the user to define a series of grade types. For each grade other 'machinability' index values are stored, which are subsequently used in both feature-based costing and case-based costing calculations.

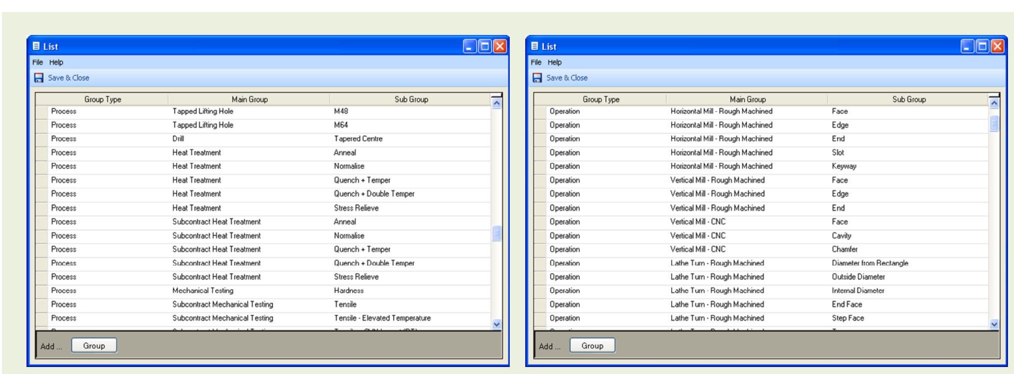


Grade							
Grade	Drill	Turn	Mill	Bore	Saw	GunDrill	MachinabilityIndex
16CR ()	0.2100	0.8470	1.9700	0.7500	4333.0000	0.6300	2.00
8630 ()	0.3400	0.6350	1.4800	1.0000	3250.0000	0.8500	1.50
21CR ()	0.6100	0.5590	1.3000	1.1400	2860.0000	0.9600	1.30
4140 (1.7225)	0.6100	0.5380	1.2500	1.1800	2750.0000	1.0000	1.30
P-20 (1.2311)	0.6100	0.5380	1.2500	1.1800	2750.0000	1.0000	1.30
P-20Mod (1.2378)	0.6100	0.5380	1.2500	1.1800	2750.0000	1.0000	1.30
CX (1.2767)	0.7400	0.5180	1.2000	1.2300	2648.0000	1.0400	1.20
4150+S (1.2312)	0.8700	0.4580	1.0700	1.3900	2344.0000	1.1700	1.10
EX (1.2714)	1.0000	0.4300	1.0000	1.4800	2200.0000	1.2500	1.10
S-1 (1.2550)	1.1300	0.3940	0.9200	1.6200	2014.0000	1.3700	0.90
H-10A (1.2885)	1.1300	0.3940	0.9200	1.6200	2014.0000	1.3700	0.90
S-4 (1.2826)	1.1300	0.3830	0.8900	1.6600	1959.0000	1.4000	0.90
H-11 (1.2343)	1.2600	0.3370	0.7800	1.8900	1723.0000	0.0000	0.80
1.2367 (0.89)	1.3900	0.3140	0.7300	1.3900	1607.0000	0.0000	0.70
H-13 (1.2344)	1.3900	0.3070	0.7100	2.0700	1571.0000	0.0000	0.70
O-1 (1.2510)	1.5600	0.2660	0.6200	2.3900	1362.0000	0.0000	0.60
420 (1.2083)	1.5200	0.2610	0.6100	2.4400	1336.0000	0.0000	0.60
1.2085 (1.13)	1.5200	0.2470	0.5800	2.5700	1265.0000	0.0000	0.60
420Mod (1.2316)	1.6500	0.2250	0.5200	2.8200	1153.0000	0.0000	0.50
A-2 (1.2363)	1.6500	0.2040	0.4700	3.1200	1044.0000	0.0000	0.50
M-2 (1.3343)	1.7800	0.1750	0.4100	3.6400	894.0000	0.0000	0.40
M-35 (1.3243)	1.7800	0.1690	0.3900	3.7600	867.0000	0.0000	0.40
1.2999 (1.7)	1.7800	0.1640	0.3800	3.8700	841.0000	0.0000	0.40
M-42 (1.3247)	1.9100	0.1370	0.3200	4.6400	701.0000	0.0000	0.30
D-2 (1.2379)	1.9100	0.1200	0.2800	5.2800	616.0000	0.0000	0.30
D-6 (1.2436)	2.0400	0.1020	0.2400	6.2200	524.0000	0.0000	0.20

Figure 64. Machinability index

- *Group editor*

Before it is possible to enter an algorithm the estimator must first create the operation (or process) 'feature code'. Creating feature codes is one of the administrative functions in METALmpe (Figure 65, Table 15) that form part of the system set up procedure. In general terms, once these are established they only require a small amount of maintenance or amendment; these functions are not normally required by the estimator in 'everyday estimating'. Feature-codes are created in the 'group editor' screen, Figure 65. The feature-code is a *case* definition which provides a *cost estimating relationship* linking to the FBC 'time equation' algorithm and subsequent CBR_{pa} 'transform equation' algorithm / CBR. Operations and processes can often be grouped into basic categories. The intention is to simplify administration by having a single entry screen, as the group type (operation or process) allows user selection.



Group Type	Main Group	Sub Group
Process	Tapped Lifting Hole	M48
Process	Tapped Lifting Hole	M64
Process	Drill	Tapered Centre
Process	Heat Treatment	Anneal
Process	Heat Treatment	Normalise
Process	Heat Treatment	Quench + Temper
Process	Heat Treatment	Quench + Double Temper
Process	Heat Treatment	Stress Relieve
Process	Subcontract Heat Treatment	Anneal
Process	Subcontract Heat Treatment	Normalise
Process	Subcontract Heat Treatment	Quench + Temper
Process	Subcontract Heat Treatment	Quench + Double Temper
Process	Subcontract Heat Treatment	Stress Relieve
Process	Mechanical Testing	Hardness
Process	Subcontract Mechanical Testing	Tensile
Process	Subcontract Mechanical Testing	Tensile - Elevated Temperature

Group Type	Main Group	Sub Group
Operation	Horizontal Mill - Rough Machined	Face
Operation	Horizontal Mill - Rough Machined	Edge
Operation	Horizontal Mill - Rough Machined	End
Operation	Horizontal Mill - Rough Machined	Slot
Operation	Horizontal Mill - Rough Machined	Keyway
Operation	Vertical Mill - Rough Machined	Face
Operation	Vertical Mill - Rough Machined	Edge
Operation	Vertical Mill - Rough Machined	End
Operation	Vertical Mill - CNC	Face
Operation	Vertical Mill - CNC	Cavity
Operation	Vertical Mill - CNC	Chamfer
Operation	Lathe Turn - Rough Machined	Diameter from Rectangle
Operation	Lathe Turn - Rough Machined	Outside Diameter
Operation	Lathe Turn - Rough Machined	Internal Diameter
Operation	Lathe Turn - Rough Machined	End Face
Operation	Lathe Turn - Rough Machined	Step Face

Figure 65. Group editor screens: 'operations' and 'processes'

Field	Input
Group Type Main Group	A drop down list that defines if the group option is a process or operation. This is the general category of process type or operation, typically designating the machine tool or equipment.
Sub-group	A sub-group of operation or process category, specifying the action required.

Table 15. Interface fields: Group editor screens: 'operations' and 'processes'

- *Machinist editor*

  This lists the machinists who perform in-house machining operations. A separate list must be maintained (to the logged on users of the system) because machinists do not enter their own performance data.

- *Operation editor*

  Once an operation as been added in the Group Editor, it can be configured for cost estimating information (time equations – section 4.4.3.4 and transform equations – section 4.4.4.4) and other required parameters, Figure 66 and Table 16.

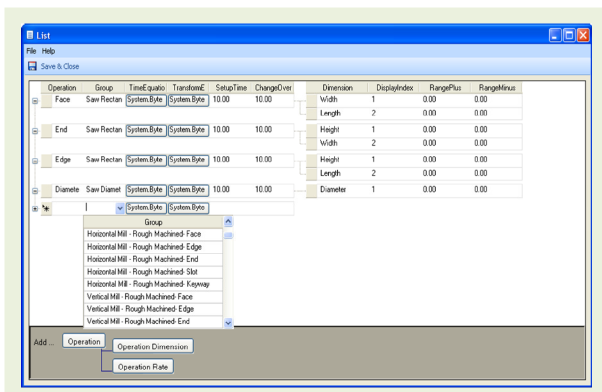


Figure 66. Interface fields: Operations screen

Field	Input
Operation	The name of the operation.
Time Equation	The equation used to calculate how long an operation would take. This calculation depends upon the selected dimensions.
Transform Equation	The equation that given an input of time and a series of dimensions will calculate how long the new operation will take.
Setup Time	The default setup time for the operation.
Change Time	This is the default change over time for an operation. This value is only relevant if an operation is performed more than once.
Dimension	A drop down list that allows the user to select a dimension from a list of dimensions in the system.
Display Index	A drop down list defines the order of the operation. This value may be modified to change the order in which dimensions are displayed to the user.
Group	Each operation will also allow the user to pick from a group, enabling users to categorize operations.
Operation Range	Each operation requires a rate per minute, which are date-sensitive and can be modified over time.
Start Date	The date from which the rate takes effect.
End Date	The date to which the rate takes effect.
Rate	This is the rate in £.

Table 16. Interface fields: Operation screens

- ***Process editor***

  Once a process is added in the Group Editor, default fields can be populated (Figure 67, Table 17).

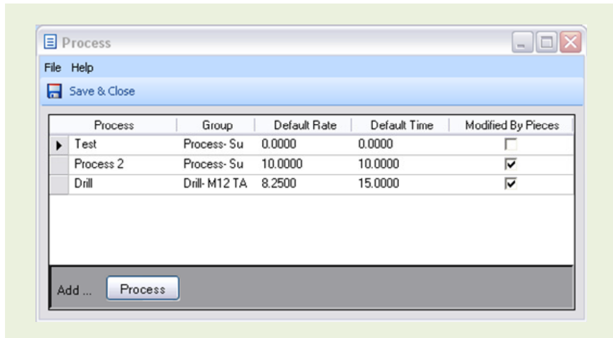


Figure 67. Process screen

Field	Input
Process	The process name.
Default Time	The estimated default time.
Default Cost	The estimated default cost.
Modify by Piece	This Boolean field determines if the time and cost are a factor of the number of pieces (or whether the number of pieces is irrelevant).
Group	This option allows the user to select a grouping for the process.

Table 17. Interface fields: Process screen

- ***Shape editor***

  Each shape record defines its own weight calculation, and a series of dimensions that define the shape. In addition each shape can select a series of dimensions that when viewed are output according to the display index.

- ***Terms editor***

  METALmpe predefines a list of both periods that quotes are valid for and payment terms. For simplicity they are maintained in the same administrative form and differentiated between by the 'term type'. *Term* is the textual description. *Term type* distinguishes between different types of term from a drop down list.

4.4.2.4 What are the characteristics of Operations?

Once the material has been specified, the estimator begins the process of defining the 'operations' and 'processes' required to produce the product. These are the value-adding features such has heat treatment and machining. An *operation* is the term used to describe any (time-variable) in-house machining activity which modifies the dimensions of a piece of material. These characteristics are those judged most critical to the estimate, hence *operations* are subjected to case-based costing in addition to feature-based costing (whereas *processes* are not). Sub-contracted machining operations are considered to be a *process*. Both operations and processes are grouped according to the pre-defined groupings, which can be selected using a drop-down menu selector (Figure 68). When no appropriate classification exists (Group-Type/Group/Sub-group), the user can generate new classifications using the Administration function 'Group'.

Estimating the time required to complete an operation (and its cost), is the most complex step of the estimating process. In all cases feature specific variables (the physical dimensions of the machined feature) will directly influence the cost of an operation. Operations are not associated with an 'item' quantity, if the operation needs to be performed multiple times on any single item, the user will need to add the same operation multiple times to that quote item.

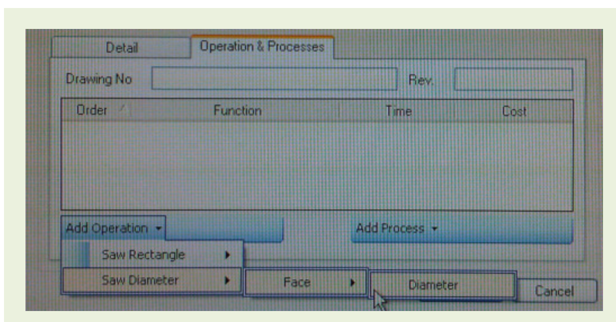
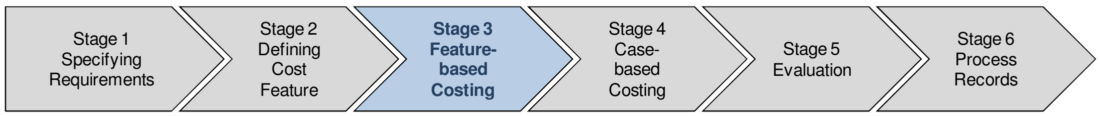


Figure 68. Operations drop-down menu

4.4.2.5 What are the characteristics of Processes?

Processes can be completed 'in-house' or sub-contracted. Estimating the cost of a process is relatively simple, and in most cases it is assumed that a default time and cost can be used. Processes are not associated with a quantity. If a process needs to be performed multiple times the user will need to add the same process multiple times to a quote item. The default time and cost for a sub-contracted process takes account of any costs that this incurs such as carriage, since a process may be completed off-site. Each process defines a rate that can be modified by the pieces (pieces being the number of duplicates a given quote item required). Some processes have a single cost regardless of the number of pieces e.g. mechanical testing, whilst others may have a cost associated to each piece.

4.4.3 Stage 3 Feature-based Costing



The overall objective for this stage is to generate a calculated cost for a particular feature of the machined part, with at least the accuracy typical of the existing manual estimating process. In the case of repeat orders, or empirical data on very similar features, the feature-based cost estimate can be less relevant than the case-based estimate. It does however produce a consistent initial costing. During this stage METALmpe aims to replicate the results of manual estimating techniques, whilst creating a resource of codified knowledge from expert estimators, Figure 69.

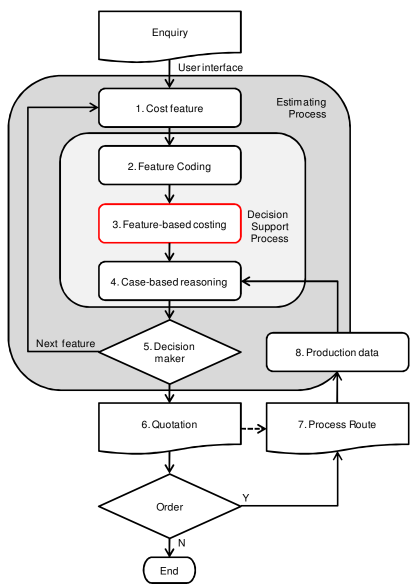


Figure 69. Stage 3: Feature-based costing

4.4.3.1 Specifying product features

A quotation is generated using METALmpe which requires the user to enter specific customer details, requirements and specifications. The estimate for each machined part is then complied as an integral part of the quotation process. For each product being quoted further levels of decomposition are accessed and the cost estimating of the product commences. Specific material requirements are entered and current stock can be searched to find the nearest available size, before a cost price for the starting material is entered.

The interface enables novice estimators to navigate their way through the features of the machined part effectively, at the same time building the process route by defining the activities required to produce a finished part. A drop-down selector aids the user in designating feature classifications and screen prompts guide the user to enter the variables required for a calculation to be processed.

4.4.3.2 Specifying an operation

From the *quote item* screen (where the user previously specified the material to be used), left clicking on the 'operations and processes' tab allows access to next system level - where the process route for manufacturing is determined. The sequence of manufacturing activities is determined by selecting either 'add operation' or 'add process' tabs (Figure 70, Table 18) – producing a route representing (as near as possible) the sequential order in which they will be executed.

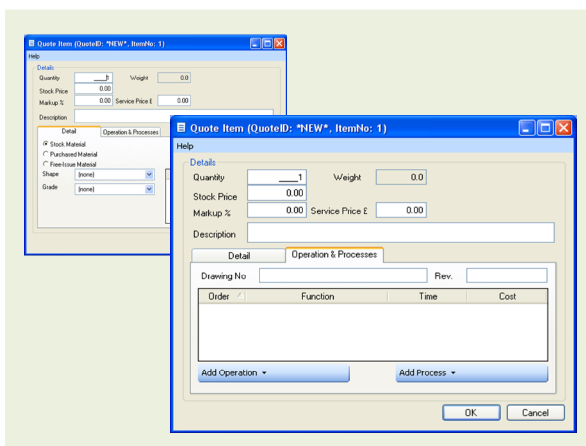


Figure 70. Operations and processes screen

Field	Input
Drawing No	This is the drawing number that describes the finished item.
Rev	The drawing revision.
Add Operation	This allows the user to add a new operation from a list of all operations in the system. Selecting an option from this list will open up a new quote item operation record.
Add Process	Selecting an option from the drop down list and selecting 'add process' adds a new process to the operations and processes list, and opens up a new process record.
Execution Order	This is the order in which each step is to be completed. This value will be modifiable via a drop down combo list that will allow the user to move operations around.
Function	This will be the operation or process name.

Table 18. Interface fields: Operations and processes screen

Selecting an operation (or double clicking on an existing operation) loads the screenshots below, Figure 71. Users are guided to enter a series of operation dimensions. Then through a combination of feature-based and case-based processing the operation is estimated in terms of time and money.

The first stage in this process requests the user to enter basic information, such as a series of required dimensions. The grid on this form presents the user with a list of these dimensions, and the user is asked to enter the appropriate properties (Figure 71, Table 19).

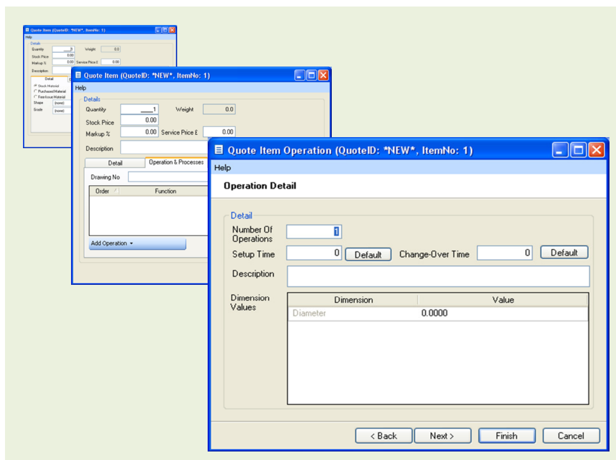


Figure 71. Quote item: operations screen

Field	Input
Number of Operations	The number of times the operation is to be completed.
Setup Time	The time cost to 'setup' the operation. A default value can be selected.
Change-Over Time	The time it takes to change over. This value is only relevant if the number of operations is greater than one. Should the number of operations be one this field will be read-only, and the default button disabled.
Description	Description that adds any additional detail to the operation.
Dimension Values	Each operation defines a series of dimensions about which it needs information. This section prompts the user to enter a value for each dimension. The unit type in the screenshot shows metric. This value reflects the measurement type selected in the quote record. Should the user select imperial the values entered would be expected to be in imperial. Please note that an automatic conversation takes place to the base measurement system.

Table 19. Interface fields: Quote item – operations screen

The estimates for operations are calculated by 'time equations' and 'transform equations' (described in sections 4.4.3.4 and 4.4.4.4), which are embedded in the operation record when it is created at the 'administration' stage.

4.4.3.3 Specifying a process

As in 4.4.3.2, from the *quote item* screen the 'operations & processes' tab accessess the next level where the process route for manufacturing is determined, adding activities in sequential order. Selecting a process (or double clicking on an existing process) loads the 'quote item process' screen, Figure 72 and Table 20. Processes are only estimated by feature-based costing (case-based costing is not applied), therefore once this page is loaded the *quote item* is populated with this estimate.

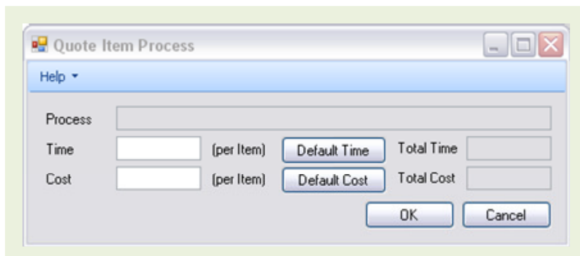


Figure 72. Quote item: process screen

Field	Input
Process	The process currently viewed. This field is read only.
Time	This is the estimated time to complete a process.
Default Time	The user can choose to use the default time as defined by the operation.
Cost	This should be the cost per process. This is a user editable field.
Default Cost	This allows the user to update the cost to reflect the default cost for the processes.
Total (Time & Cost)	Each process can be affected by the quantity, as per the field 'ModifiedByPieces' in the process table. If cost is a factor of the quantity, this total simply multiplies Pieces by Time|Cost.

Table 20. Interface fields: Quote item – process screen

4.4.3.4 Time equations: Managing expert knowledge

This section describes a critical stage of the METALmpe methodology, as it defines the mechanism by which the knowledge of expert estimators is codified as algorithms within this decision support process. The METALmpe application is developed so these algorithms can range from simple equations e.g. calculating the time to saw a particular surface area, through to much more complex calculations.

A novel aspect of METALmpe is that whilst the process methodology aims to be generically applicable to SME machine shops, this stage (the management of specific engineering knowledge) purposely sets out to capture how individual organizations apply their own specific estimating knowledge in cost engineering in their own environment.

It may be that many algorithms could be equally applied to other organisations, at least for a 'rough cut' estimate, but that is not the original intention of developing METALmpe - which is to capture very specific organizational knowledge. The important consideration for this stage is to reduce the risk of reliance on individuals by codifying the method by which estimates are calculated, so that this knowledge can be distributed and shared within the organization.

In the following example (described in section 4.2.1), which of calculates the time required to rough machine a post on the end of a rectangular forging, the calculations were codified as follows:

TurnLength/((TurnFPM*12/(SQRT(Height^2+Width^2)*3.142)*Feed)
*(CEIL((SQRT(Height^2+Width^2)Diameter)/2/DepthofCut))

This algorithm can them be applied to the relevant 'operation' using the *operation editor* function (Figure 73) in the administration menu.

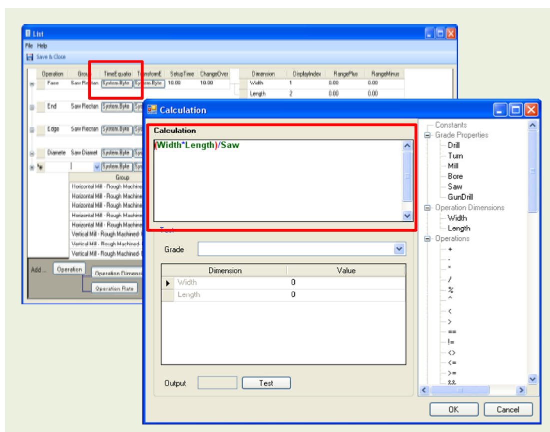


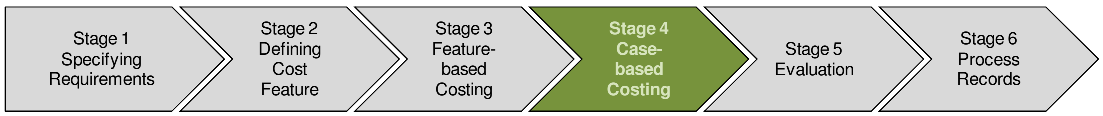
Figure 73. METALmpe - calculation screen: Time Equation algorithms

Selecting the 'time equation' tab in the 'new operations' screen opens up the calculation form which is used in feature-based costing. The calculation form facilitates building up the calculation through a series of fields that can be dragged onto the form. The values vary depending upon the calculation type. Dimensions are not intended to accurately describe shape, they are only required to provide the most basic information necessary for costing.

Once a time equation is entered it enables an operation time estimate to be generated, acting on the user inputs:

1. Preselected material specification and starting size
2. Selected operation
3. Input specific feature dimensions

4.4.4 Stage 4 Cased-based Costing



The overall objective for this stage is to compare the cost feature to empirical data stored from previous production activities, Figure 74. The nearest matching production data is then adapted to produce a costing comparison for the current feature.

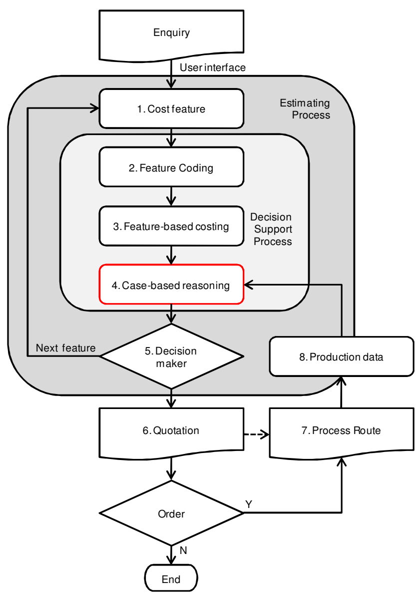


Figure 74. Stage 4: Case-based costing

4.4.4.1 Building the 'case base'

Case-based Reasoning (CBR) provides a cognitive model of how people solve problems. CBR uses a structured case memory and context-based indexing method to retrieve and then reuse of previous production times and costs. CBR is effective for estimating repeat orders or when estimating new features which are similar to those already produced on other parts, i.e. changes in material specification or dimensions which can be compensated for by parameter adjustment.

4.4.4.2 Searching the case base for nearest matching cases

The *case* provides the matching criteria which links to the appropriate algorithm and results in a theoretical estimate of the time and cost of the operation. Furthermore the *case* also provides the matching criteria for subsequent CBR. CBR is applied to each *feature*, comparing each new case against empirical production data. In CBR case retrieval is of primary importance, an effective indexing and matching process for retrieving cases leads to more effective computation in the later stage of *case adaption*. For efficient retrieval, the application organises cases hierarchically through *shared feature networks*, Figure 75. The new case is matched against the contents of each node at the highest level, then its descendant levels, until the best-matching node is returned.

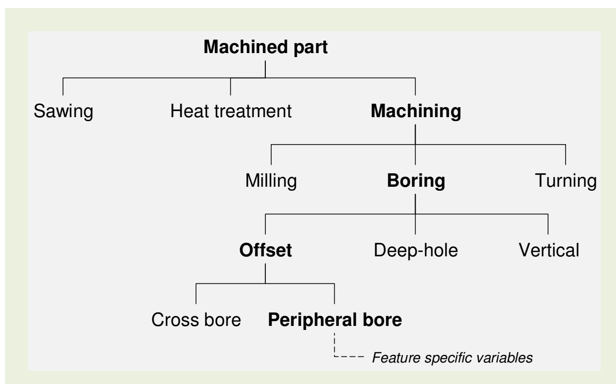


Figure 75. Shared feature network

Let N = the top node.
Repeat until N is a case
Find the node under N
that best matches the input.
Return N.

Thus, METALmpe only retrieves cases from its database of past production cases that best resemble the characteristics of the part which is being estimated. The information provided by the retrieved case is reused or modified using algorithms (depending on degree to which the retrieved case matches the feature being estimated) providing a solution to the current estimating problem. The revised case is subsequently evaluated by a human estimator to assess its suitability, and a decision is made whether the solution is to be retained or discarded. Importantly, whilst CBR may provide the estimator with fast access to information, the quality of this information is highly dependent on effective linkages to similar past cases. Therefore, 'feature code' administration is a critical aspect of the METALmpe application software.

Partitioning the data makes retrieval more efficient than a serial search, but keeping the network optimal as further cases are added is critical for efficient searches of relevant data. Within the application, the mechanism for defining the cost features (as either an *operation* or a *process*) is specifically designed to maintain an efficient network and manage case storage and retrieval effectively.

4.4.4.3 Ranking returned cases by similarity

Returned cases are ranked by the degree of their similarity to the new case, which is computed in terms of the *most specific common abstraction*. For each past case the 'difference' from the current case is determined. Cases are then ranked firstly by the *dimension difference* and then by the *machinability difference* in ascending order. Both the dimension difference and the machinability difference are defined by the author according to equation 1 and equation 2 as shown below.

$$Dimension\ difference = \sum_{n=1}^{n=N} |CD_n - PD_n| \times DI \qquad \text{… Equation 1}$$

$$Machinability\ difference = |CGMI - PGMI| \qquad \text{… Equation 2}$$

Where:

CD_n = nth dimension for current case

PD_n = nth dimension for past case

DI = *Display Index* for nth dimension (as defined below)

CGMI = current case grade machinability index

PGMI = past case grade machinability index

N= number of dimensions used to characterise the component

The Display Index is a priority weighting given to the specific dimensional fields of a feature, this is designated when defining an operation in the Operation Editor (figure 66). This prioritises a particular dimensional field of a feature for matching and subsequent ranking purposes, e.g. when milling a rectangular bar, if the display index for the width is 1 and the length 2, then the matching and ranking process will identify nearest matching *widths* in prior cases.

Cases which match exactly the new case are reused. When a significant number of cases are retrieved which all match exactly with the requirements of the new case, the recommendation is calculated based upon the average value of these cases. When only partially matching cases are retrieved, the new estimate is calculated by manipulating the old data using *parameter adjustment*, a heuristic for adjusting numerical parameters: the old solution is adapted by the extent to which features specific variables differ to the new case.

If the grade differs METALmpe returns the calculated time. If the grade matches METALmpe returns the average partitioned by the dimension difference. Table 21 below demonstrates this partitioned variance with some simple examples.

Case	Width	Time (From timesheet)	'Actual Time'
Current Case	10	?	?
Past Case 1	10	20	20 + 60 / 2 = **40** (Past Case 1 & 5)
Past Case 2	11	30	30 + 40 / 2 = **35** (Past Case 2 & 3)
Past Case 3	11	40	30 + 40 / 2 = **35** (Past Case 2 & 3)
Past Case 4	12	50	50 / 1 = **50** (no other matches)
Past Case 5	10	60	20 + 60 / 2 = **40** (Past Case 1 & 5)

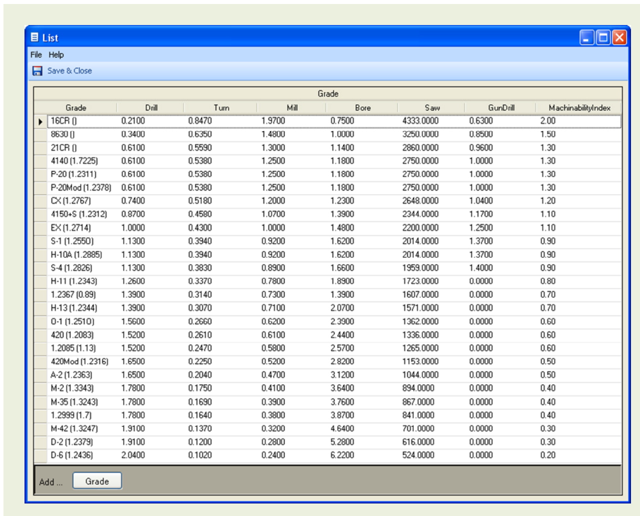
Table 21. Partitioned difference

4.4.4.4 Transform equations

Transform equations relate to time equations, in that for a specific operation they provide the algorithm used in *parameter adjustment*. Parameter adjustment is the method by which an existing estimate is adapted by the extent to which its feature specific variables (e.g. material grade and physical dimensions) differ to those required by the new estimating requirements.

When METALmpe searches the case-base (the repository of empirical production data for operations), it selects the closest matching cases to that represented by the new estimating requirements. However, in some instances even the nearest matching cases will not be close enough a match to reuse production times recorded, unless it is adapted by parameter adjustment. Typically, near matching cases will differ due to different material specifications, variation in the sizes of one or dimensions, or both.

Transform equations provide the algorithm which compensates for the differences between grade machinability (Figure 76) and physical dimensions.



Grade							
Grade	Drill	Turn	Mill	Bore	Saw	GunDrill	MachinabilityIndex
16CR ()	0.2100	0.8470	1.9700	0.7500	4333.0000	0.6300	2.00
8630 ()	0.3400	0.6350	1.4800	1.0000	3250.0000	0.8500	1.50
21CR ()	0.6100	0.5590	1.3000	1.1400	2860.0000	0.9600	1.30
4140 (1.7225)	0.6100	0.5380	1.2500	1.1800	2750.0000	1.0000	1.30
P-20 (1.2311)	0.6100	0.5380	1.2500	1.1800	2750.0000	1.0000	1.30
P-20Mod (1.2378)	0.6100	0.5380	1.2500	1.1800	2750.0000	1.0000	1.30
CX (1.2767)	0.7400	0.5180	1.2000	1.2300	2648.0000	1.0400	1.20
4150+S (1.2312)	0.8700	0.4580	1.0700	1.3900	2344.0000	1.1700	1.10
EX (1.2714)	1.0000	0.4300	1.0000	1.4800	2200.0000	1.2500	1.10
S-1 (1.2550)	1.1300	0.3940	0.9200	1.6200	2014.0000	1.3700	0.90
H-10A (1.2885)	1.1300	0.3940	0.9200	1.6200	2014.0000	1.3700	0.90
S-4 (1.2826)	1.1300	0.3830	0.8900	1.6600	1959.0000	1.4000	0.90
H-11 (1.2343)	1.2600	0.3370	0.7800	1.8900	1723.0000	0.0000	0.80
1.2367 (0.89)	1.3900	0.3140	0.7300	1.3900	1607.0000	0.0000	0.70
H-13 (1.2344)	1.3900	0.3070	0.7100	2.0700	1571.0000	0.0000	0.70
O-1 (1.2510)	1.5600	0.2660	0.6200	2.3900	1362.0000	0.0000	0.60
420 (1.2083)	1.5200	0.2610	0.6100	2.4400	1336.0000	0.0000	0.60
1.2085 (1.13)	1.5200	0.2470	0.5800	2.5700	1265.0000	0.0000	0.60
420Mod (1.2316)	1.6500	0.2250	0.5200	2.8200	1153.0000	0.0000	0.50
A-2 (1.2363)	1.6500	0.2040	0.4700	3.1200	1044.0000	0.0000	0.50
M-2 (1.3343)	1.7800	0.1750	0.4100	3.6400	894.0000	0.0000	0.40
M-35 (1.3243)	1.7800	0.1690	0.3900	3.7600	867.0000	0.0000	0.40
1.2999 (1.7)	1.7800	0.1640	0.3800	3.8700	841.0000	0.0000	0.40
M-42 (1.3247)	1.9100	0.1370	0.3200	4.6400	701.0000	0.0000	0.30
D-2 (1.2379)	1.9100	0.1200	0.2800	5.2800	616.0000	0.0000	0.30
D-6 (1.2436)	2.0400	0.1020	0.2400	6.2200	524.0000	0.0000	0.20

Figure 76. Machinability index

The transform equation algorithms provide the mechanism by which parametric adjustment can be applied within the CBR cycle. The logic supporting the transform equation process is shown in Figure 77, which represents stages 2 to 4 of the CBR cycle (discussed previously in section 2.5 and Figure. 29).

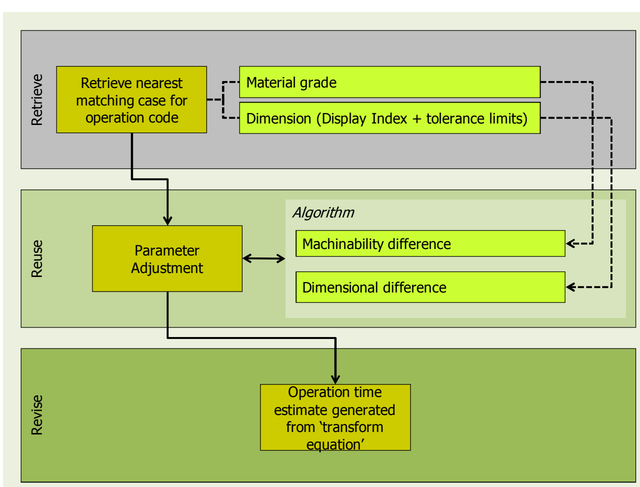


Figure 77. The transform equation process

The algorithms are created in much the same way as time equations are, and they are entered at the same time that the operation is created. The algorithms are entered using the 'calculation' screen which is accessed by 'transform equation' tab in the *operation editor*, Figure 78.

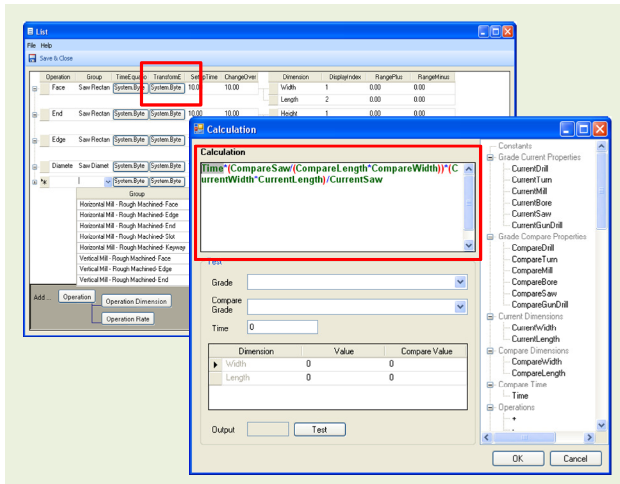


Figure 78. METALmpe - calculation screen: Transform Equation algorithms

The transform equations require as inputs *the time to complete an operation once* and the relevant *dimensions*. The process of retrieving data for use in the transform equations is:

(1) Retrieve the total time spent on the past operation case.

(2) Subtract from (1) the past case setup time, and the change over time by the number of operations on the past case minus one.

(3) Divide the time taken in (2) by the number of pieces on the past case, and then the number of operations on the past case.

This *machining time* (which is the actual input to the transform calculation) is thus:

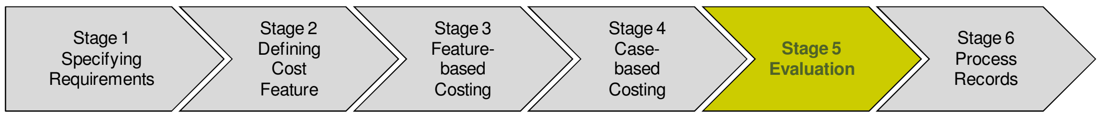
((CaseActualTimeCaseEstimatedSetup(CaseEstimatedChange*
(CaseNumOp-1)))/NumOperations)

The final *case-based time* value is then calculated:

(CBREstimate * NumOp) + SetupTime+
(ChangeOverTime*(NumOp – 1))

Actual production performance times are recorded using *Timesheet records*. The timesheets record data based on how long an operation took, they do not distinguish between set up times, change over times or machining time. Therefore when reusing such data in case-based costing an assumption is made that the *set up* and *change over* times originally designated when specifying an operation, are sufficiently accurate to be excluded from parameter adjustment. This is important because in instances when machined-parts are ordered in multiples, e.g. 10 off processed in a batch, then the initial machine set up time /cost should be apportioned across all the individual piece parts. An evaluation of set up and changeover times used in the configuration of METALmpe at the case study company was conducted in-situ.

4.4.5 Stage 5 Evaluation



The overall objective for this stage is to enable the decision maker to assess the estimates generated by both the FBC and CBR stages of the process and make a selection as to which estimate he will use (Figure 79), or alternatively enter a time which is a compromise between the two.

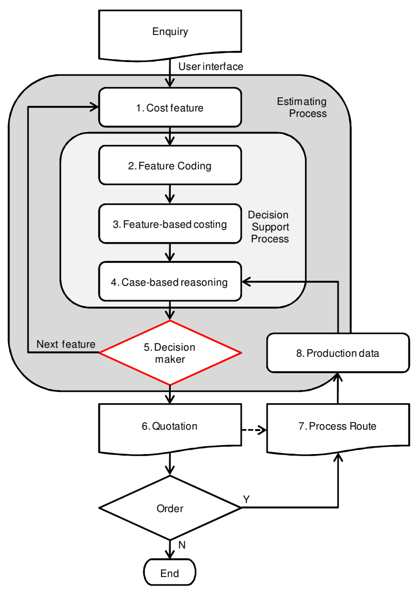


Figure 79. Stage 5: Evaluation

4.4.5.1 Decision support: Finalising feature estimates

Following the feature-based and case-based costing processes, the user interface displays a listing of nearest matching past cases, a recommended time derived by CBR and a theoretical time derived by FBC. At this point the user can intervene, selecting either the calculated time or the recommended CBR time; alternatively they may decide upon an intuitive time (Figure 80, Table 22). The cost of the operation is populated by the system, based upon predefined hourly machine costs.

The final ‘quote item operation’ screen presents a summary to the user for the selected operation. The cost of the operation is populated by the system, based upon predefined hourly machine costs, see *operation editor,* section 4.4.2.3. All fields on the final screen are read-only (Figure 81). If the user needs to modify any of the values they will need to navigate to the previous screen to effect the required changes. Once the estimate for a specific feature is complete the user can proceed to add further features, or they can close the estimating process and finalise the quotation.

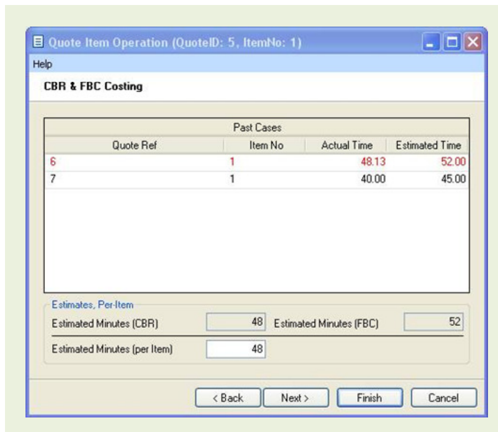


Figure 80. CBR & FBC costing screen

Field	Output
Quote Ref	This value identifies the quote that has been identified as a relevant past case. The user can double click on a past case that will open the quote in a read-only format.
Actual Time	Actual time that it took to complete the operation.
Estimated Time	This is the time that it was estimated by the past case as to how long it would take to complete the quote.
Estimated Time (CBR)	The estimated time to complete the operation based on the selected past case. This value is calculated through the transform calculation and returns a new estimated time. The transform equation takes as its input the past case actual time and its relevant dimensions. This equation allows certain dimensions to be given priority, or even ignored. CBR values include both the setup and changeover times.
Estimated Time (FBC)	The FBC is a cost value that simply calculates the estimated time based on the input dimensions. To this value will be added the setup time plus the cost of changeover multiplied by the required number of operations minus 1.
Estimated Time	The system asks the user to enter this value. It is the time that the system user is estimating the operation will take.

Table 22. Interface fields: CBR & FBC costing screen

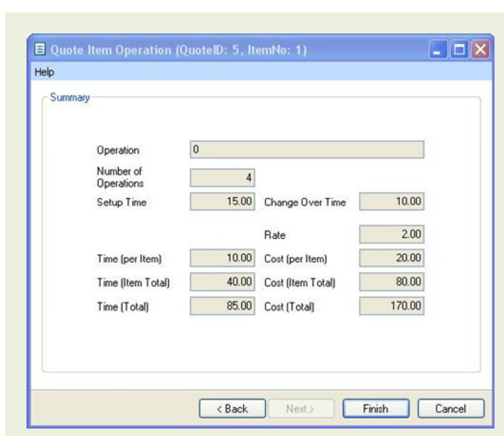
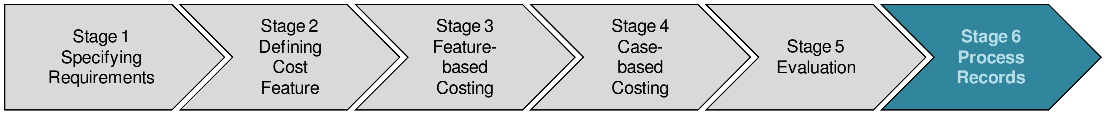


Figure 81. Operation summary screen

4.4.5.2 METALmpe reports

The estimating process aims to represent company-specific operating performance; the standard analysis makes a broad analysis of all production information for a specific cost feature. However, the process of recording actual data for definable features enables comparison between combinations of *production variables* e.g. different operators / different machine tools. Therefore a reporting option is made available which enables a closer examination of operator/machine performance. These ‘best practice’ values are particularly useful when highly competitive quoting is required. However, there is a caveat to using specific combinations: reliance on the optimum production route reduces flexibility for the machine shop planner and requires more advanced capacity scheduling.

4.4.6 Stage 6 Process Records



The overall objective for this stage is record the performance of production activities in order to assess the accuracy of the earlier estimate. This also adds to the knowledge resource in the case-base so that future reasoning can take into account a broader range of empirical data. During this stage METALmpe is used to:

- Produce a quotation (step 6, Figure 82).
- Produce a 'production route' card for conveying manufacturing instructions (step 7, Figure 82).
- Register actual production times against estimates, updating the 'case-base' (step 8, Figure 82).

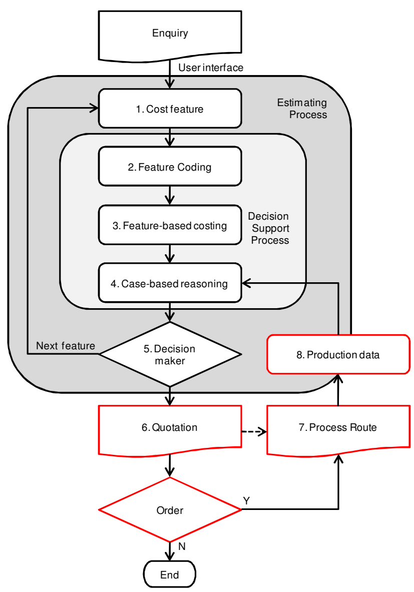


Figure 82. Stage 6: Process records

4.4.6.1 Completing the quotation process

Once an estimate is completed for each specific feature of the machined part, the user can close the estimating process for that particular item and save that line of the quote. If further parts are required on the same enquiry, the user can repeat the complete cycle against multiple line items using the same quote. Once all machine part estimates are complete, the user can close the quotation process and finalise the offer. METALmpe generates an official Quote, which can be emailed or printed for faxing/posting to the customer.

4.4.6.2 Order acceptance and production documentation

On receipt of an order the quote information is reused to produce all subsequent sales and production documentation. The only user inputs required at this stage relate to entry of order numbers etc. Providing no other amendments are necessary, all relevant fields for: Contract Reviews, Sales Orders Acknowledgements, Production Route Cards, Delivery Notes and Invoices, are populated from the Quote record by METAL.

Within the production route template, the process / operation description field allows additional free-text instructions to enable production control to clarify specific process instructions.

4.4.6.3 Recording actual performance using Timesheet Records

Throughout the production process the actual time taken to complete each operation is recorded on the system. At the point of data entry, the time being recorded can be excluded from future case retrieval by designating that case ‘nonconforming’. This may be necessary if performance on a particular operation is significantly different to the estimate due to assignable causes of variation; such instances would distort future case-based reasoning. This ensures that when matching cases are reused in future estimating, the CBR value will represent reproducible operating performance.

The timesheet record (Figure 83, Table 23) collects information about how long individual operations take to complete. Accurately describing the time took to complete a given quote item operation may occur across multiple timesheets. For a quote item to be considered complete all operations must be marked with complete. There is no conflict detection to determine if a quote has been marked as completed multiple times.

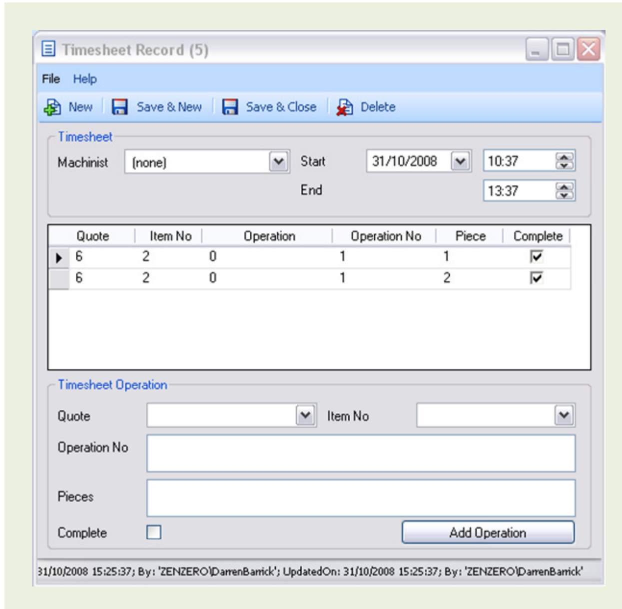


Figure 83. Timesheet record screen

Field	Input
Machinist	The timesheet is entered for this person.
Start	The start time of the work.
End	The finish time of the work.
Quote	Quote the user has completed.
Item	Particular item that has been completed.
Operation No	Operation No is a multi-selection checkbox that allows the user to select one or more operations relevant to the quote and quote item.
Pieces	'Pieces' is a multi-selection checkbox that allows the user to select that multiple pieces were worked on.
Complete	This indicates if the work was considered complete.

Table 23. Interface fields: Timesheet record screen

4.5 Chapter summary

This chapter discusses how the commercial aim of the project at the case study company was addressed i.e. the development of an estimating system capable of providing intelligent decision support. The chapter describes the process by which the concept of a feature-driven case-based machined part estimating cost model; based on a hybrid feature-based costing / case-based reasoning technique was realised through the METALmpe application.

METALmpe adopts both parametric estimating (feature-based costing) and analogy-based reasoning (case-based reasoning) techniques to derive estimates. The system contains a repository of codified knowledge elicited from existing practice and stored as algorithms, in addition to a database of actual production times. These algorithms can be applied to the costing of similar products, using established *cost estimating relationships*, mimicking the behaviour of the human expert by utilising the potential similarity between empirical information and new requirements.

When estimating the cost of new products the case study company rely on expert judgement, based on intuition and experience. When analysing new products, experts make numerous assumptions and judgements to speed up the estimating process, but the lack of a structured method decreases the transparency of the process making analysis by non-experts difficult. The system development described in this Chapter seeks to make estimating process easier for novice estimators to learn, thus providing an alternative solution to reliance on expert judgement.

For SMEs, it is important that any technology solution helps to reduce the workload burden on individuals, particularly in 'small' engineering enterprises where individuals typically perform a number of roles. Therefore user acceptance of the system is critical to the continued use of this cost model, however gaining user acceptance for a new technology can be challenging as many individuals are resistant to change.

Where detailed and accurate estimates are required, the literature reviewed in Chapter 2 suggested that approaches to estimating which use information technology can improve estimating efficiency. Analysis of the capacity for METALmpe to satisfy the aims and objectives for the research which is the subject of this thesis is provided in the next chapter.

Chapter 5 Analysis and results

5.1 Introduction

The results reported in this chapter of the thesis, and the subsequent analysis, establish the extent to which the METALmpe feature-driven cased-based estimating process would enable the research questions in section 2.6.2 to be satisfied. Therefore, findings are presented which provide a clear impression of:

1. The level of accuracy obtainable through the use of both feature-based costing and case-based reasoning methods of estimating in the METALmpe cost model.
2. The cost implications and viability of the solution for SME machining facilities, most notably for the case study company.
3. The efficacy of the feature definition and algorithm codification mechanism, and the process by which production knowledge is continuously captured.
4. Benefits in terms of: responsiveness to RFQs; and supporting workplace learning.
5. The external validity of the METALmpe application solution.

This chapter demonstrates the approaches used to analyse the data collated, and the appropriateness of that analysis to the context in which this research is set.

5.2 Results from the survey of SME engineering machine shops

A questionnaire was used to establish wider opinion on the use of ICT for estimating in SMEs, opening up a network of complimentary (or substitutable) information sources. The questionnaire was designed so that it posed questions in each of the following four areas of investigation, with emphasis on the estimating process:

- What ICT do they have?
- What do they do with ICTs?
- What do their existing ICTs do for them?
- What could be done better?

Anticipating a low response rate, particular care was required in the design of the questionnaire, following guidance and advice in three documents by Summerhill and Taylor (1992). Specific techniques for laying out options for respondents were followed and the questionnaire was trialled with colleagues at the case company and Cranfield University (revising the wording of a number of questions). The one page questionnaire was accompanied by an introductory letter in which an option was offered for feedback on the survey and an opportunity for further participation in systems development.

17 responses were received to the questionnaire distributed to 83 engineering machine shop SMEs; a return of 20%, the details of which are provided in Appendix A. Attention is drawn to the following principal findings:

- 76% of respondents employed less than 9 employees.
- 59% of respondents spend less than 9 hours per week estimating, 29% between 10 and 19 hours, and 12% between 20 and 39 hours.
- 59% of respondents state that their estimating process is ‘almost entirely manual’, with only 12% using ICT to a significant extent.
- 76% of respondents rated their current approach satisfactory or better. 90% of respondents with ‘almost entirely manual’ estimating process rated their current approach satisfactory or better.
- There was no clear preference for estimating methods.
- Only 1 respondent had previously purchased a COTS package, which they rated as ‘poor’.

- 53% of respondents considered their reliance on human expertise a 'quite important' influence on whether they would decide to adopt a system approach to estimating.

The results indicate that in *micro* and *small* sized engineering enterprises the estimating function is predominately *not* a full time role. This leads to the assumption that, in such circumstances, knowledge of estimating is only one aspect of the demands on particular individual's cognition. Increasingly, individuals have to absorb, process and disseminate larger quantities information. This problem of *information overload* is a critical challenge facing organizations today, and one which a systems approach to estimating suggests potential benefits – in terms of providing decision support and reducing dependency on human expertise.

In an environment increasingly driven by technology, authors such as Buratti and Penco (2001) suggest that SME's operating processes often do not reach their optimal technological level, impinging on their competitiveness. The survey findings appear to support this, in that the significant response to *the degree of automation in the process,* indicates a predominately *manual approach* to estimating. Also, the response to *rating the performance of current approaches*, indicates a significant proportion of the sample consider the *manual approach* 'satisfactory' - further analysis of the responses from the 10 firms who operate 'almost entirely manual' estimating.

Interestingly a number of these same respondents also recognize the inherent risk of relying on expert human estimators. This author makes the assumption that this risk is compounded in SMEs where there are less likely to be a number of individuals with similar degrees of expertise who can 'cover' their colleagues absence.

5.3 Results from verification testing

In response to Research Question 1 (section 2.6.2), a study was undertaken to evaluate the effectiveness of METALmpe for estimating new products. Estimating experiments were conducted on a range of oil tool valve block forgings, which are machined on six faces. New product sizes introduced in 2009 were processed through METALmpe, where up to three batches of each size were processed during that year. Therefore in addition to initial estimates by feature-based and case-based (using parameter adjustment) methods, it was also possible to assess the effect of the case-based reasoning process over multiple iterations of the quoting process. Each set of production data was processed through the decision support system, in chronological order. Each product size was provided with a sample number, see Table 24.

The following estimates were prepared for the initial batches:

(i) A manually calculated estimate prepared by the expert estimator

(ii) A 'FBC' estimate produced by a novice estimator using METALmpe

(iii) A estimate generate by METALmpe using parameter adjustment on the nearest matching case in the database – 'CBR_{pa}'

Once, the actual production orders for the above samples had been processed, METALmpe records were updated with 'actual' times using the 'timesheet' feature.

This enabled an evaluation to be carried out on the 1st iteration for these new parts, shown in Table 24. Significantly, the estimates produced by the expert estimator were the least accurate for the whole sample, with the CBR_{pa} being the most accurate and FBC second. In this 1st iteration the total production time for all samples equalled 253 hrs; the estimated total times were:

- Expert estimates - 328 hrs (overestimated by 29.5%)
- METALmpe FBC estimates - 288 hrs (overestimated by 13.8%)
- METALmpe CBR_{pa} estimates - 230 hrs (underestimated by 9.1%)

Following completion of the 2nd iteration, the CBR values calculated by METALmpe (now reusing exact matching case data, rather than parameter adjustment) proved to be the more accurate estimating method in each sub-set. After this point the CBR values remained the most accurate METALmpe estimating method in all but 1 case (METALmpe FBC: 970249 3rd iteration), see Table 24. The summary reports for each sample are shown in Appendix L.

Sample No.	Estimate type	1st iteration (hrs)	2nd iteration (hrs)	3rd iteration (hrs)	4th iteration (hrs)
970249	Expert	6.75	6.75	6.75	
	FBC	6.01	6.01	6.01	
	CBR_{pa}	5.94	-	-	
	CBR	-	5.27	6.34	
	Ave Actual	*4.90*	*5.41*	-	
970502	Expert	7.37	7.37	7.37	
	FBC	6.59	6.59	6.59	
	CBR_{pa}	6.27	-	-	
	CBR	-	7.51	7.53	
	Ave Actual	*7.55*	*7.55*	-	
970505	Expert	5.50	5.50	5.50	5.50
	FBC	5.24	5.24	5.24	5.24
	CBR_{pa}	3.65	-	-	-
	CBR	-	5.82	4.91	5.25
	Ave Actual	*5.90*	*4.95*	*5.28*	-
980066	Expert	6.75	6.75	6.75	6.75
	FBC	5.44	5.44	5.44	5.44
	CBR_{pa}	5.16	-	-	-
	CBR	-	4.68	6.95	7.19
	Ave Actual	*4.45*	*6.80*	*7.08*	-
980197	Expert	6.50	6.50		
	FBC	5.73	5.73		
	CBR_{pa}	3.66	-		
	CBR	-	4.96		
	Ave Actual	*5.00*	-		
970244	Expert	6.87	6.87	6.87	
	FBC	6.22	6.22	6.22	
	CBR_{pa}	4.64	-	-	
	CBR	-	4.97	4.53	
	Ave Actual	*4.45*	*4.37*	-	
970165	Expert	5.75	5.75		
	FBC	5.01	5.01		
	CBR_{pa}	3.25	-		
	CBR	-	4.75		
	Ave Actual	*4.50*	-		

Table 24. Experiment results used in the evaluation of FBC and CBR estimates of new products

Table 25 provides a summary report of the experiment using sample 970244. This shows that after 15 parts had been produced, the average actual machining time was 4.37 hrs per part. The average CBR estimate for machining time was 4.97 hrs per part. This sample illustrates a significant improvement in estimating accuracy by using CBR estimates, compared with the inaccurate overestimate of the expert estimator.

Figure 84 illustrates the convergence of the CBR estimates towards the actual production times. These graphs illustrate:

(i) How the accuracy of CBR estimates improve with increasing iterations

(ii) How CBR estimates ‘smooth’ the effect of variation which is inherent in the manufacturing process.

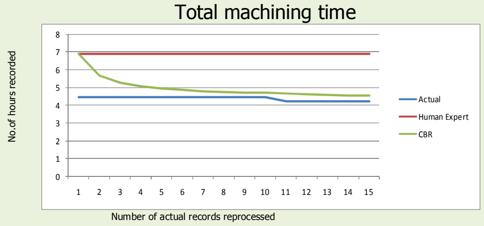
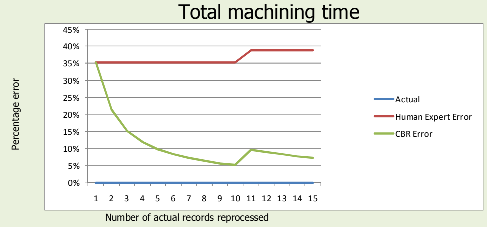
Case-based Reasoning Test Results: Sample 970244			
Process route 201		Description	4" TEC BOP Body
Actual times (Ave)	4.37 hrs	Number of parts produced	15
Expert estimate	6.87 hrs	Accuracy of expert Vs ave 'actual' time	+57.21%
CBR estimate (Ave)	4.97 hrs	Accuracy of CBR Vs ave 'actual' time	+13.73%
Total machining time 		Total machining time 	

Table 25. Case-based reasoning test results for sample 970244 – Appendix L.

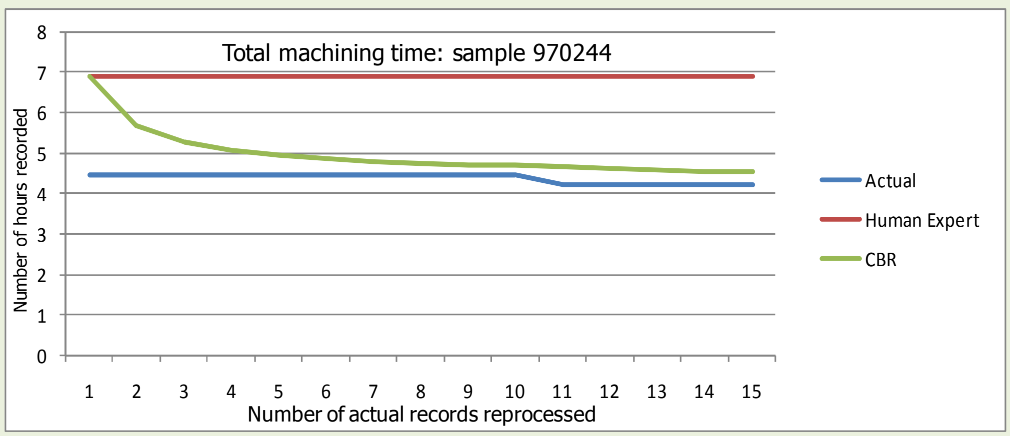


Figure 84. Graph showing hours recorded for each record within the sample 970244

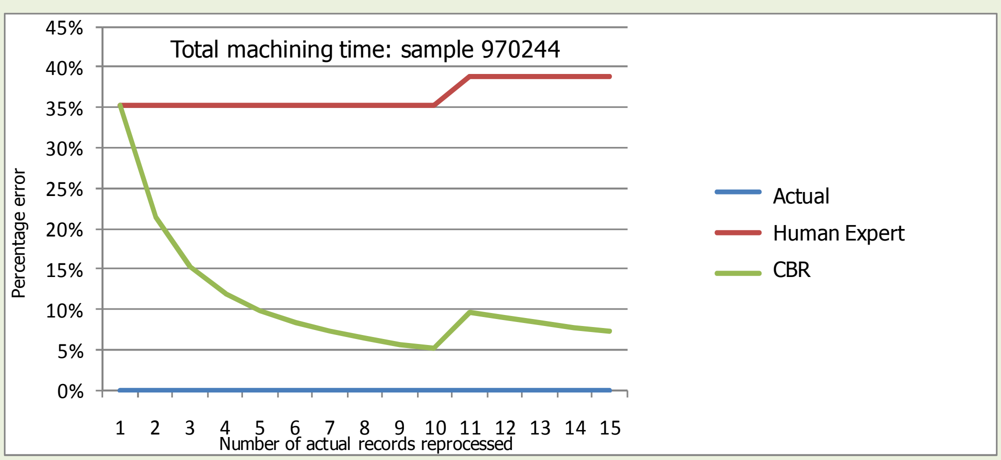


Figure 85. Graph showing percentage error for each record within the sample 970244

The graph ‘Total machining time – Percentage error’ (Figure 85), illustrates the different accuracy levels of both ‘expert’ and ‘CBR’ estimates compared with the ‘actual’ machining times (the zero baseline), in this instance all errors were positive i.e. over-estimates.

The total combined machining time for these 2009 samples reported in Appendix L equalled 495.85 hrs. The expert estimates were overestimated by 13.3%, whereas the CBR estimates underestimated the production requirements by -1.7% (Table 26). This overestimating by the human estimator using a manual method of estimating is similar to that reported in Chapter 1, i.e. 12% overestimate in a sample of 186 machined parts produced in 2005.

Sample No.	Actual time (hrs)	Expert estimate (hrs)	CBR estimate (hrs)	Accuracy of expert estimate	Accuracy of CBR estimate	Difference (hrs) between CBR and expert estimate
970165	22.50	28.75	23.75	+21.7%	+5.3%	5.00
980066	141.60	131.40	117.00	-7.8%	-21.0%	14.40
970505	79.20	82.50	80.55	+4.0%	+1.7%	1.95
980197	50.00	65.00	57.70	+23.0%	+13.3%	7.30
970244	65.55	103.05	74.55	+57.2%	+12%	28.50
970249	61.50	67.50	58.90	+9.8%	-4.2%	8.60
970502	75.50	73.70	75.00	-2.3%	-0.7%	-1.30
Total	**495.85**	**551.90**	**487.45**	**+13.3%**	**-1.7%**	**66.25**

Table 26. Summary of results from in-situ experiments Appendix L: AISI 8630 MOD oil tool forgings milled six faces

The results shown in Table 24 and Table 26, provide evidence that both initial CBR_{pa} estimates and subsequent CBR estimates can improve estimating performance to within -5% / +10% of the actual production requirements – see section 2.6.2 Research Question 1.

A further significant study was undertaken to verify the above achievement, in which the detailed historical production records of 415 semi-finished machined parts were reprocessed through METALmpe. Figure 86 shows a typical example of these machined parts, and details the machining operations used in the CBR testing reported in Appendix M. This study, which encompassed a wide size range of components, represented 11,680 of actual machining time. The significance of this comprehensive verification testing (reported in Appendix M) was that each data set included a variety of machining operations, illustrated in Table 27.

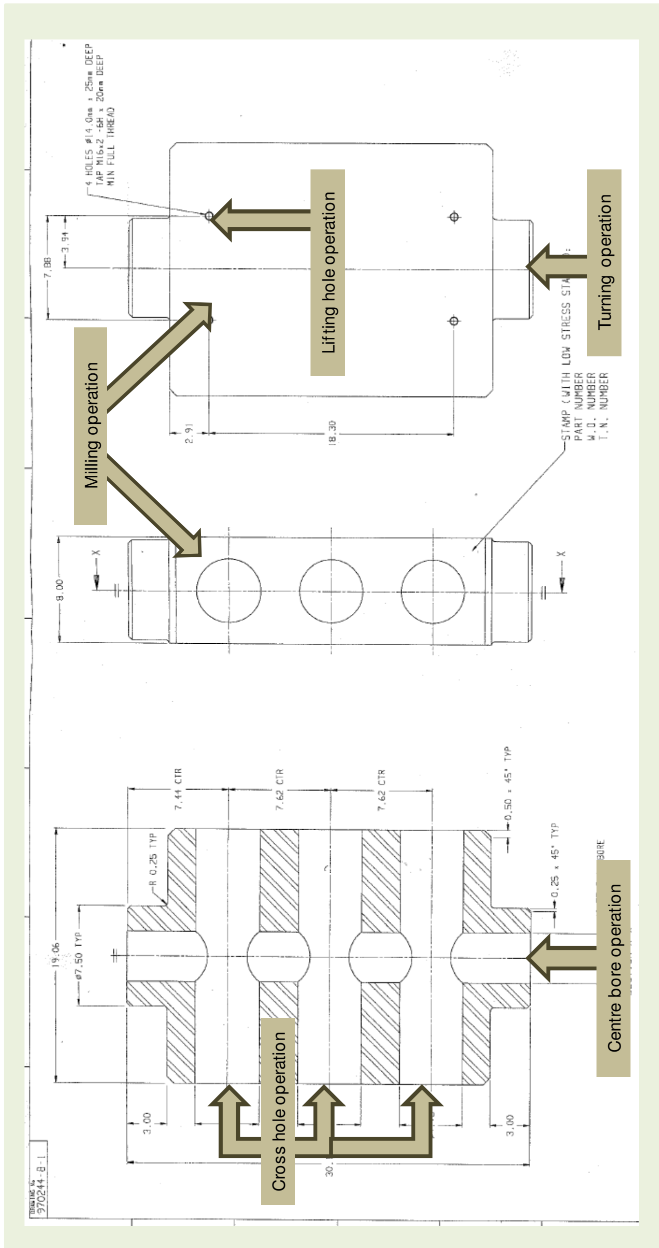
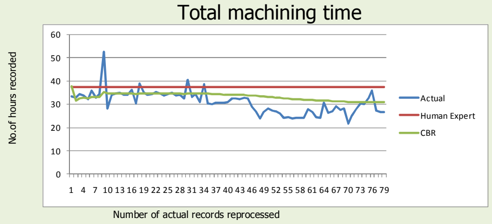


Figure 86. Product range used for verification testing

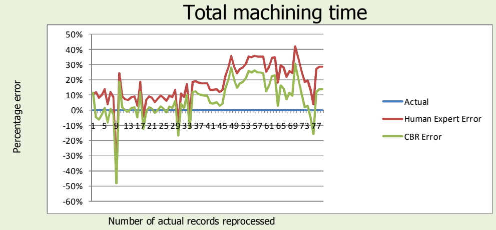
The specific sample (No.6) shown in Table 27, comprises of 79 sets of empirical production data for the machining of the part detailed in Figure 86. The information contained within this table illustrates the extent of improved accuracy in estimating resulting from using CBR within METALmpe.

Case-based Reasoning Test Results: Sample 6			
Process route	20	Description	4" TEC BOP Body
Actual times (Ave)	30.97 hrs	Number of parts produced	79
Expert estimate	37.75 hrs	Accuracy of expert Vs ave 'actual' time	+20.62%
CBR estimate (Ave)	33.61 hrs	Accuracy of CBR Vs ave 'actual' time	+8.54%

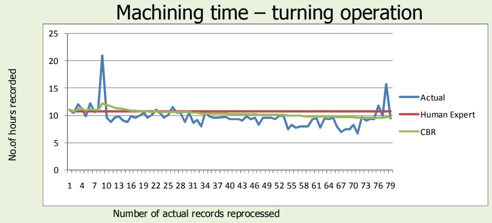
Total machining time



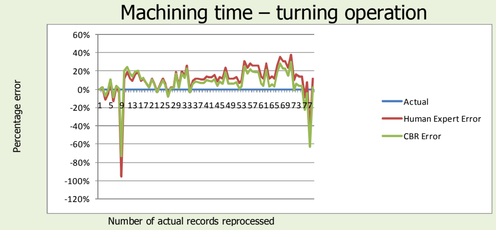
Total machining time



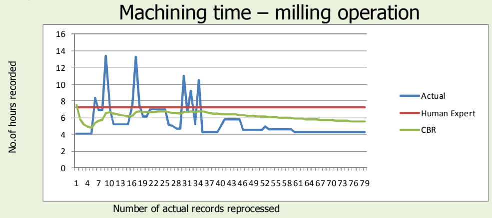
Machining time – turning operation



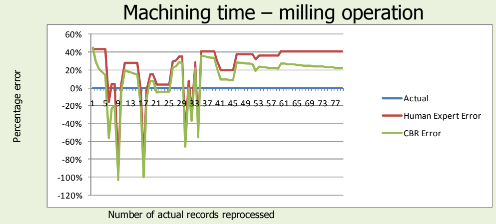
Machining time – turning operation



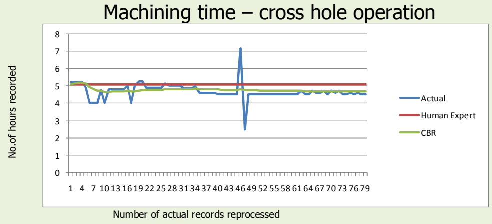
Machining time – milling operation



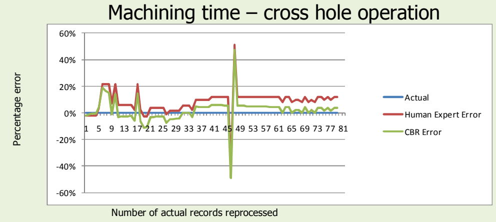
Machining time – milling operation



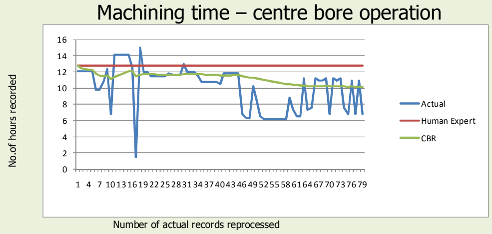
Machining time – cross hole operation



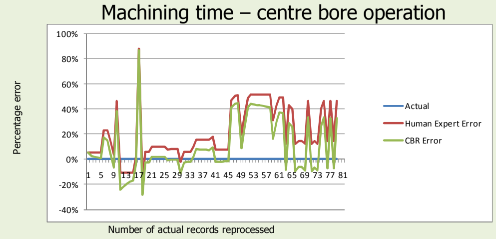
Machining time – cross hole operation



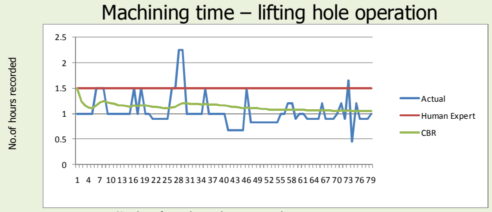
Machining time – centre bore operation



Machining time – centre bore operation



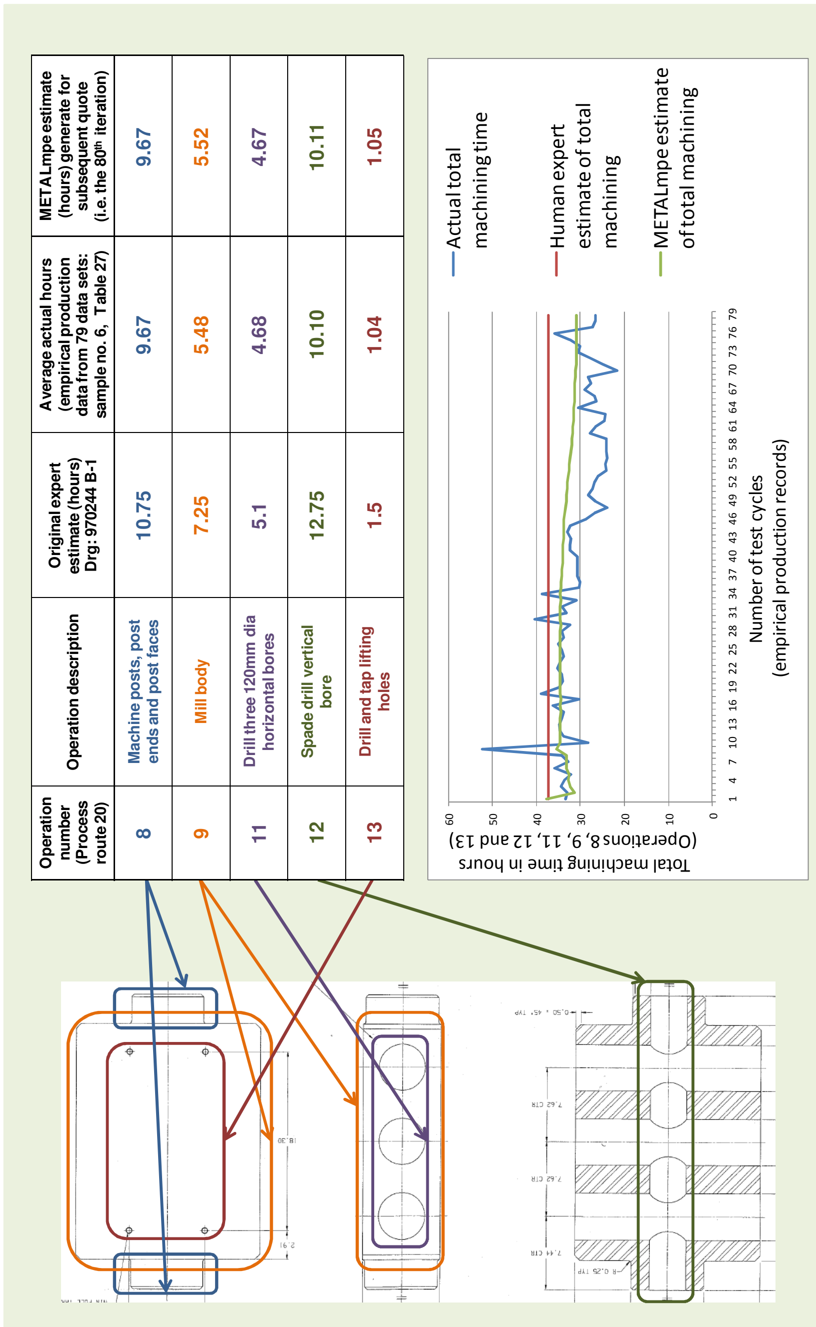
Machining time – lifting hole operation



Machining time – lifting hole operation

Table 27. CBR test results Appendix M- sample 6: AISI 8630 MOD rough machined forgings

Figure 87 is presented to show how METALmpe provides an increasingly more accurate estimate of machining time as the number of iterations increases, notably in operations (or combinations of operations) that exhibit significant variation in processing times. This is particularly relevant in organisations, such as the case study company, where the sum of the factors which influence production mean that 'standard costing' practices are not the most effective measures of performance.



Operation number (Process route 20)	Operation description	Original expert estimate (hours) Drg: 970244 B-1	Average actual hours (empirical production data from 79 data sets: sample no. 6, Table 27)	METALmpe estimate (hours) generate for subsequent quote (i.e. the 80th iteration)
8	Machine posts, post ends and post faces	10.75	9.67	9.67
9	Mill body	7.25	5.48	5.52
11	Drill three 120mm dia horizontal bores	5.1	4.68	4.67
12	Spade drill vertical bore	12.75	10.10	10.11
13	Drill and tap lifting holes	1.5	1.04	1.05

Figure 87. Illustration of improving estimate accuracy in Sample 6 (Table 27)

Each set of production data was reprocessed through METALmpe, in chronological order, so that the CBR values generated at subsequent iterations simulated the actual production performance across that timeframe (2004-2007). Table 28 summarises the results of total machining times for each sample. Table 29 summarises the results of combined sample times for each machining operation.

Sample No.	Actual time (Average hrs)	Expert estimate (hrs)	CBR estimate (Average hrs)	Accuracy of expert estimate	Accuracy of CBR estimate
1	19.52	22.48	20.09	+15.3%	+2.9%
2	24.01	26.03	24.45	+9.5%	+1.8%
3	24.99	26.85	26.25	+7.4%	+5.0%
4	26.21	26.60	27.87	+1.5%	+6.3%
5	28.82	32.72	29.62	+13.5%	+2.8%
6	30.97	37.75	33.61	+20.6%	+8.5%
7	30.41	32.22	29.94	+6.0%	-1.6%
8	36.29	48.09	37.15	+32.5%	+2.8%
9	46.61	51.98	45.54	+11.5%	-2.3%

Table 28. Summary of results from Appendix M, total machining times: AISI 8630 MOD rough machined blow out preventor forgings

Operation	Actual time (hrs)	Expert estimate (hrs)	CBR estimate (hrs)	Accuracy of expert estimate	Accuracy of CBR estimate	Difference (hrs) between CBR and expert estimate
Turning	3816.28	4213.74	3920.02	+10.4%	+2.7%	293.72
Milling	2090.66	2432.70	2212.50	+16.4%	+5.8%	220.20
Cross hole	1539.54	1770.10	1630.88	+14.9%	+5.9%	139.22
Centre bore	3737.68	4049.80	3846.80	+8.3%	+2.9%	203.00
Lifting holes	496.40	622.50	539.36	+25.4%	+8.6%	83.14
Total	**11680.56**	**13088.84**	**12149.56**	**+12.1%**	**+4.0%**	**939.28**

Table 29. Summary of results from Appendix M – classified by machining operation: AISI 8630 MOD rough machined blow out preventor forgings

The results reported in Tables 28 and 29 confirm that METALmpe can improve the average estimating accuracy to greater than -5% / +10%. Figure 88 illustrates the 'estimating results within the specified acceptance range' for the whole of the sample in Appendix M.

These results show:

- 35% of expert estimates met the accuracy criteria -5% / +10%
- 47% of CBR estimates met the accuracy criteria -5% / +10%

The extent of improvement through CBR is highlighted when this acceptance criterion is restricted even further:

- 18% of expert estimates met the accuracy criteria -5% / +5%
- 32% of CBR estimates met the accuracy criteria -5% / +5%

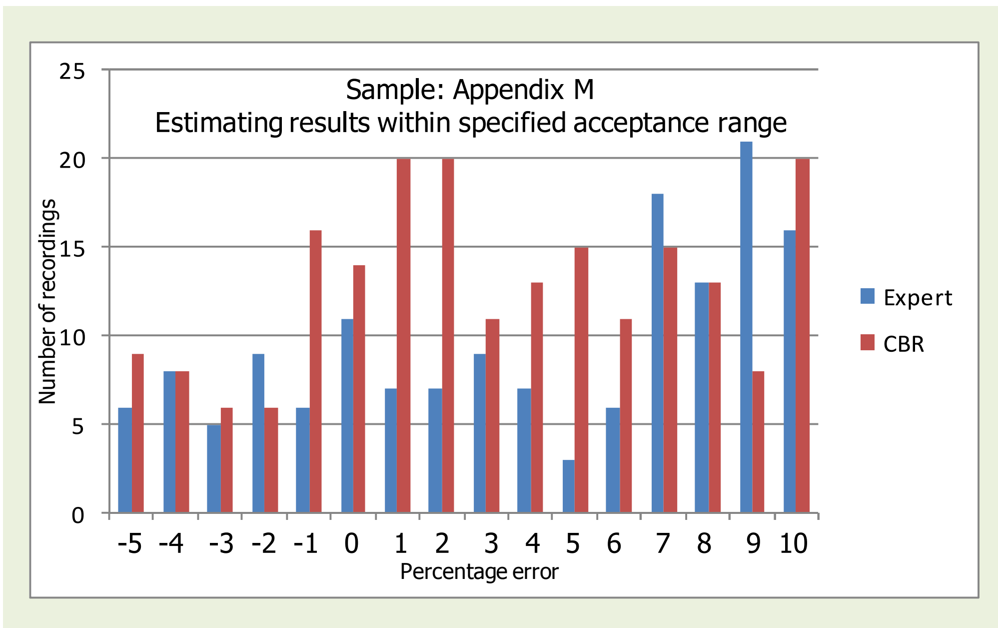


Figure 88. Estimating results within specified acceptance range for sample detailed in Appendix M

Further manipulation of the data from the samples in Appendices L and M enabled a comparision between the error ranges of estimates in both sets of samples. The percentage error for each data record was extracted and collated by Appendix number, each of the two new data sets were then re-ordered so that the largest negative error was record 1, through to the largest positive number, (record 438 for Appendix M – Figure 89, and record 85 for Appendix L – Figure 90). This illustrates a similarity in the error curves for both estimating methods, although the CBR curve is more preferable.

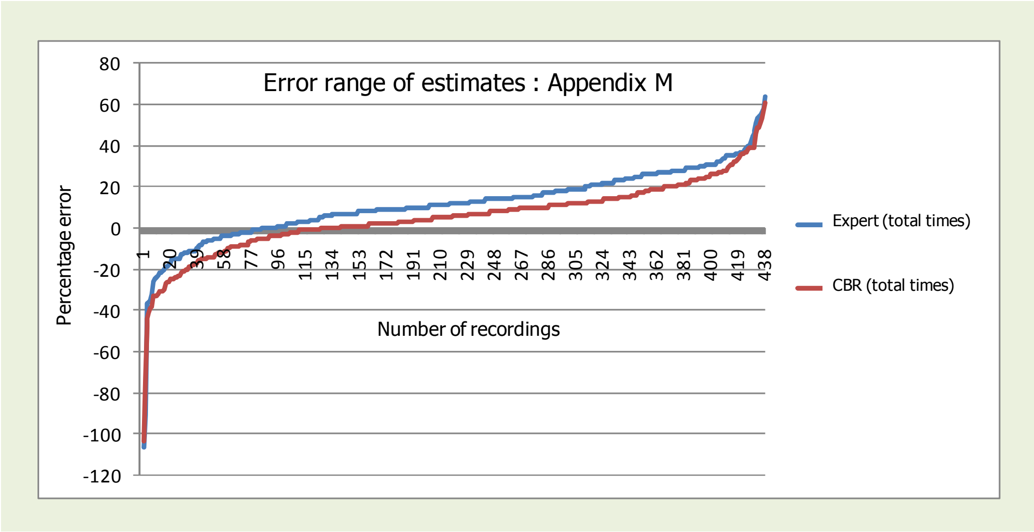


Figure 89. Error range of estimates for sample detailed in Appendix M

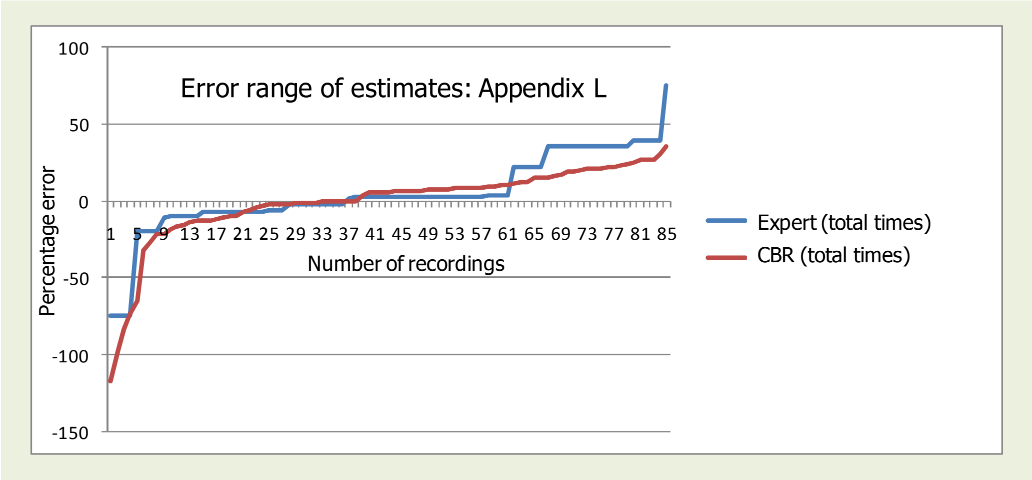


Figure 90. Error range of estimates for sample detailed in Appendix L

5.4 Internal validation of the METALmpe process.

Two workshops were held to introduce the functionality of METALmpe. The first was attended by the project sponsor and the expert estimator. A second was attended by two novice estimators, one week later. Following demonstrations and practical examples of using METALmpe to generate estimate of relatively standard products, the users were allowed to trial the software (uninterrupted) following the estimating method described in the workbook (Figure 36). After each workshop those who attended completed a questionnaire at the end of the workbook.

These questions were carefully chosen and worded, to test the key success criteria *suitability*, *feasibility* and *acceptability*, and the responses were subsequently used to facilitate the validation process. The participants were allowed to take the workbooks away and reflect on the workshops and their initial introduction to METALmpe before completing the questionnaire. When the participants had formulated their responses a further meeting was arranged on a one-to-one basis, where an informal respondent validation process was undertaken. This ensured that the completed questionnaire and additional commentary provided a clear and unambiguous evaluation of METALmpe. The findings are presented in Table 30.

Key success criteria		Expert	Novice 1	Novice 2	Sponsor	Score
Suitability	Could the methodology be followed in its entirety?	4	4	3	4	94%
	Did you feel that any of the stages used in methodology conflicted, or the sequence of the stages was inconsistent?	4	4	4	4	100%
	Did you find the methodology applicable to our organisation?	3	4	3	4	88%
Feasibility	Would the method consume excessive resources of time and people?	0	2	3	4	75%
	Does the methodology provide a practical process?	3	4	3	4	88%
Acceptability	Please rate the likely success of the overall process of the feature-driven case-based estimating method.	2	2	2	3	75%
	Is it easy to navigate around the interfaces?	2	3	3	3	92%
	How do you rate the method by which expert knowledge is codified?	2	2	2	4	63%
	How do you rate the process for producing estimates?	3	4	3	4	88%
	How do you rate the process for recording production data?	4	4	4	4	100%
	Can you identify potential benefits from applying the methodology?	1	1	1	1	100%
	Would you support using the methodology?	1	1	1	1	100%

Table 30. Validation results from internal assessments

5.5 External validation

Three SME machining companies evaluated the external validity of the METALmpe solution, C.H. Clarke Engineering Ltd, RAM Machining Ltd and Bishop Engineering Ltd (Appendices I, J and K). Key decision makers from each organisation reviewed the application software in conjunction with the METALmpe workbook. A further evaluation was conducted at Deutsche Edelstahlwerke in Germany (Appendix H), to gain a perspective from a large, state-of-the-art machining organisation.

A questionnaire was completed by the participants, which once again probed the same key success criteria proposed by Johnson and Scholes (2003). For the purposes of external validation, emphasis was placed on validating the feature-driven case-based estimating methodology and establishing whether it could be applicable to other SMEs. The findings are presented in Table 30.

Key success criteria		CH Clarke	RAM	Bishops	DEW	Score
Suitability	Could the methodology be followed in its entirety?	3	4	3	4	88%
	Did you feel that any of the stages used in methodology conflicted, or the sequence of the stages was inconsistent?	4	4	4	4	100%
	Did you find the methodology applicable to your organisation?	3	3	0	3	56%
Feasibility	Would the method consume excessive resources of time and people?	2	1	1	0	25%
	Does the methodology provide a practical process	3	2	1	1	44%
Acceptability	Please rate the likely success of the overall process of the feature-driven case-based estimating method.	2	0	1	2	42%
	Can you identify potential benefits from applying the methodology?	1	0	0	1	50%
	Would you use the methodology in your organisation?	1	0	0	0	25%

Table 31. Validation results from external assessments

5.6 Assessment of the commercial project

5.6.1 Monetary benefits

Throughout the project at the case study company costs were accurately allocated and recorded to enable a realistic appraisal of the project benefits in monetary terms. These costs are presented as a 'cost curve' in Figure 91. These actual costs exceeded the *budgeted cost of work scheduled* (Figure 42), owing to subsequent revisions to the 'software requirement specification' and unforeseeable project delays which also contributed to an extension in the project timescale.

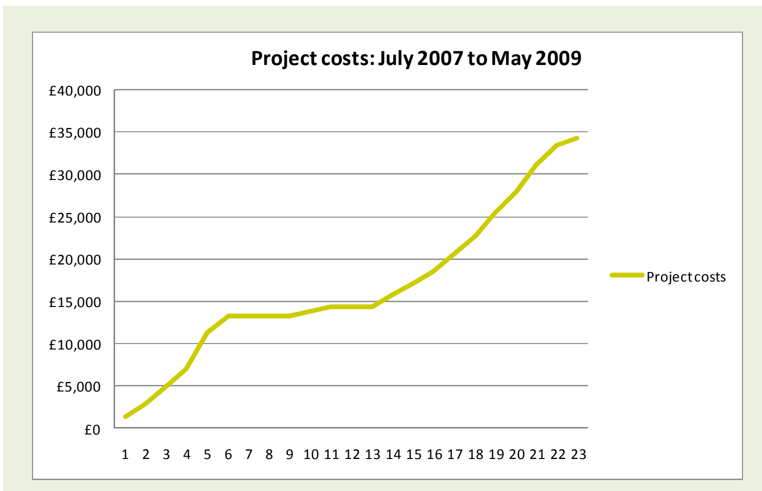


Figure 91. Actual cost curve for METALmpe project

Financial best practises dictate that 'analysis should only take account of cash flows that vary according to the decisions in the analysis (Atrill and McLaney, 2004),' i.e. 'relevant costs'. Cash flows that remain the same irrespective of the decision under review should be ignored. Of the £34,300 project cost, only circa £6,000.00 were classed as relevant costs. The balance, circa £23,000, would more appropriately termed 'opportunity costs' (Atrill and McLaney, 2004).

In terms of estimating the monetary benefit from this project, it was possible to estimate a payback period (PP) (Atrill and McLaney, 2004), Table 32. These calculations were based on METALmpe 'going live' in August 2009. At that time the assumption was made that after the first 6 months operating period, sufficient data would have been captured in METALmpe that no additional personal would need to be employed to replace the retiring estimator, i.e. the estimating workload would be shared around the remaining expert estimator and sales staff (the novice estimators). This has proven to be the case, the estimator retired at the end of October 2009 and the company has no plans to employ another 'expert' estimator in the foreseeable future.

A payback period of 13 months, justifies the decision to develop METALmpe for the case study company, regardless of the future benefits from cost savings and increased revenue which are expected to accrue.

In terms of METALmpe being a viable solution for other SMEs; costs for initial hardware, installation, software, training and support (for a 5 user agreement) would be circa £16,000. The literature review suggests that in 2006 SMEs typically invested between £20,000 and £50,000 in ICTs per annum, thus METALmpe can be considered financially viable for SMEs. This finding satisfies Research Question 2 (section 2.6.2).

The inflows and outflows were / are expected to be:

Time		*Net cash flows* £000	*Cumulative net cash flows* £000	
May 2009	Cost of METALmpe	(11)	(11)	
7 months' time	Net saving in personnel costs	(8)	(19)	(-11 -8)
12 months' time	Net saving in personnel costs	17	-2	(-19 +17)
18 months' time	Net saving in personnel costs	20	18	(-2 +20)

Therefore the payback period is 13 months.

Table 32. Payback period for METALmpe project

5.6.2 *Tangible benefits*

The requirements for commercial project at the case study company set out clear quantifiable benefits and a visionary purpose for the research and systems development, these are described by the benefits dependency network, Figure 54.

It is clear from the verification testing described in section 5.3, that the METALmpe cost model and software application can clearly meet and exceed the 'acceptance range' provided by the case study company as a desirable measure of accuracy. The verification process made use of extensive company records, making comparison with both actual production data and human 'expert' estimates easily achievable. The analysis presented in this chapter supports the argument that METALmpe can improve the accuracy of estimates, and can through CBR provide significantly improved estimates in many cases, compared to those prepared manually by hand using 'theoretical' calculations of time and cost. Referring to Table 2, which states accuracy ranges from a number of sources, METALmpe satisfies the level of accuracy considered necessary for definitive, detailed estimating – further supporting this authors' view that METALmpe satisfies the primary research question (Research Question 1).

The codification of cost engineering knowledge and an effective configuration of feature definitions, cost estimating relationships and algorithms to calculate times and costs, are fundamental requirements for METALmpe to be able to produce accurate estimates. Coupling this functionality with the ability to capture newly evolving knowledge (measures of production performance and the creation of new 'operations' or 'processes'), and reuse historical data through case-based reasoning; ensures METALmpe is a robust solution capable of reducing the extent to which human expertise is relied upon. The implementation of METALmpe at the case study company has reduced their dependence on experienced personnel. Standard machining enquiries can now be handled quickly and competently by novice estimators, reducing a 'bottleneck' at the remaining expert estimator's desk which often delayed responses to customers request for quotations. In responding to Research Question 3, it can be seen that METALmpe reduces dependence on experts, but it should be clear that it cannot wholly replace human expertise. The benefits envisaged from applying the METALmpe process of feature-driven cased-based estimating, are at this stage complimentary to those benefits provided through human expertise e.g. experience, intuition, flexibility etc.

Improving the company's ability to engage non-experts in estimating was a further driver of the research (Research Question 4). Engaging users in the development activities, ensured that the application not only met the needs of the business processes, it also met with approval and user acceptance from those tasked to operate it. The case study proved that non-experts can learn how to produce accurate quotes without learning the whole range of technical skills and acquiring the know-how which are the attributes of a human expert. By tightly coupling the METALmpe application to its workplace context, it becomes a knowledge tool which supports and enhances learning opportunities in this limited domain.

The final research question, the extent to which the method and software application can be shown to be generically applicable, is answered in section 5.5. The participants in the validation process clearly believed the estimating methodology was *suitable* for use in an SME environment. The extent that it was considered both *feasible* and *acceptable*, appeared to be more context specific. However, the findings presented in Table 31, give confidence to the assertion that METALmpe can provide a generic solution to machined part estimating, in similar environments to that described at the case study company.

5.7 Chapter summary

The satisfactory results of the verification testing conducted at the case study company, demonstrate that METALmpe can be used effectively to: define a network of product features, establish cost estimating relationships, and facilitate the specification of algorithms to be used for feature costing; all of which contribute to reducing dependence on human expertise and improving process capability. Figure 92 represents the perceived shift in process capability in terms of the importance that machined part estimating plays in being competitive. In terms of managing knowledge, this was considered to be a 'qualifying' aspect of businesses in this sector, however the existing processes were considered to be weak. The improvements in knowledge management encapsulated in the METALmpe process and the high potential, strategic application delivered in the commercial project (Figure 93) will strengthen the company's ability to compete in their business environment.

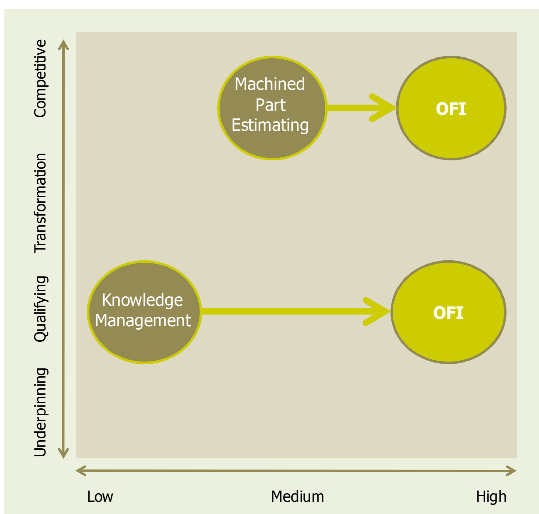


Figure 92. Process capability overview

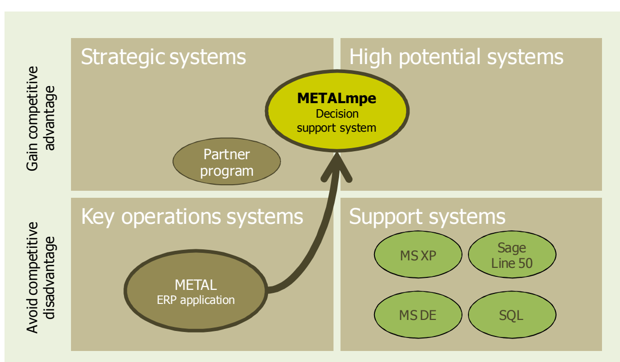


Figure 93. IT systems overview: transformation potential

Chapter 6 Discussions and conclusions

6.1 Discussion of research findings

This thesis considered the estimating processes at the case study company where, although part of a large international Group, the machining department displayed many of the characteristics and experienced many of the problems which challenge SMEs within this particular business sector. The day-to-day challenges of operating in a competitive environment were compounded in that the case study company recognised that by the year 2010 both of the expert estimators employed at the company were due to retire. In order to stabilize the estimating function for the future, METALmpe was developed as a robust and dependable decision support system solution; an alternative to complete reliance on human expertise.

The essence of the commercial project was the development of a process for managing the estimating function, which the literature review suggested could lead to the development of a valuable knowledge tool (and a strategic asset) to an SME. The literature supported arguments that the demands on human estimators are considerable, and cannot easily be addressed by information system solutions. However, the literature provided evidence that applying intelligent (decision support) systems can drive process improvement and to an extent reduce dependence on human expertise (although not replace it). Appropriate deployment of *suitable*, *feasible* and *acceptable*, information technology solutions can help to reduce the likelihood of overburdening individuals with information, which might otherwise impair their decision making ability.

The literature related to cost estimating surfaced a number of approaches to estimating, and this body of knowledge clearly supported the opinion that the importance of accurate estimating is central to effective competitive strategy. Accurate estimates are of primary importance to the decision making processes within the sales / commercial / production functions of any business. Of the estimating approaches identified in the literature, both feature-based costing and case-based reasoning offered potential beneficial approaches to solving estimating problems. Further evaluation of the application of these techniques in other settings suggested that a hybrid approach, capitalising on the strengths of the individual methods to produce a robust, unified solution could at least match the estimating performance of the existing, detailed estimating process.

In the evaluation the estimating process at the case company, emphasis was placed on exploiting the advantages of structured and systemic evaluation of work measurement and cost estimating. The case company were unhappy with their traditional approach to work measurement and the process by which a 'standard time' was calculated. *Standard time* (Slack *et al*, 2004) is a reference to the time taken by a qualified worker, doing a specified operation at standard performance with allowances for personal needs, contingencies, synchronisation, introductions, unusual conditions and unoccupied time, which reflect the conditions under which the work is performed. The case company aimed particular criticism at problems with defining operator skill levels and performance levels, and the lack of flexibility associated with excessively rigid 'specified production routes'. In their increasingly dynamic environment the case company identified the need for increased flexibility in their operations, and viewed increased accuracy in estimating to be an important early step.

The case company were opposed to predetermined motion-time studies which they perceived as counter-productive; considering them to be instrusive, subjective and easy to manipulate. One of the problems associated with the established approach to estimating related to the reward structure, in that employees could calculate the time required to maximise the bonus payment when completing an operation – and have no further motivation to reduce the operation time further. The case company were seeking an alternative approach which would facilitate a shift in the factors of motivation.

However, the importance of understanding the relationship between work and time was recognised and whilst developing the METALmpe cost model other work measurement techniques for calculating 'standard times' were considered such as synthesis from elemental data; analytical estimating and activity sampling (Slack *et al* , 2004). Consideration of the potential benefits from the use these techniques contributed to the development of the hybrid feature-based costing / case-based reasoning cost model described in this thesis, influencing the decision to:

- Build up the time by totalling operation times obtained from previous studies in other jobs containing the operations concerned.

- Estimate the time required to carry out operations from knowledge and experience of the operations concerned.
- Evaluate a large number of observations made over a period of time for similar operations.

However, estimates generated using the METALmpe cost model evolve over time for the same operation, therefore it was difficult for the case company to use these increasingly accurate values to evaluate operator performance in a consistent manner. Similarly, encouraging a flexible use of resources strengthen the argument that a new approach to calculating performance related payments was required. The case company approached this by firstly compensating operator basic wage rates based on a percentage of the prior year average performance related payment for each individual. This was judged to be a fair compensation for differences in individual's performance. Further to this, an additional bonus payment was introduced, calculated based on a percentage of the operating profit per month.

The METALmpe application software is designed to allow flexibility in how individual companies configure the feature-code network. The feature-code (Figure 65) defines the *cost estimating relationship* linking to the FBC 'time equation' algorithm, CBR and subsequent CBR_{pa} 'transform equation' algorithm. In the design and implementation of METALmpe at the case company, the *operation (or process) description* method of defining feature codes was adopted. This approach meant that the Main Group field described the characteristic of the task i.e. 'horizontal mill-rough machine'. Thereby, all subsequent 'Sub-Groups' would specify a *rough machining activity on a horizontal milling machine*. This approach was deliberate, the case company did not wish to be *overly* prescriptive or restrictive in defining how the activity was performed, preferring to empower the operators with the choice (albeit from a limited pool of resources) of machine tool, settings, etc. Then when required, further specific instructions are added in the free-text field on the process route.

Alternatively, should an organisation wish to be more prescriptive in their approach to defining how features are realised, a *specified machine* method of defining feature codes is possible. This approach would require that the Main Group field defines the equipment to be utilised i.e. 'H211 Kearns Richards SJ100'. Thereby, all subsequent 'Sub-Groups' would specify a *machining activity on the fixed asset identified H211*.

The essence of the METALmpe cost model is that it is not an off-the-shelf solution comprising predefined feature codes or algorithms for calculating times and costs, rather it is a model which facilitates 'company-specific' estimating and knowledge management.

Feature-based costing is useful when initially estimating a product. In METALmpe the FBC function calculates machine times and costs using the same cognitive process as the human estimator. This technique is particularly useful when theory, rather than experience, is the primary source of knowledge, i.e. the company does not have sufficient historical data from similar parts to make an informed decision based on known production performance. The strength in case-based costing (using CBR) is that it takes known context specific production performance knowledge and either directly reuses (for exact matching cases) or modifies it by parameter adjustment (for near matching cases), thus is more applicable when experience rather than theory is the primary source of knowledge. By combining both estimating techniques, METALmpe addresses a gap in current software and provides a robust method for evaluating estimating from both perspectives. A novel aspect of METALmpe is that whilst the process methodology aims to be generically applicable to SME machine shops, the mechanism by which features are defined and specific engineering knowledge is codified purposely sets out to capture how individual organisations apply their own specific estimating knowledge in cost engineering in their own environment. The hybrid approach of the METALmpe cost model allows both the capture and reuse human expertise or knowledge during the development of a cost estimate.

The use of case-based reasoning in a wide range of applications was recognised in the literature, although no specific references to machined part estimating in similar contexts to that at the case company could be found. Nevertheless the literature provided sufficient information to ascertain how the approach could be applied in a machined part estimating context, and how the mechanisms of case storage, retrieval, adaption and evaluation could be applied in the research reported in this thesis.

The research addressed the following questions:

1. Can METALmpe produce estimates of production times which are accurate (-5% to +10%) when compared with the actual times taken?

2. Is the viability of METALmpe justifiable in terms of cost?
3. Can the METALmpe process method configure networks of feature definitions, cost estimating relationships and algorithms which can be used to codified and capture knowledge and thus reduce future dependence on the expert estimator?
4. What benefits can be gained from the development of bespoke application software for the feature-driven case-based cost model?
5. To what extent can the method and software application be shown to be generically applicable?

The research agenda was carefully selected to ensure it was methodologically rigorous, even though the situation of interest was small scale with only focussed qualitative and quantitative evidence available. Suitably robust verification and validation procedures were implemented which accounted for the multiple stakeholder interests and the quality measures: internal validity, construct validity, external validity and reliability.

Having conducted the research and evaluated the findings presented in Chapter 5, it is the opinion of the author that the research methodology described in Chapter 3 was appropriate for use in this setting. The triangulation of research types i.e. survey, experiment and case-study provided sufficient scope, depth and accuracy in the research. The use of quantitative experiments to verify the results from METALmpe and qualitative evaluation of the validity of the research (the 'feature-driven case-based' estimating method embodied in METALmpe), ensured the research findings stand up to critical review. The analysis presented in Chapter 5 supports the claim that the METALmpe cost model and software application meets or exceeds the 'acceptance range' provided by the case study company as a desirable measure of accuracy. METALmpe satisfies the level of accuracy considered necessary for definitive, detailed estimating.

At the outset of the project the experienced estimators at the case study company expressed doubts on the concept of a *systems approach* to estimating for managing estimating knowledge. Creating a decision support system which assisted novice estimators to produce credible estimator was perceived to be a difficult task. The responses to the survey of SME engineering machine shops (section 5.2), further illustrated the extent to which SMEs still predominately rely on expert estimators rather than technology to produce estimates. Even so, recognition of the inherent risk from relying on human expertise was evident in the findings from the survey.

Codifying estimating calculations within METALmpe reduces the risk to the business should an estimator be taken ill, retire or leave the company – which would otherwise impact on the company's short-term ability to produce accurate estimates. It also enables this knowledge to be accessible across a wider network, as remote network access means that quotations can be produced and / or empirical data interrogated from remote locations.

In terms of organisational learning, the knowledge management perspective offers possible solutions to specific areas of dependence on human expertise. The importance of expertise, knowledge and an ability to innovate is recognised in the literature, as is the need to support and enhance learning opportunities within specific communities of practise. However, the problems associated with knowledge management initiatives in small firms e.g. an individual's fear of redundancy, are recognised and the KM perspective needs to be balanced against wider social and systemic dimensions of learning, i.e. the perceived 'benefits to all' arising from the notion of *learning organisations*. The use of systems methods during the research enabled all the participants to engage in the development of the systemic solution. This research identifies a method for effectively managing cost engineering knowledge in SMEs, the author concludes that the METALmpe cost model both aids the transformation of tacit knowledge into explicit knowledge and facilitates knowledge integration.

The METALmpe cost model can support and enhance organisational learning, when used as a tool embedded in work activities to support collaborative working and learning. During testing at the case company, a novice estimator participated in generating the estimates and reprocessing the empirical data used in system testing. The ease with which the system was adopted illustrates that a novice estimator could use the system effectively. Encapsulating learning opportunities, through enriched work representations in the development of METALmpe, made it easier for non-experts to engage within estimating. The design of the user interface was well received and the ease of use made it possible for non-experts to produce accurate estimates, effectively shortening the period of training required for novice estimators. This broke down some of the traditional barriers to entry into the estimating community, making the acceptance of novice estimators by their expert peers moderately easier.

The research concluded that METALmpe facilitates appropriate learning for non-experts tasked with producing estimates, and contributes towards effective knowledge management and building an agile organisation. The implication for the future training of novice estimators is a shift in emphasis from learning the time-consuming manual approach to estimating, to learning how to use METALmpe. The expectation is that learning the METALmpe approach will be much quicker than the traditional approach to learning estimating (through a master-apprentice relationship), whilst also reducing the cognitive demands on the estimator.

The findings of the research conducted support the conclusion that the case study company, through the development and application of METALmpe, have established a dependable method of estimating which:

(i) Enabled improvements in the accuracy and reproducibility for calculations of processing times and costs.
(ii) Made estimating process more accessible to non-experts, thus reducing reliance on human expertise.
(iii) Reduced the time taken to produce estimates and quotations for standard machined products, i.e. milling, turning and boring operations on ex. stock material.

6.2 Quality, validity and implications of findings

The tests of internal validity produced high scores (Table 30, section 5.4) for the generic criteria *suitability*, *acceptability* and *feasibility*. Coupling these results with the accuracy results from verification testing provide conclusive answers to the following research questions.

In response to research question 1, which challenged whether the novel use of the hybrid feature-based costing / case-based reasoning cost model could produce estimates which would be accurate to within -5% to +10% of actual production time taken, this research concludes that METALmpe can demonstrate this required level of accuracy. Following analysis of the total machining costs detailed in Appendix M, Figure 94 illustrates how METALmpe out-performed the level of accuracy of the human estimator for three separate accuracy ranges.

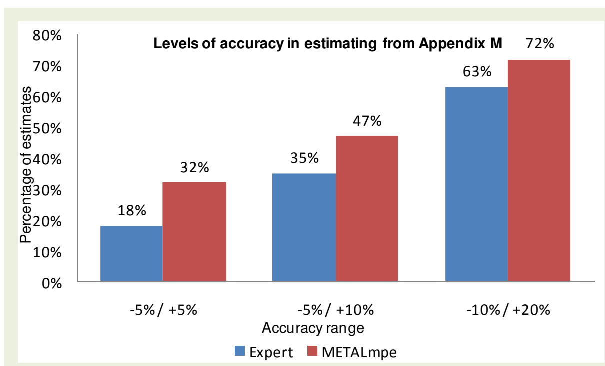


Figure 94. Levels of accuracy in estimating semi-finishing of oil tool valve blocks (Appendix M)

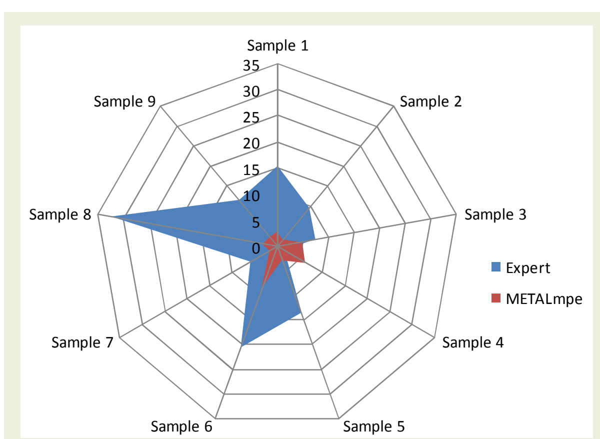


Figure 95. Percentage inaccuracy in estimates of total times for each sample detailed in Appendix M.

Figure 95 illustrates the extent to which METALmpe estimates were more accurate than those of the expert estimator in the tests detailed in Appendix M, segmenting the findings sample-by-sample. This identifies a much tighter accuracy grouping around the actual performance (represented by 0) for the METALmpe estimates.

A final view of the data collated in Appendix M (Figure 96) illustrates the findings at an 'operation' level, which further supports the research conclusion that METALmpe provides an accurate, dependable alternative to reliance on human estimating expertise.

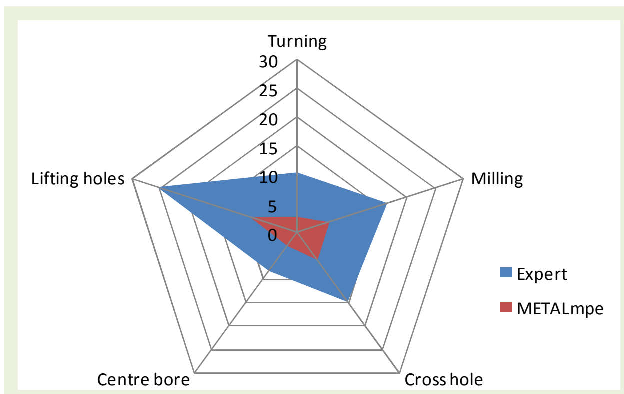


Figure 96. Percentage inaccuracy in estimates of operation times for combined samples detailed in Appendix M.

The second research question probed the viability of the cost of implementing METALmpe for an SME, making the assumption of a typical annual investment in ICTs for SMEs of 1% of turnover (which was suggested to be appropriate following the literature review). The total project investment at the case study company was confirmed at £34,300 (0.5% of turnover) and the project demonstrated a payback period of 13 months, which the case company considered to be good. However, the cost of replicating a similar implementation in another comparable SME environment was costed at £16,000 in 2010. Therefore this thesis concludes that appropriate implementation of METALmpe is economically viable for SMEs.

Research question 3 examined if the METALmpe process method could effectively configure networks of feature definitions, cost estimating relationships and algorithms, enabling the codification of cost engineering knowledge and the capture of evolving estimating and production knowledge; thus reducing future dependence on the expert estimator.

The novel feature coding function in METALmpe satisfies both the codification and knowledge capture issues; codifying both existing and new estimator knowledge through 'time equations' and 'transform equations'; then subsequently capturing new production knowledge through the timesheet process and retaining that information for reuse via the cost estimating relationships defined in the feature code. The results of verification testing discussed in section 5.3 (and the improved accuracy illustrated in Figure 87 and Figure 94), coupled with the responses of the participants involved in the internal validation process, support the conclusion that METALmpe can be effective is reducing dependence on human expertise in estimating.

A further objective of the research, and the subject of research question 4, was the evaluation of the benefits gained from the development of bespoke application software for the feature-driven case-based cost model, specifically in terms of (i) shortening the time taken to produce estimates, and (ii) creating a learning platform which will support and enhance workplace learning. This thesis finds that standard machining enquiries can now be handled quickly and competently by novice estimators, reducing a 'bottleneck' at the remaining expert estimator's desk which often delayed responses to customers request for quotations. The ability for novice estimators to quickly learn how to estimate using METALmpe demonstrates how the process supports and enhances workplace learning.

The tests of external validity (Table 31, section 5.5) score high on *suitability* but lower on *acceptability* and *feasibility*. However, this thesis describes research concerned within a very narrow organisational context. The research deliverables provide a practical solution to machined part estimating in SMEs operating conventional machine tools for producing low volume, medium and large sized machined forgings. Whilst there are many SMEs machine shops, there are relatively few who operate on the same scale and in similar products to the situation of interest at the case study company. This must be taken into account when considering the external validity of the research.

Implementing METALmpe in another setting during 2010 would initial cost circa £16,000, if the company did not already have access to suitable hardware. Purchasing the software alone would cost circa £8,000, with additional support for a 5 user agreement costing a further £2,500 per annum. When considering the typical investments in ICTs by SMEs, indicated by the literature from 2006 in section 2.2.1, as being between £20,000 and £50,000 per annum; the cost of METALmpe is not considered to be a prohibiting factor.

The final research question probed the extent to which the cost model and software application could be shown to be generically applicable. The validation results from external assessments (shown in Table 31), support the conclusion of the author of this thesis that the METALmpe cost model has serious potential to be effectively applied in other SMEs where a methodical approach to estimating production times and costs is required. Whilst the author concedes that the likely scope of application and instances of adoption will be relatively small, the conclusion reached by the research is that METALmpe is not soley applicable to the case company and that it to a large extent it can be seen to be generically applicable.

The commercial aim of the project at the case study company was addressed through the implementation of the METALmpe application software. Previously the company had relied wholly on a combination of expert judgement (based on intuition and experience) and detailed estimating. The lack of structure in these estimates meant that it was difficult for anyone other than the original estimator to analyse them. This also left the company exposed to risk, as the context specific estimating knowledge was stored in the 'heads' of a some number of individuals. The functionality of METALmpe provides an appropriate solution to this reliance on human expertise, providing estimates which are at least as accurate as the expert estimator in many cases, as demonstrated by the verification test results presented in section 5.3.

The deliverable from this research needed to be a low cost solution, which integrated seamlessly the relevant business processes, without demanding significant additional human or financial resources. The payback period for the project was calculated to be 13 months, which is considered to be satisfactory given the context in which the research is set and the two year payback target originally set by the Management Board. The high scores witnessed in the internal validation processes further supports the assertion that METALmpe provides a viable solution to the situation at the case study company, which satisfies the commercial aim and objectives of the research, stated in section 2.6.1 (ii). Table 33 provides a summary of the quality of research findings.

	Research Question	Quality of research findings	Do the research findings answer the research questions?
1	Through novel use of the hybrid feature-based costing / case-based reasoning cost model, can METALmpe produce estimates of production times which are accurate (-5% to +10%) when compared with the actual times taken?	Good	Yes
2	Is the viability of METALmpe justifiable in terms of cost for: (i) Schmolz + Bickenbach UK Ltd? (ii) SME business solutions?	 Good Acceptable	 Yes Yes
3	Can the METALmpe process method configure networks of feature definitions, cost estimating relationships and algorithms which enable: (i) Codification of cost engineering knowledge, (ii) Capture of evolving estimating and production knowledge.	 Good Good	 Yes Yes
4	What benefits can be gained from the development of bespoke application software for the feature-driven case-based cost model? In terms of: (i) Shortening the time taken to produce estimates and quotations. (ii) Creating a learning platform which will support and enhance workplace learning.	 Acceptable Acceptable	 Yes Yes
5	To what extent can the method and software application be shown to be generically applicable?	Good	Yes

Table 33. Summary of the quality of research findings

6.3 Research limitations

The configuration of METALmpe at the case study company is designed for the estimating of low-alloy steel products. It is permissible to use the cost model for alternative materials, but the machinability index would need to be calibrated to the particular materials being processed.

The research tested the accuracy of METALmpe in estimating relatively basic machining operations, i.e. conventional milling, turning, and boring. *Product* complexity can be handled by METALmpe i.e. complex combinations of features where each feature can be machined conventionally. Complex *features* such as contours and mould impressions (which required CAD/CAM technologies) are not suited to the METALmpe cost model.

The estimating method described in this thesis is not intended for application in high volume manufacturing environments, or those producing intricate, close tolerance machine parts, or within organisations which operate computer numerical controlled machine tools.

The use of METALmpe requires an alternative approach to measuring performance compared with the typical mechanisms used for calculating efficiency and performance related pay. In order to assess the effectiveness of operator performance it is necessary to introduce a complementary method of statistical process control (based upper and lower control limits for performation variation) to identify non-standard variation in operator performance – this option could implemented at the discretion of the organisation considering the use of the METALmpe cost model.

6.4 Conclusion

6.4.1 Appropriateness of the research

There are three significant aspects of EngD research which are addressed by this thesis. Firstly, a research project which addressed a problem of direct relevance to the case study company. Secondly, that the work carried out was multi-disciplinary in nature and provided an understanding of the business and commercial implications of the research work. Finally, the research demonstrates an original contribution to knowledge. All of these aspects are satisfied by the research which is the subject of this thesis.

In section 2.6.3 observations from the literature review which influenced the conceptualisation of the METALmpe software application were acknowledged. These observations were:

- Further research was needed to investigate how to capture and reuse human expertise or knowledge during the development of a cost estimate.
- Commercial software could not fully address the capacity to capture and reuse expert knowledge in an intelligent manner.
- There was a need to develop low cost engineering software for Small and Medium scale Enterprises (SMEs).

All of the requirements from the above observations were factored into the METALmpe cost model.

The research which is the subject of this thesis was set in the context of small scale production of medium and large-sized machined steel forgings; produced using manually controlled, conventional machine tool equipment. The research findings validate the concept of a feature-driven case-based estimating cost model; based on a hybrid feature-based costing / case-based reasoning technique specifically tailored to meet the needs of specialist engineering SMEs. The commercial deliverable, 'METALmpe' application software, provides an estimating system capable of providing intelligent decision support for the case company with the following benefits:

- Improved accuracy of estimates.
- Reduced dependence on experts.

- Increased participation in machined part estimating.
- Creation of improved learning opportunities in machined part estimating.

The METALmpe (hybrid feature-based costing and case-based reasoning) cost model provides the following further benefits:

- The capture and reuse of human expertise or knowledge during the development of an estimate.
- Capture and reuse of expert knowledge in an intelligent manner.
- Low cost engineering software for SMEs.

The METALmpe decision support process is specifically developed for use in SMEs where there is little current use of computerised decision support. The purpose of the hybrid feature-based costing / case-based reasoning approach to cost estimating is to provide an integrated and systemic solution that would enable SMEs to develop their knowledge resources, using adaptable software which can be easily tailored to the requirements of differing companies. The use of METALmpe can benefit managers, estimators, trainers and novice engineers for whom 'engineering cost estimating' is an important activity.

Companies who could benefit from adopting this approach would typically be those which face the following challenges:

- An accurate, dependable estimating process is critical to the competitiveness of the organisation.
- Improving the ability to react to customer enquiries in a more timely and dependable manner would be a competitive advantage.
- Dependence on human expertise in the estimating process is considered to be a risk.
- Constraints on resources mean there is little opportunity for investment of time, expertise and capital in development of information systems.

Using the METALmpe approach to decision support in quotation and estimating processes provides the following organisational benefits:

- Shortens the time taken to produce estimates and quotations.
- Improves the reproducibility and dependability for calculations of process time and cost.
- Captures evolving organisational knowledge; to inform future decision making and reduce reliance on individual 'experts'.

- Manages both the quantity of information and quality of information processing, to address the challenge of 'information overload' and reduce the potential risks and errors it generates by overburdening individuals.
- Creates learning platform which will support and enhance organisational learning.

6.4.2 Suitability of METALmpe for SME engineering companies

Manual estimating places a significant demand on the knowledge structures of individuals, often requiring a breath of knowledge across many business functions. Manual methods are laborious, time consuming and risk human error. For those SME companies who might now wish to further investigate the use of a decision support system for estimating, the conclusion of this thesis is that the METALmpe cost model can significantly enhance the estimating processes in comparable organisations to the case company featured in this research.

METALmpe ensures that key estimating activities are not wholly dependent on specific individuals. Such dependence is a risk as an individual may be taken ill, decide to retire or leave the organisation to progress their career elsewhere – resulting in a gap in knowledge. Codifying estimating calculations within the METALmpe cost model reduces the risk to the business and enables this knowledge to be accessible across a wider network. Improvements in IT networking and remote access mean that quotations can be produced and empirical data interrogated from remote locations. METALmpe provides a mechanism for knowledge management and deliveries decision support; creating an asset which can be utilised to deliver sustainable competitive advantage, avoid expensive mistakes, assist employee development and improve customer service.

The solution provided by METALmpe is needed because the core capabilities and competitiveness of SME machine shops stem from their knowledge and expertise (an individual organisation's principle source of value and their most strategic asset). METALmpe captures newly evolving estimating and process performance knowledge, within a repository that is independent of expert estimators and manufacturing managers, thus converting intangible knowledge resources into a tangible asset. The repository of codified estimating knowledge (elicited from existing practice and stored as algorithms for calculating the time and cost of manufacturing activities) can be applied to the costing of similar products, mimicking the behaviour of the human expert by utilising the potential similarity between empirical information and future requirements. Through the use of CBR techniques, METALmpe extracts information from empirical data, shortening the time taken to produce estimates significantly. The research findings support the conclusion that METALmpe estimates accurately reflect trends in actual manufacturing performance and reduce the significance of inherent performance variation in manufacturing processes.

For many companies, a significant percentage of enquiries received are for 'standard products', which comprise of a series of operations which are relatively easy to calculate. METALmpe provides a mechanism for obtaining dependable estimates for these products very quickly, generally taking less than 10 minutes to complete this type of quotation at the case company. The remaining balance of enquiries can require significantly more resources to obtain an accurate estimate, including the manual interpretation of engineering drawings.

The flexibility provided by METALmpe's functionality reduces the constraints placed on the estimator by some software packages. Typical system constraints, such as size capacity ranges, are precise and lack the flexibility of a human expert's decision making ability, thus leading many organisations to consider that the human expert is irreplaceable. Through the use METALmpe it is possible to cost a wide range of manufacturing processes and operations within the organisations manufacturing capability. The increased accuracy of METALmpe estimates eliminates the need for the estimator to build a 'safety factor' into their calculations. This is particularly beneficial when the machining work is not repeatitive and a wide breadth of general machining knowledge is required to quote accurately. Feedback received from SME machine shops suggested that it was common for them to try to establish a formulae for calculating machining times and costs, but that they found this problematic because of variables such as material type, material left on prior to machining etc, which made it difficult to effectively utilize this approach. For example, an equation for costing top and bottom machining of rolled mild steel plate can be created relatively easily because of the standard tolerances on material thickness. Whereas tolerances for forged or sawn thicknesses are greater and less consistently maintained, thus a simple equation becomes more complicated as it needs to account for the potential variations in thickness. In the smaller organizations participating in this research, it was considered quite normal to keep a record of prices quoted and then monitor actual performance in order to ‘fine tune’ prices as the relationship with the customer developed.

This research found that even with all the technology at their disposal, large machining facilities still often retain the services of expert estimators for manually producing estimates. However, feature-based costing does offer the opportunity to complete an estimate in much the same way that such a task would be tackled by a human estimator, so it is reasonable to assume that the feature-driven case-based approach to estimating could also be valuable tool in such larger organisations.

The research identified that cost was an important factor to be considered, in so far as compared with larger organisations, SMEs often have less opportunity for investment of time, expertise and capital in development of information systems to support effective decision making. The software solution, which is a deliverable of this research, was purposefully designed to be a low cost technological solution.

6.4.3 Effectiveness of the METALmpe cost model

An accurate and consistent estimating process is vital for the future success of most manufacturing organisations. However, the case company featured in this thesis had witnessed that their existing process often resulted in significant differences between the original estimate for a machined part and its actual cost. In terms of effective cost control achieving estimating accuracy better than +/- 10% is recognised as good. However, in terms of customer satisfaction, ensuring that delivery can be maintained within +/- 1 day of scheduled completion date is considered to be efficient enough on longer lead time orders (e.g. orders taking over 4 days to complete).

The analysis of actual production records discussed in Chapter 5 confirmed varying levels of accuracy in the estimated time for machining operations and inherent variation in the reproducibility of specific machining operations. Producing estimates by manual methods leads to problems in reproducibility, as no two estimators will produce exactly matching estimates. This uncertainty requires that all knowledge informing the decision making should be continuously subjected to test and evaluations, to rational and continuous criticism. The principle of continuous evaluation is influential in the METALmpe cost model, alongside the necessity to capture newly evolving estimating and process performance knowledge. Analogical reasoning based on past case performance is widely used in estimating, using case-based reasoning to incorporate this estimating technique within the METALmpe cost model significantly reduced dependence on human expertise. When compared with the previous performance from expert estimating, the CBR functionality of METALmpe significantly reduced the degree of difference between estimated times and actual recorded times.

Prior to the development of METALmpe, the case study company relied on expert judgement based on intuition and experience. Experts have a tendency to make numerous assumptions and judgements to speed up the estimating process, but the lack of a structured method decreases the transparency of the process making analysis by non-experts difficult. The METALmpe cost model provides an alternative solution to reliance on expert judgement, creating effective information through the transformation of experience and reusing information in order to reduce workload.

The review of literature on feature-based costing revealed the most significant difficulty with this estimating technique is considered to be the definition and categorising each feature within a coding structure that enables cost estimating relationships to be established. METALmpe addresses this problem through the feature coding function *Group Editor*, which provides the mechanism for creating a hierarchical feature structure. This network of available features is displayed to a subsequent user of the application via an easy to follow drop-down menu. The application software is designed to facilitate the easy addition of further features, therefore eliminating the need for a predefined set of generic features.

Cases are selected from a database of past production cases that best resemble the characteristics of the part which is being estimated. The information provided by the retrieved case is reused or modified using algorithms (depending on degree to which the retrieved case matches the feature being estimated) to provide a solution to the current estimating problem. The revised case is subsequently evaluated by a human estimator to assess its suitability, and a decision is made whether the solution is to be retained or discarded.

The results achieved demonstrated the application software was able to produce initial FBC estimates which closely matched those of the human estimator. Further to these, the CBR results illustrated the extent to which estimates improved in accuracy after a number of iterations. The CBR estimates responded to trends in manufacturing performance, reducing the significance of inherent performance variation in the manufacturing processes. Estimates based upon CBR values would have allowed better optimisation of resource allocation by improving the accuracy of the time required for operation, which in turn could have allowed greater productivity. The results proved that the application software could improve the accuracy of estimates significantly and that CBR would reflect the impact of process improvements and operator performance into the future.

6.4.4 Improvements in knowledge management and organisational learning.

A key aspect of the primary research was the knowledge capture exercise, increasing the understanding of the cognitive processes used by expert estimators. This information is used as a knowledge repository, making (what was previously tacit) knowledge explicit for future learning. The METALmpe decision support system improved the lateral transfer of knowledge for machined part estimating at the case company. The case study demonstrated that effective application of knowledge management techniques can improve process stability and contribute to organizational learning in machined part estimating.

The way in which an individual's skills and abilities are developed at work has major effects upon quality, customer service, organisation flexibility and costs, particularly in terms of flexibility in SMEs. The case study illustrated that adopting METALmpe to managing estimating knowledge influenced user behaviour, business performance and organisational learning. This change in operational processes necessitates a different approach to how new-comers will learn machined part estimating.

6.4.5 Contribution to knowledge

This thesis finds that by replacing manual estimating processes with a systems approach, improvements in responsiveness, accuracy and reliability can be achieved, in turn strengthening strategic assets and core competencies. The research findings support the conclusion that the METALmpe approach to estimating provides good quality information that facilitates effective decision making in a timely manner, whilst at the same time reducing the volume of information processed by individuals. The relatively low cost of implementing the METALmpe cost model (£8,000 to £16,000 in 2010, depending on existing technology infrastructure), can make this solution attractive to other SMEs given the potential benefits.

This thesis presents the case that the practical method for feature-driven case-based machined part estimating demonstrates an original contribution to knowledge, through the design and validation of a model for estimating practise which uses a hybrid feature-based costing / case-based reasoning technique to estimate production times and cost. This work is considered to be original in that it encompasses '*being cross-disciplinary and using different methodologies*' and by '*adding to knowledge in a way that hasn't been used before*' (Phillips, 1992).

It is the conclusion of the author that the research aim and the commercial aim and objectives, defined in section 2.6.1 have been satisfied through the application of appropriate research and development activities, the research methodology and subsequent analysis described in this thesis.

6.5 Future work

One of the major difficulties with feature-based costing is defining and categorise features. This research approached this problem with a very flexibly sub-system for configuring feature codes which are context specific. METALmpe approaches the configuration of feature codes with a three-tier coding structure: Group Type, Group and Sub-group (shown in Figure 97).

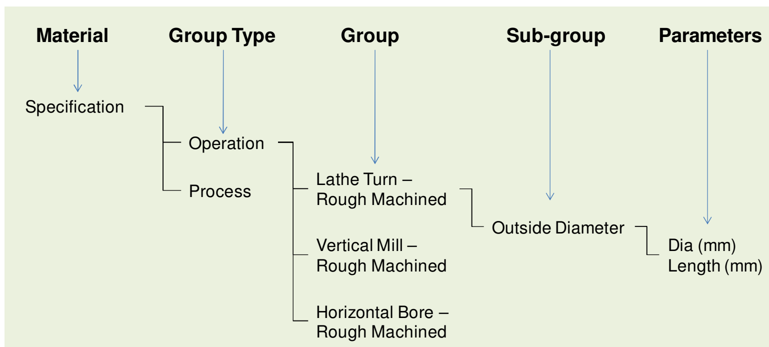


Figure 97. Structure of feature codes in the METALmpe cost model

This does not prohibit the use of METALmpe in other settings, as each company can easily define their own codes. However, one area of further research which could be addressed by future work is the development of a generic feature code structure. Providing a version of METALmpe with 'off-the-shelf' feature codes (with or without the feature-based costing algorithms) may make initial implementation easier in some circumstances, but the ability to add new features and modify the standard features should be maintained, not to do so would severally restrict the potential of the application.

A particular aspect of this work which generated further interest related to the application of case-based reasoning / analogical reasoning. Whilst one company who participated in the external validation process had built enormous reporting capabilities into their systems, they did not fully realise the potential of their valuable knowledge resource. This company failed to effectively reuse records of actual performance when reviewing new estimates, representatives of their sales department discussed how they frequently manually check performance on past orders when there are similarities with a live enquiry, but there is no facility within the estimating information system to conduct these checks in an effective and efficient manner. Following a demonstration of the case-based reasoning capability in the METALmpe cost model, the possibilities of a collaborative project (with the German SAP 'gold partner' company itelligence) was discussed in order that the company could further assess the possibility of adopting the CBR functionality.

Having established a reliable method for estimating machining times with the METALmpe cost model, it is envisaged that further benefits can be expected in terms of capacity scheduling. Given that empirical case information can be used to update the machine part production routes, these 'evolving' routes could be used in the development of a finite capacity scheduling application. Importantly, improved accuracy and consistency (in estimating capacity and machine-time requirements) can reduce variability and improve performance in the production system, with the potential to reduce lead times and improve customer service.

It is discussed in the conclusions of this thesis that the case company radically changed their approach to rewarding operator performance following the implementation of METALmpe. The author of this thesis recognises that this approach would not be considered equally acceptable for some potential users. Further research is recommended to identify alternative methods of assessing performance, including the use of statiscal process contol, which are compatiable for use with the feature-driven case-based cost model.

The estimating of low-alloy steel machined parts was the major focus of this thesis, however the cost model which is the subject of this thesis could also be applied in other manufacturing sectors. One potential application identified is Indium Tin Oxide Coating (ITO). Costing the ITO process has similarities with machined part processing, thus the potential exists to apply the feature-driven case-based cost model to ITO processing.

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Appendix A Survey: Machined part estimating in small engineering companies

Respondents were:

1. C.H. Clarke & Co, Griffin Industrial Estate, West Midlands, B65 0SP
2. RAM Machining Ltd, Providence Street, West Midlands, DY9 8HR
3. Metallicut Ltd, Deepdale Lane, West Midlands, DY3 2AE
4. T.D. Pressings, Neachells Lane, West Midlands, WV11 3RG
5. Linear Motion Ltd, Park Street, Wes Midlands, WV2 3 JH
6. Datum Engineering, Leamore Industrial Estate, West Midlands, WS2 7PH
7. Micron Machining Services, High Street, West Midlands, DY8 5SD
8. Clews Tipco UK Ltd, Maybrook Industrial Estate, West Midlands, WS8 7DG
9. Bishop Engineering Ltd, Milk Street, West Midlands, B5 5TP
10. Undergear Engineering Ltd, Blake Lake, West Midlands, B70 0PD
11. Quality Engineering Services, Speedwell Close, West Midlands, B25 8HT
12. Wilco Manufacturing Ltd, Tyseley Industrial Estate, West Midlands, B11 2LQ
13. Gee Jay Duttonguild, Hotchkiss Way, West Midlands, CV3 2RL
14. RJ Precision Engineering, Premier Business Centre, DY9 8RU
15. Bespoke Engineering, Tyburn Road, West Midlands, B24 9NY
16. JJM Machinery, Dunstall Hill Industrial Estate, West Midlands, WV6 0PJ
17. High Precision Machining, Washington Centre, West Midlands, DY2 9RE

Purpose of questions posed	Approach to analysis
Need to establish whether respondent is an SME.	Differentiate respondents by size classification. Identify correlation within each classification and the overall sample.
Is the respondent using ICT for machine part estimating?	Establish how much they rely human 'expert' estimators. Seeking to identify if there are significant trends within firm size classifications. Most of the quantitative data analysis will simply use ordinal scaling.
Do the respondents recognise problems in machine-part estimating?	Measure the extent of responses indicating 'opportunities for improvement'.
How integral is ICT to the estimating process in SME's?	Categorise respondents according to the sophistication of their ICT support.
Does ICT feature in the responding organisations processes for managing knowledge?	Establish the extent to which organisations rely on human experts, leading to an assessment of potential risks attributed to lack of knowledge management.
Establish the extent of the estimating role, hence the potential for process improvement.	Ultimately, this data could be used in the justification of whether there would be / would not be a significant benefit from the use of ICT.
Establish the extent of bespoke software development.	Identify popular commercial off the shelf software packages for further investigation. Qualitative techniques – (Hussey and Hussey, 1997)
Identify whether there are any other systems using feature-based costing and/or case-based reasoning. Particularly those targeting the SME market.	Quantitative assessment of responses for FBC and CBR, alongside qualitative techniques for understanding 'other' responses – (Hussey and Hussey, 1997).
Have the respondents associated risk with the continuity of the estimation function?	Assess attitudes to risk within firm size classifications.
Establish perceptions of the value of ICT to enhance machined-part estimating.	Quantitative assessment of responses to identify prevailing perceptions.
Establish the extent to which estimating is still considered to be an expert engineering discipline.	Seeking to identify any significant trends within firm size classifications, in looking to reduce reliance on human estimators.
Establish perception of benefits dependency.	Qualitative techniques – (Hussey and Hussey, 1997)

Table A.1. Reasoning for the style of questions posed

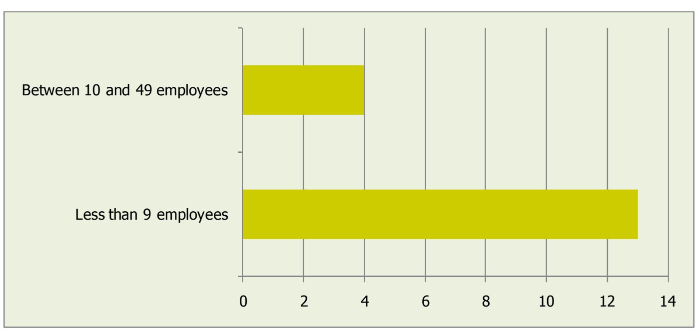


Figure A.1. SME survey responses to question one: How many people are employed by your company?

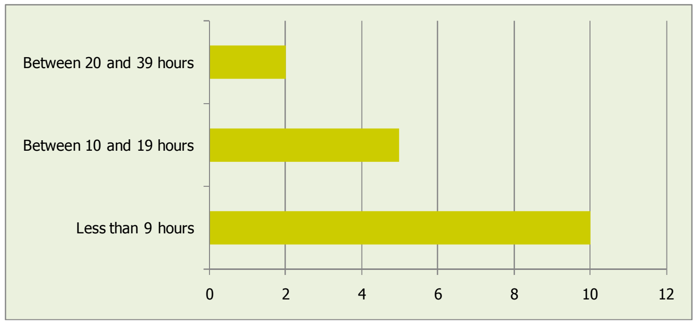


Figure A.2. SME survey responses to question two: How many 'man-hours' per week are dedicated to machined part estimating?

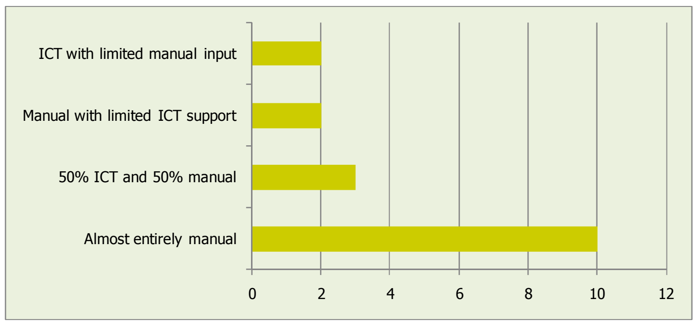


Figure A.3. SME survey responses to question three: Please identify the phrase that best expresses the degree of automation of your quotation process.

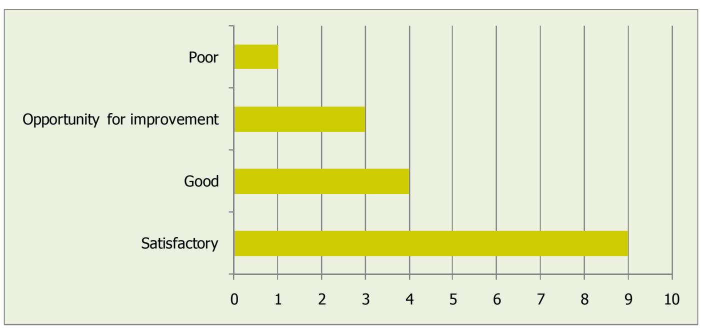


Figure A.4. SME survey responses to question four: Please rate the overall performance of your current approach to estimating.

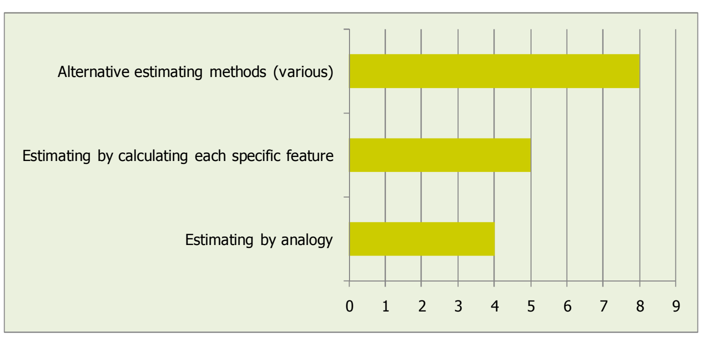
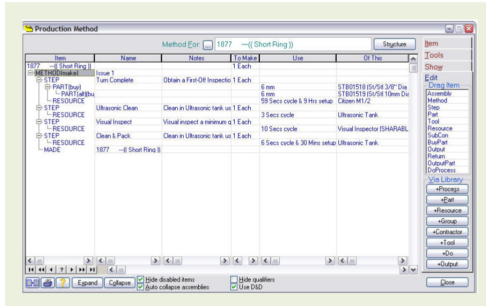


Figure A.5. SME survey responses to question five: Does your existing system use any of the following approaches to calculate an estimate?



'Match it'

Figure A.6. SME survey responses to question six: Have you used any commercial off-the-shelf software for estimating?

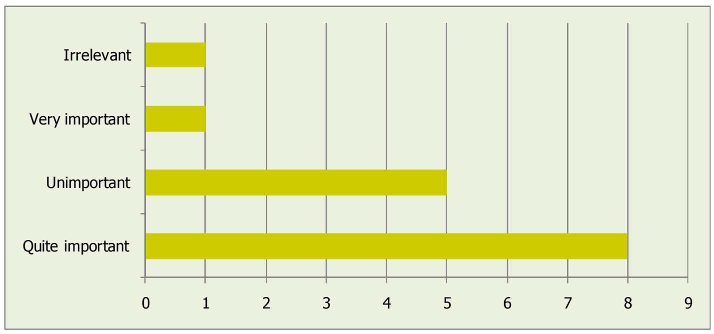


Figure A.7. SME survey responses to question seven: Relying on expert estimators is risky since they might leave, retire or fall ill. In your opinion, how important is this risk factor in the decision to adopt ICT based estimation?

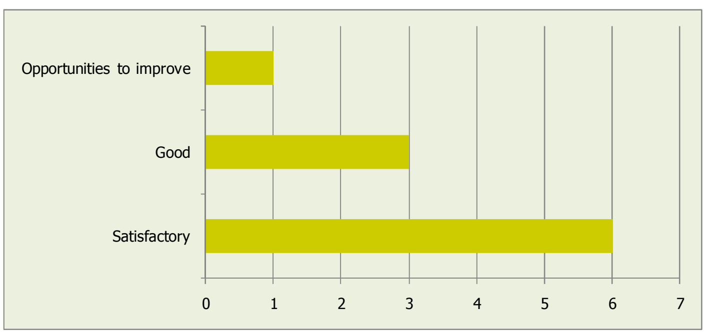


Figure A.8. Perceptions of performance of 'almost entirely manual' estimating processes.

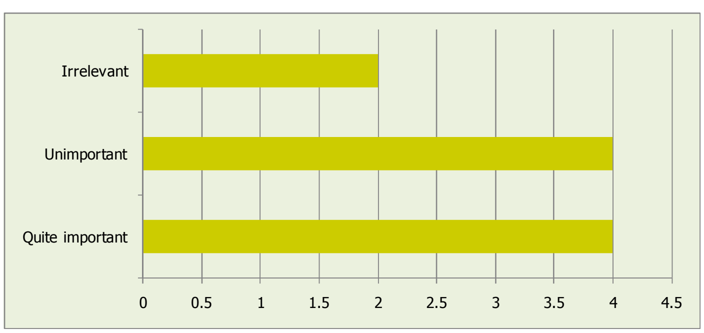


Figure A.9. Perceptions of risk from dependence on expert estimators in those firms reliant on 'almost entirely manual' estimating processes.

Appendix B XPat knowledge capture exercise

Top Level View		
Input	Process	Output
1.1 Physical and non-physical inputs 1.2 Source of inputs 1.3 Frequency of inputs	1.1 Activities 1.2 Tasks 1.3 Methods 1.4 Guides 1.5 Enablers 1.6 Metrics 1.7 Assumptions	1.1 Physical and non-physical outputs 1.2 Destination of outputs 1.3 Frequency of outputs

Table B.1. The *inputs*, *processes* and *outputs* of a system-of-interest: Knowledge capture for 'machined part estimating' process using the XPat Approach

First, capture knowledge regarding outputs:

O1 List all outputs from the process.

- Detailed production route
- Cost estimate
- Quotation

O2 Why would you need each of the outputs?

- The production route drills down into the sequence of operations required to produce the machined parts. Providing information on machine and operator selection; activity duration; float and critical path. This information will be hugely important in allocating resources using finite-capacity scheduling.
- The cost estimate itself crucial is the commercial analysis of the enquiry. Accurate and reliable estimates enable effective decision making on price setting and contract reviews.
- The quotation document forms the basis for future contractual agreement, therefore the information provided must be technically and commercially robust and complete.

O3 How do you get the outputs?

- Both the detailed production route and the cost estimate are derived from the specific customer requirements detailed within material specifications and drawings by an estimator. The estimator utilises his personal skills and experience (and where appropriate sub-contractor quotations) to determine production sequence, times and costs, in what is predominately a manual process.
- The quotation is essentially a summary document, produced again by the estimator, based upon the findings from the estimating procedures.

O4 How would you use the outputs?

- The production route provides sufficiently detailed instructions to support product realisation activities (route card) as an integral component of a contract file/ production documentation.
- The cost estimate provides a basis for commercial and financial decision making. It also provides metrics for process monitoring and evaluation.
- The quotation is the first document which links customer requirements to an offer to supply. It is a baseline document within the quality system, which subsequently drives order reviews and sales order processing documentation.

O5 What is the source of the output?

- The cost estimate is a handwritten document which follows a basic generic layout, but it is to a large extent indistinguishable to anyone other than the estimator.
- The production route is generated (manual keyed entry) using bespoke 'METAL' software and creates a template in a 'route' repository within the 'production' directory.
- The quotation is generated (manual keyed entry) using bespoke 'METAL' software and creates a record within the 'sales order processing' directory.

O6 What is the frequency of the output?

- Each of the three outputs is generated for every machine shop enquiry received. However, as 'stranger' orders become 'repeaters' and 'runners' the iterative review process increases their accuracies and enables a variable degree of re-use of information.

Then, establish the inputs:

I1 List all the inputs to the process.

- Customer enquiry
- Product drawings
- Product specifications
- National and International standards
- Industry norms

I2 Why would you need each of the inputs?

- The customer enquiry states the specific customer requirements and expectations for any subsequent contract. Detail should be unambiguous as to quantity, description and quality standard of the required product(s).
- Product drawings detail the specific physical shape and tolerances on size and finish for the machined part.
- Product specifications stated the required material characteristics, physical properties and chemical composition of the base material used in producing the machined part.
- National standards and specifications provide recognised controls and measures to ensure consistent interpretation of requirements and product realisation.
- Industry norms – relevant requirements which may not be stated by the customer, but company knowledge and integrity infer should be considered alongside the customer's specified requirements.

I3 How do you get the inputs?

- Direct from customer.
- Industry and trade associations.
- Company knowledge base.

I4 How would you use the inputs?

- Customer enquiry – this is used in the capability analysis, when the estimator (in liaison with commercial dept) determines whether order is suitable for produce in-house, out-source to a sub-contractor or decline.
- Product drawings – used to determine machining route, tooling requirements and operation skills necessary.

- Product specifications – influence selection of material, heat treatment and testing.
- National and International standards – provide recognised frameworks within which designated control mechanisms aim to increase the probability that a consistent and predictable product will be produced. These considerations need to built into the fabric of the organisation processes and decision making.
- Industry norms – compliment customer specifications in order to optimise product characteristics.

I5 What is the source of the inputs?

- Customer's intellectual property
- Published standards and guidelines
- Company based explicit and tacit knowledge

I6 What is the frequency of the input?

- In most cases each of the inputs is required, except for when 'customer supplied product' is to be machined only.

I7 When would you generate this input?

- Customer documents are controlled within the standard practise 'Enquiry and order review' which defines how external enquiries are handled.
- Dependant on product complexity, numerous process instructions (PI's) are consulted to establish specific process parameters.
- Reliance on expertise of specific staff.

I8 What is the relationship between inputs and outputs ?

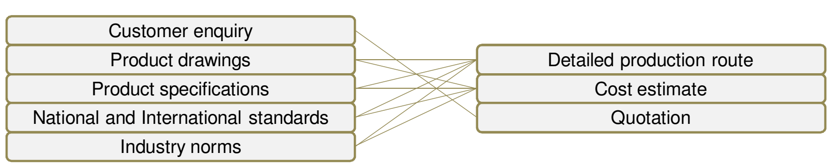


Figure B.1. The *inputs* and *outputs* of a system-of-interest: Knowledge capture for the 'machined part estimating' process using the XPat Approach

Finally, the process involved:

P1 Identify a top-level activity

- Machined-part estimating

P2 List all the tasks specific to that activity

- Determine customer requirements

- Determine material requirements
- Determine machining requirements
- Establish capability to produce
- Derive likely costs
- Evaluate and recommend sales price
- Produce quotation

P3 Identify matching inputs and outputs of each task

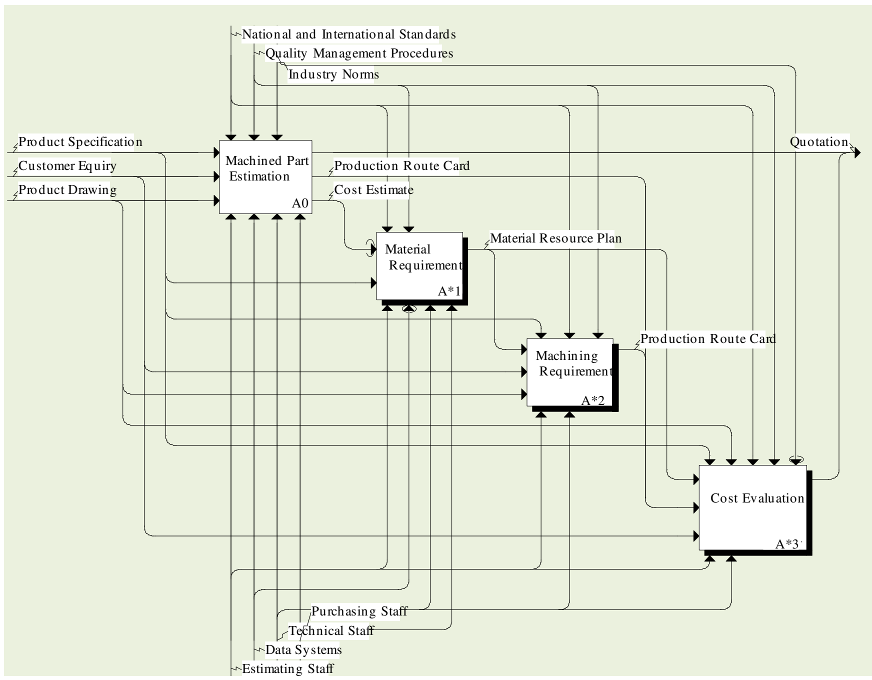


Figure B.2. IDEF0 Functional model of the existing estimating process

P4 List all the guides specific to the task (policy doc's, standards)

- Determine customer requirements
  - QA procedure PF-EOR Enquiry and Order Review
- Determine material requirements
  - QA procedure PF-EOR Enquiry and Order Review
  - QA procedure PF-PC Production Control
  - QA procedure PF-HTT Heat Treatment and Testing
  - Industry Standards as applicable e.g. API 6A
  - International Standards e.g. BS EN series, ASTM series, etc
  - Customer specifications e.g. Elmar EMS-001
- Determine machining requirements

    - International Standards e.g. BS EN series, ASTM series, etc
    - Supplier / Manufacturer guides (tooling and machinery)
- Establish capability to produce
    - QA procedure PF-EOR Enquiry and Order Review
    - QA procedure PF-QP Quality Planning
    - QA procedure PI-MST Machine shop Tolerances
    - QA procedure PI-HTT Heat Treatment Tables
    - Industry Standards as applicable e.g. API 6A
    - International Standards e.g. BS EN series, ASTM series, etc
- Derive likely costs
    - International Standards e.g. BS EN series, ASTM series, etc
    - Supplier / Manufacturer guides (tooling and machinery)
    - QA procedure PF-PRI Purchasing
    - QA procedure PF-SA Supplier Assessment
    - Empirical data
- Evaluate and recommend sales price
    - Market research / customer relationship management
- Produce quotation
    - QA procedure PF-EOR Enquiry and Order Review

P5 When would you use these guides?

- As specified in customer enquiry or in conjunction with established quality assurance processes.

P6 How would you use these guides?

- Industry Standards – would be used to verify numerous factors of the estimating process e.g. material qualification, equipment qualification and quality levels
- International Standards – are used to establish standard practice e.g. material chemical compositions, steel production techniques, methodologies for mechanical and non-destructive testing etc.
- Customer specifications – specific physical property requirements or process parameters. Used in assessment of sub-contract supplier capability analysis.

- QA procedures – sequential process flow information or detailed process instructions, to provide a framework for assuring consistent process performance.
- Supplier / Manufacturer guides (tooling and machinery) – purchasing information for tooling / establishing machining durations.
- Empirical data – estimating by analogy.
- Market research / customer relationship management – used for commercial purposes in determining appropriate margins / pricing / contractual terms and conditions.

P7 List the tools used in each task.

- Determine customer requirements
  - Technical review
- Determine material requirements
  - 'Inventory' module on bespoke METAL software
  - 'Heat Treatment' module on bespoke METAL software
- Determine machining requirements
  - Reliance on human expertise
- Establish capability to produce
  - Capability analysis
  - Supplier assessment
  - 'Production' module on bespoke METAL software
- Derive likely costs
  - 'Inventory' module on bespoke METAL software
  - 'Production' module on bespoke METAL software
  - 'Sales Order Processing' module on bespoke METAL software
- Evaluate and recommend sales price
  - 'Customer' module on bespoke METAL software
- Produce quotation
  - 'Quotes' module on bespoke METAL software
  - Management Review

P8 How would you know when you have completed a task?

- Appropriate checks and controls detailed within established quality assurance processes

P9 List assumptions used in each task.

- Determine customer requirements
  - o Customer enquiry states correct version / revision of product specifications.
- Determine material requirements
  - o Specifications are complete and appropriate to final application
- Determine machining requirements
  - o Near-perfect information in terms of machining characteristics and machine response
- Establish capability to produce
  - o Steady state processes
  - o Supplier QA
- Derive likely costs
  - o Expert judgement is appropriate
  - o Steady state processes
  - o Probability for costs of non-conformance
- Evaluate and recommend sales price
  - o Oligopoly market conditions
  - o Transparency in competition pricing
- Produce quotation
  - o Prior 'stage and gate' checks completed satisfactorily

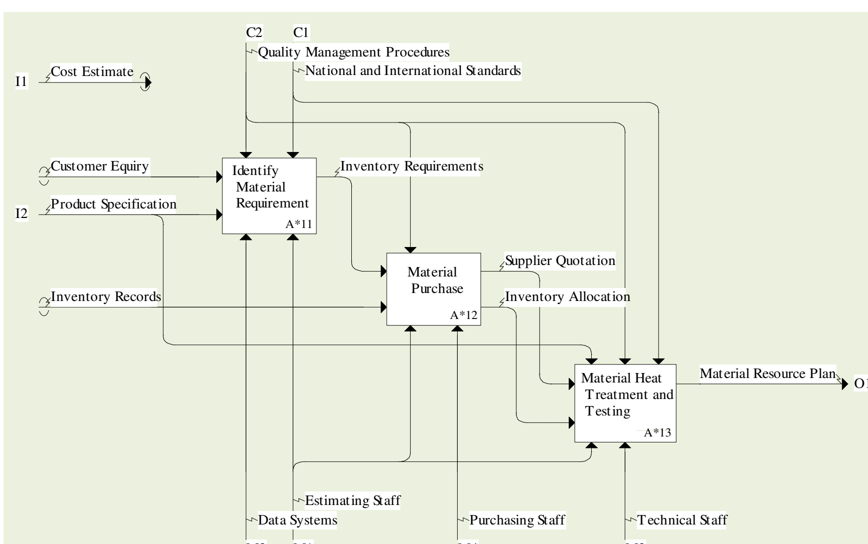


Figure B.3. IDEF0 Functional model: Decomposition level for material requirement

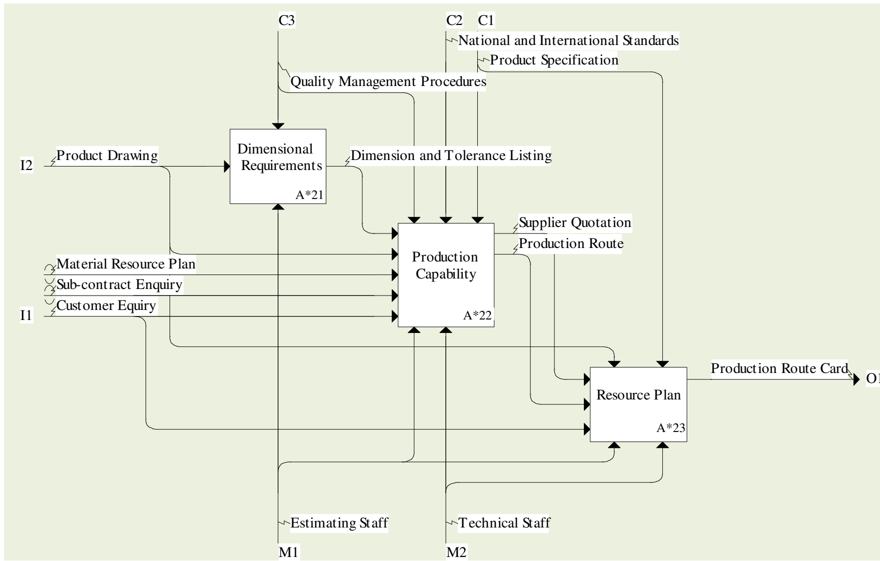


Figure B.4. IDEF0 Functional model: Decomposition level for machining requirement

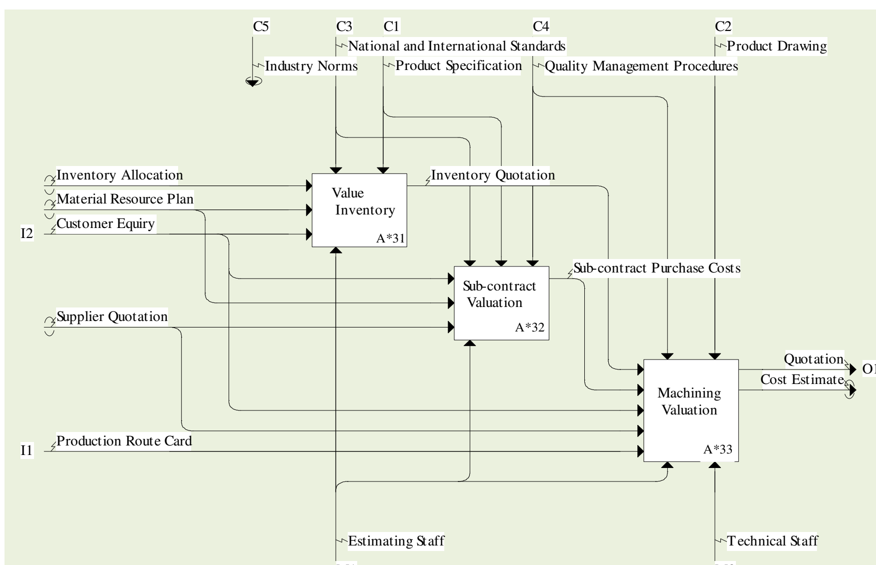


Figure B.5. IDEF0 Functional model: Decomposition level for cost evaluation

Appendix C Stakeholder, force field and risk analysis

The opinions of all stakeholders were compiled to produce a 'force field analysis' (Lewin, 1952), analysing the case study company's readiness to change, Figure C.1. This analysis identified a number of forces that are strongly related to human acceptance or resistance to the proposed changes and forces that would not be manageable directly from within the case study company:

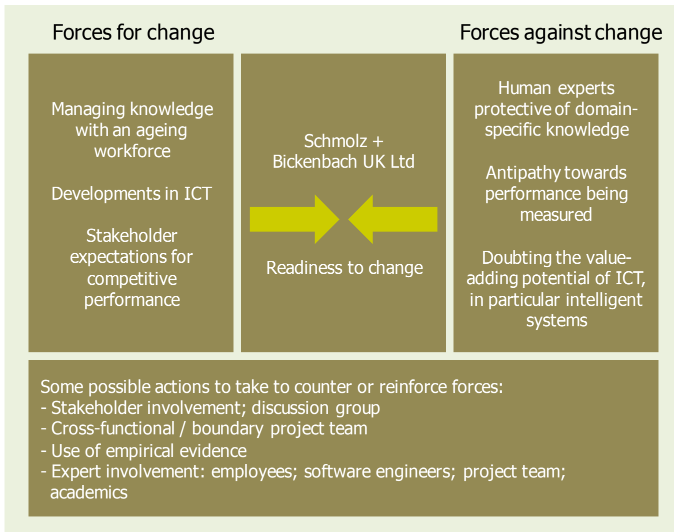


Figure C.1. Force field analysis (based on Lewin, 1952)

- Forces (driving/resisting) that are strongly related to human acceptance or resistance to the changes:
  - *Staff succession planning:* The primary driver for the project which is fully supported the case study company's Managing Director.
  - *Lean and agile:* To thrive in an increasingly competitive market, operations must be both lean (efficiency and waste reduction) and agile (responsive to customer needs, market conditions). The proposed project is recognised as contributing to these goals.
  - *Continued professional development:* Central to planned career progression at the case study company.
  - *Internal change:* 18 employees, many of which are time-served operators, often reluctant to embrace change. The project will be both 'broad reaching' (impacting numerous tasks and processes) and

'deep' (distinct contribution to knowledge in feature-based costing / case-based reasoning), therefore the 'resistance culture' will require careful management.

- *Lack of software expertise:* Reliance on Zenzero Solutions for software development, testing and integration.
- *Estimator:* Perceived covert opponent, although contributing information on request. Generally dismissive of ICT, requires careful management to ensure successful transfer of knowledge.
- *Conflicting personal interests:* Some evidence of resentment from peripheral staff, of which the Managing Director is aware, likely to create superficial problems which will not determine success or failure.

- Forces (driving/resisting) that would not be manageable from within the case study company:
  - *Customer pressure:* Increasing pressure from both UK and overseas markets for keener pricing and more responsive deliveries. Reliance on accurate estimating becoming increasingly important.
  - *Academic interest:* Collaboration with Cranfield University on technical aspects / methodologies and partial funding by the EPSRC.

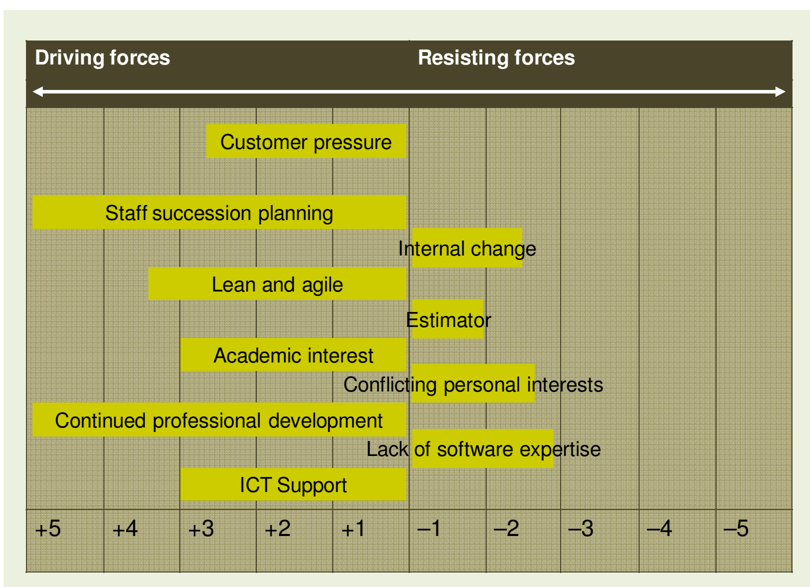


Figure C.2. Force field analysis: forces driving and resisting change at the case study company

The prominent driving forces significantly outweighed the resisting forces (Figure C.2) and the senior management / project sponsor committed to the availability of all necessary resources. This was a highly integrated project involving cross-boundary initiatives and inter-organisation collaboration. Sensitivity was required in managing the strategic aspects of *culture*, *systems* and *change*. Action taken to maximise the likelihood of success included:

- Establishing cross-boundary working group, encouraging participation.
- Use of Gantt chart project schedules to track progress in appropriate timeframes.
- Monthly meetings for reviewing progress, amending schedule and implementing corrective actions.

Although the technical aspects of the initiative were challenging in their own context, the management of change within the case study company's working practices was also a significant factor influencing the outcome of the initiative.

Having considered the all of these issues, it was possible to identify the significant project risks, shown in Table C.1, and justify reasons for their selection. Table C.2 prioritizes these risks and describes the actions planned to manage them.

Area of significant risk	**Reason for selection**
FBC and CBR methods not producing viable estimate information	This development is expected to use sophisticated intelligent system methodologies, notably a novel feature-based costing approach. There is limited literature on the application of such technologies within the SME environment, hence the project is likely to produce a significant 'contribution to knowledge.'
Failure to delivery system before project deadline (when estimator retires).	This is the prime driver for the project, therefore it would consider a significant failure if the system was not at least proven in abstracted experiments and clear of system integration testing before the human estimator actually retired.
Outsourced software development.	The case study company do not employee software engineers. Bespoke developments and systems maintenance are outsourced to Zenzero Solutions Ltd. Zenzero have supplied specialist ICT support for 10 years and are respected and trusted. However, being an external organisation, an element of risk is introduced e.g. the company could cease trading before completion.
Lack of compliance of expert estimator in the knowledge transfer process.	Knowledge transfer and managing knowledge is a difficult, complex exercise, particularly when tacit knowledge is equally as prevalent as explicit knowledge. Successfully elicitation from the human estimator, regarding both the cognitive processes and engineering calculations, is important for the success of the project – but relies on the estimator complying with the knowledge capture process.
Inability to integrate module with METAL application.	Requires converting existing software into MS.net and then seamlessly integrating the new development.

Table C.1. Reasoning behind the identification of project risks

Priority	Risk description	Management strategy/action to be taken
1	FBC and CBR methods not producing viable estimate information	Risk transfer – involving the technical expertise of specialist business information software developers, alongside the academic support of a leading UK University's Manufacturing Systems Department, will negate this threat – giving the project the best possible opportunity for success.
2	Failure to delivery system before project deadline (when estimator retires).	Risk reduction – establishing cross boundary teams and quarterly review meetings should ensure that the project objectives do not 'drift', or that the schedule of activities falls behind the appropriate timeframes and milestones. Contingency planning would also help to provide an alternative way forward should a risk materialise.
3	Outsourced software development.	Risk management – formal agreement should be documented on recovery plans should serious incidents occur which potentially prevent Zenzero Solutions (owned by S+B's former IT Manager) from completing the development work. These should include relevant issues relating to intellectual property rights and access to information.
4	Lack of compliance of expert estimator in the knowledge transfer process.	Risk reduction – regular reviews can help to reduce the risk associated with knowledge transfer. Contingency planning could also help to provide an alternative way to accessing substitutable knowledge from other reliable sources should this risk materialise.
5	Inability to fully integrated new module with existing bespoke 'METAL' application software.	Risk transfer – passing the responsibility for a difficult task within a project to another organisation with more experience in that field – may require the use of external consultants.

		Risk impact		
Likelihood of occurrence		High	Medium	Low
	High			
	Medium	FBC and CBR methods not producing viable estimate information.	Lack of compliance of expert estimator in the knowledge transfer process.	
	Low	Failure to delivery system before project deadline (when estimator retires). Outsourced software development.	Inability to fully integrated new module with existing bespoke 'METAL' application software.	

Table C.2. Prioritizing project risks and management strategies

Appendix D Benefits assessment and evaluation

When developing a decision support system, it is important that sufficient emphasis is focussed on the business processes and not solely the development of an information system. The use of benefits evaluation techniques, which are interwoven into the research methodology, ensured that focus is maintained on the quantified benefits and visionary purpose for this research at the case study company.

An initial requirement specification was used to rapidly develop of 'rough cut' prototype application. The prototype was used in a preliminary evaluation of the efficacy of the proposed model for knowledge management and information system development. Once the decision was made to fully develop a systems approach to estimating, where ICT would feature extensively, a process for control and monitoring of the IT application development was required. 'Benefits management' (Lambert, 2005) (Hotchkiss, 2006) is a process of organising and managing ICT projects such that the potential business benefits arising from the use of information technology are actually realised. The process is constructed from the fundamental assumption that benefits flow from the use of IT, not directly from IT itself, and thus benefits management aims to be a whole life-cycle approach to getting beneficial returns on IT investments. Benefits management and change management disciplines are closely related – without change, benefits are unlikely to accrue. Hotchkiss (2006) describes a six step approach to benefits management:

(i) Develop a Benefits Dependency Framework (BDF), Figure D.1.

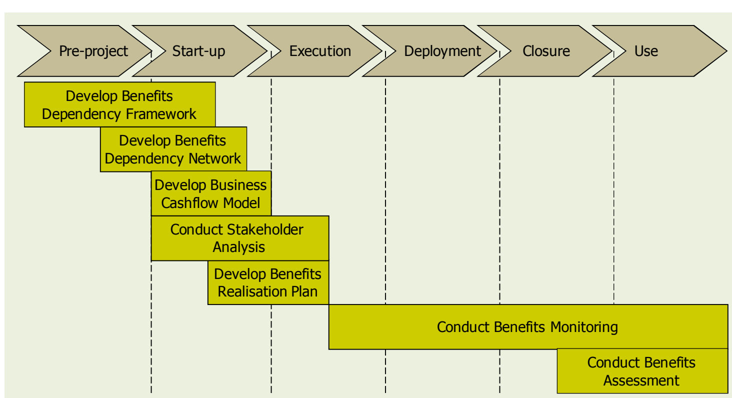


Figure D.1. A framework for benefits evaluation and management

(ii) Develop a Benefits Dependency Network (BDN)

- links vision, outcomes and benefits to business processes, Figures D.2 & D.3.

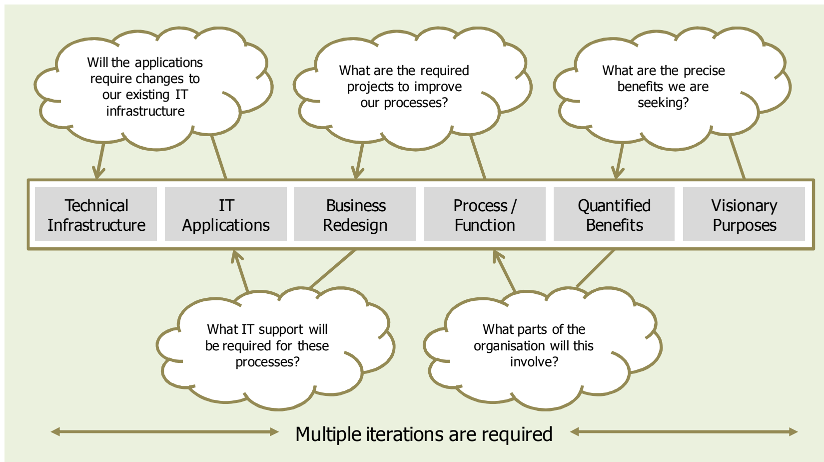


Figure D.2. Benefits dependency networks (adapted from Lambert, 2005)

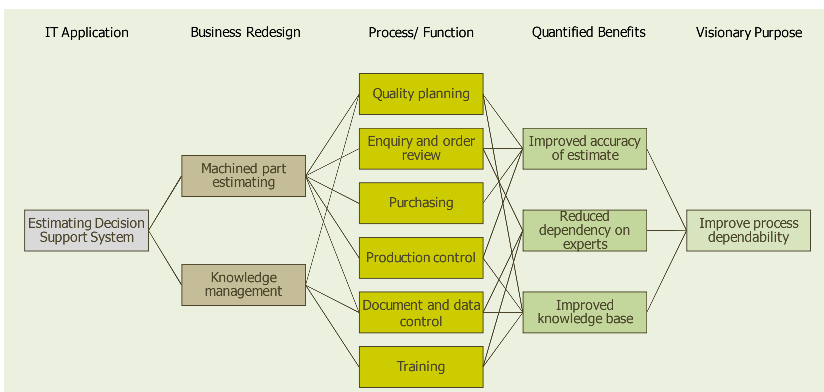


Figure D.3. The benefits dependency network for the project

A benefits dependency network was produced in order to identify the perceived commercial benefits to the case study company. It serves to illustrate (from right to left) the activities and development stages which are expected to facilitate delivery of the project objectives, illustrating the different aspects of the initiative, their connectivity and dependence. The project benefits from developing a benefits dependency network as it:

- links project activities to measurable outcomes

- provides shared understanding of project dependencies and required order of activities

(iii) Complete stakeholder analysis
- identifies who is involved and impacted by the project, their perceptions and resistance

(iv) Complete the Benefits Cash flow Model
- converts the identified measures from the BDF into tangible, monetary estimates of the benefits

(v) Complete Benefits Realisation Plan (BRP)

Potential Benefit	Business Benefits		
	Characteristic to be measured	*Current Performance Level*	*Required Performance to Achieve Benefits*
Improved accuracy	Comparison between estimated time and actual performance	+/- 12% with significant variation	-5% / +10% with reduced variation
	Customer satisfaction	6.9 (out of 10)	>7.0 (out of 10)
Reduced expert dependency	Usability of process by novice estimators	Operator perception: 'Poor'	Operator perception: 'Good'
	Cycle time to produce quote	Not measured	<24hrs
Reusable knowledge base	Ability to codify calculations	Human Centred; manually entering calculated figures into templates	IT Centred; generate estimates using the decision support process
	Ability to capture evolving production knowledge	Data collected but no reused for estimating	Estimate standard features based on reused data

Table D.1. Benefits realisation plan

Producing a benefits realisation plan facilitated project and resource planning and identified accountabilities between all the interested parties. This plan served to describe how the delivery of the business change and the IT enablers would realise benefits, and how those benefits (summarised in Table D.1) will be tracked and assessed. For each quantifiable objective, it defines:

- Current performance baseline
- Target performance with achievement date

For each business process affected, if defines:

- Current and desired working practices
- Current performance
- Target performance

(vi) Complete Benefits Monitoring and Assessment

- reports progress towards benefits realisation against the plan takes place both during the project and after completion

Appendix E Calculation tables for detailed estimating

WALDRICH MILLER

CUTTER SIZE	NO OF TEETH	TOOTH LOAD	LOAD PER CUTTER	DIA CUTT FEET	FT/MIN 50.000	FT/MIN 90.000 S.S.	FT/MIN 110.000	FT/MIN 120.000 EX	FT/MIN 170.000 P20	FT/MIN 200.000	FT/MIN 225.000	FT/MIN 250.000	FT/MIN 275
1.250	6.000	0.005	0.030	0.327	4.583	8.250	10.083	10.999	15.582	18.332	20.624	22.915	25.2
1.250	6.000	0.008	0.048	0.327	7.333	13.199	16.132	17.599	24.932	29.332	32.998	36.665	40.3
1.250	6.000	0.012	0.072	0.327	10.999	19.799	24.199	26.398	37.398	43.997	49.497	54.997	60.49
1.250	6.000	0.015	0.090	0.327	13.749	24.749	30.248	32.998	46.747	54.997	61.871	68.746	75.621
3.875	8.000	0.005	0.040	1.015	1.971	3.548	4.337	4.731	6.702	7.885	8.870	9.856	10.842
3.875	8.000	0.008	0.064	1.015	3.154	5.677	6.939	7.569	10.723	12.616	14.193	15.770	17.347
3.875	8.000	0.012	0.096	1.015	4.731	8.516	10.408	11.354	16.085	18.924	21.289	23.655	26.020
3.875	8.000	0.015	0.120	1.015	5.914	10.645	13.010	14.193	20.106	23.655	26.611	29.568	32.525
4.875	9.000	0.005	0.045	1.276	1.763	3.173	3.878	4.231	5.993	7.051	7.932	8.814	9.695
4.875	9.000	0.008	0.072	1.276	2.820	5.077	6.205	6.769	9.589	11.281	12.692	14.102	15.512
4.875	9.000	0.012	0.108	1.276	4.231	7.615	9.307	10.153	14.384	16.922	19.037	21.153	23.268
4.875	9.000	0.015	0.135	1.276	5.288	9.519	11.634	12.692	17.980	21.153	23.797	26.441	29.085
6.250	10.000	0.005	0.050	1.636	1.528	2.750	3.361	3.666	5.194	6.111	6.875	7.638	8.402
6.250	10.000	0.008	0.080	1.636	2.444	4.400	5.377	5.866	8.311	9.777	10.999	12.222	13.444
6.250	10.000	0.012	0.120	1.636	3.666	6.600	8.066	8.799	12.466	14.666	16.499	18.332	20.165
6.250	10.000	0.015	0.150	1.636	4.583	8.250	10.083	10.999	15.582	18.332	20.624	22.915	25.207
7.875	12.000	0.005	0.060	2.062	1.455	2.619	3.201	3.492	4.947	5.820	6.547	7.275	8.002
7.875	12.000	0.008	0.096	2.062	2.328	4.190	5.121	5.587	7.915	9.312	10.476	11.640	12.803
7.875	12.000	0.012	0.144	2.062	3.492	6.285	7.682	8.380	11.872	13.967	15.713	17.459	19.205
7.875	12.000	0.015	0.180	2.062	4.365	7.857	9.603	10.476	14.840	17.459	19.642	21.824	24.007
8.500	10.000	0.005	0.050	2.226	1.123	2.022	2.471	2.696	3.819	4.493	5.055	5.617	6.178
8.500	10.000	0.008	0.080	2.226	1.797	3.235	3.954	4.313	6.111	7.189	8.088	8.986	9.885
8.500	10.000	0.012	0.120	2.226	2.696	4.853	5.931	6.470	9.166	10.784	12.132	13.480	14.828
8.500	10.000	0.015	0.150	2.226	3.370	6.066	7.414	8.088	11.458	13.480	15.165	16.850	18.534
12.000	12.000	0.005	0.060	3.142	0.955	1.719	2.101	2.292	3.246	3.819	4.297	4.774	5.251
12.000	12.000	0.008	0.096	3.142	1.528	2.750	3.361	3.666	5.194	6.111	6.875	7.638	8.402
12.000	12.000	0.012	0.144	3.142	2.292	4.125	5.041	5.500	7.791	9.166	10.312	11.458	12.603
12.000	12.000	0.015	0.180	3.142	2.864	5.156	6.302	6.875	9.739	11.458	12.890	14.322	15.754
14.000	8.000	0.005	0.040	3.666	0.546	0.982	1.200	1.309	1.855	2.182	2.455	2.728	3.001
14.000	8.000	0.008	0.064	3.666	0.873	1.571	1.921	2.095	2.968	3.492	3.928	4.365	4.801
14.000	8.000	0.012	0.096	3.666	1.309	2.357	2.881	3.143	4.452	5.238	5.893	6.547	7.202
14.000	8.000	0.015	0.120	3.666	1.637	2.946	3.601	3.928	5.565	6.547	7.366	8.184	9.002

Table E.1. Calculation table for detailed estimating: Milling data

LOCHE BORER

DIA IN MMS	DIA IN INS	DIA IN FT	FEED PER REV	FEED PER REV	FEED PER REV	0.003 INS/MIN 150.000	0.003 INS/MIN 200.000	0.005 INS/MIN 225.000	0.005 INS/MIN 250.000	0.008 INS/MIN 300.000
20.000	0.787	0.206	0.003	0.005	0.008	2.183	2.910	5.457	6.063	11.641
23.000	0.906	0.237	0.003	0.005	0.008	1.898	2.531	4.745	5.272	10.123
25.000	0.984	0.258	0.003	0.005	0.008	1.746	2.328	4.365	4.850	9.313
38.000	1.496	0.392	0.003	0.005	0.008	1.149	1.532	2.872	3.191	6.127
38.100	1.500	0.393	0.003	0.005	0.008	1.146	1.528	2.864	3.183	6.111
40.000	1.575	0.412	0.003	0.005	0.008	1.091	1.455	2.728	3.032	5.820
42.000	1.654	0.433	0.003	0.005	0.008	1.039	1.386	2.598	2.887	5.543
44.650	1.758	0.460	0.003	0.005	0.008	0.978	1.304	2.444	2.716	5.214
44.450	1.750	0.458	0.003	0.005	0.008	0.982	1.309	2.455	2.728	5.238
45.000	1.772	0.464	0.003	0.005	0.008	0.970	1.293	2.425	2.695	5.174
50.080	1.972	0.516	0.003	0.005	0.008	0.872	1.162	2.179	2.421	4.649
57.430	2.261	0.592	0.003	0.005	0.008	0.760	1.013	1.900	2.111	4.054
63.500	2.500	0.655	0.003	0.005	0.008	0.687	0.917	1.719	1.910	3.666
63.780	2.511	0.657	0.003	0.005	0.008	0.684	0.913	1.711	1.901	3.650
76.400	3.008	0.788	0.003	0.005	0.008	0.571	0.762	1.428	1.587	3.047
89.123	3.509	0.919	0.003	0.005	0.008	0.490	0.653	1.225	1.361	2.612
120.000	4.724	1.237	0.003	0.005	0.008	0.364	0.485	0.909	1.011	1.940
140.000	5.512	1.443	0.003	0.005	0.008	0.312	0.416	0.780	0.866	1.663
170.000	6.693	1.753	0.003	0.005	0.008	0.257	0.342	0.642	0.713	1.369
115.00	4.528	1.186	0.003	0.005	0.008	0.379	0.506	0.949	1.054	2.024
150.00	5.906	1.546	0.003			0.291	0.388	0.728	0.808	1.552

BAR CHANGE 20/45 MINS
MAX LENGTH FROM ONE END 1150MMS

MAX HEIGHT FROM TABLE TO CENTRE OF JOB 350MMS

Over 120 - 2nd bore.

Table E.2. Calculation table for detailed estimating: Horizontal, offset boring data

	GUN DRILLING			
	Depth		Depth	
Dia mm	Inches per min		MM / min	
8	0.75		19.05	
10	0.625		15.88	
12	0.625		15.88	
14	0.625		15.88	
15.2	0.625		15.88	
19	0.5		12.70	
24	0.375		9.53	
30	0.25		6.35	
Setting up time			1.5 to 4 hrs	
Additional settings			3./4 hr each set	
Re Grinding Drill time			2 to 4 hrs	
D & tap			5 mins per hole	
Awaiting instructions			3-4 hours	
Inspection			1 hr	

Table E.3. Calculation table for detailed estimating: Gun drilling data – horizontal borer

SAWING

MATERIAL	UP TO AND INC 9.0"	9.1 TO 16.0	16.1 TO 24	24.1 AND OVER	
	2.625	2.8125	7.14 cm²	72 mm per min	
ALL CARBONS UP TO AND INCLUDING EN9,AD SPEC 1100 A 350 LF2	2.9 SQ/INS	4.6 SQ/INS	6.0 SQ/INS	7.5 SQ/INS	
LOW ALLOYS UP TO AND INCLUDING EN 19,AISI 4130/4140 AND P20	2.4 SQ/INS	4.0 SQ/INS	5.2 SQ/INS	6.75 SQ/INS	4.5975
IN THE ANNEALED CONDITION EN24,25,26,27 QIN EX SOMDIE HYDIE BESTEM,S98,S154,H65,A350 LF3 EN31	2.15 SQ/INS	3.75 SQ/INS	4.30 SQ/INS	4.75 SQ/INS	
IN THE HARDENED CONDITION. ALL THE ALLOY STEELS AS DIRECTLY ABOVE	1.75 SQ/INS	2.75 SQ/INS	3.25 SQ/INS	3.50 SQ/INS	2.8125
H13,VWMC,AISI410,XER6,THERMODIE,H10,H11,H21 HYTUF AND EN30B.	1.75 SQ/INS	2.75 SQ/INS	3.25 SQ/INS	2.75 SQ/INS	2.625
F304,F316,F321,F6NM,17/4PH,FV520B,MMS 3018 416S37,DUPLEX	0.90 SQ/INS	1.40 SQ/INS	1.60 SQ/INS	1.30 SQ/INS	1.3
TITANIUM	1.25 SQ/INS	2.00 SQ/INS	2.40 SQ/INS	2.00 SQ/INS	

Table E.4. Calculation table for detailed estimating: Vertical bandsaw cutting data

TWIST DRILLS

DRILLING		Circumference			10	20	30	40	50	100
Dia in inches	Dia inMM	In Ft	Ft/Min 20 RPM	Feed	Depth per Minute	Dept per Minute	Depth per Minute	Depth per Minute	Depth per Minute	Depth per Minute
0.125	3	0.033	611	0.002	0.611	1.22	1.833	2.444	3.055	6.111
0.250	6	0.065	306	0.003	0.458	0.92	1.375	1.833	2.292	4.583
0.375	10	0.098	204	0.005	0.509	1.02	1.528	2.037	2.546	5.092
0.500	13	0.131	153	0.005	0.382	0.76	1.146	1.528	1.910	3.819
0.625	16	0.164	122	0.005	0.306	0.61	0.917	1.222	1.528	3.055
0.750	19	0.196	102	0.005	0.255	0.51	0.764	1.018	1.273	2.546
0.875	22	0.229	87	0.005	0.218	0.44	0.655	0.873	1.091	2.182
1.000	25	0.262	76	0.005	0.191	0.38	0.573	0.764	0.955	1.910
1.125	29	0.295	68	0.005	0.170	0.34	0.509	0.679	0.849	1.697
1.250	32	0.327	61	0.005	0.153	0.31	0.458	0.611	0.764	1.528
1.375	35	0.360	56	0.005	0.139	0.28	0.417	0.556	0.694	1.389
1.500	38	0.393	51	0.005	0.127	0.25	0.382	0.509	0.637	1.273
1.625	41	0.425	47	0.005	0.118	0.24	0.353	0.470	0.588	1.175
1.750	44	0.458	44	0.005	0.109	0.22	0.327	0.436	0.546	1.091
1.875	48	0.491	41	0.005	0.102	0.20	0.306	0.407	0.509	1.018
2.000	51	0.524	38	0.005	0.095	0.19	0.286	0.382	0.477	0.955
2.125	54	0.556	36	0.005	0.090	0.18	0.270	0.359	0.449	0.899
2.250	57	0.589	34	0.005	0.085	0.17	0.255	0.339	0.424	0.849
2.375	60	0.622	32	0.005	0.080	0.16	0.241	0.322	0.402	0.804
2.500	64	0.655	31	0.005	0.076	0.15	0.229	0.306	0.382	0.764
2.625	67	0.687	29	0.005	0.073	0.15	0.218	0.291	0.364	0.727
2.750	70	0.720	28	0.005	0.069	0.14	0.208	0.278	0.347	0.694
2.875	73	0.753	27	0.005	0.066	0.13	0.199	0.266	0.332	0.664
3.000	76	0.786	25	0.005	0.064	0.13	0.191	0.255	0.318	0.637
3.125	79	0.818	24	0.005	0.061	0.12	0.183	0.244	0.306	0.611
3.250	83	0.851	24	0.005	0.059	0.12	0.176	0.235	0.294	0.588
3.375	86	0.884	23	0.005	0.057	0.11	0.170	0.226	0.283	0.566
3.500	89	0.916	22	0.005	0.055	0.11	0.164	0.218	0.273	0.546
3.625	92	0.949	21	0.005	0.053	0.11	0.158	0.211	0.263	0.527

Mild Steel	8630	P20	EX
Ft/Min	Ft/Min	Ft/Min	Ft/Min
100	30	20	10

all depths x 1.3

Mild Stel

Table E.5. Calculation table for detailed estimating: Drilling data

Appendix F Operation time calculations for feature-based costing

OPERATION				TIME CALCULATION
MILL	VERTICAL	FACE	Rough Machine	(((Width of flat mm / 302[cut width]round up to whole number x 1.25[relaxation factor]) x (Length of flat mm + 455[cutter overrun]) x 3[number of cuts]) / (100*[grade factor])) = mins per face
MILL	VERTICAL	FACE	Finish Machine	(((Width of flat mm / 302[cut width] round up to whole number x 1.25[relaxation factor]) x (Length of flat mm + 455[cutter overrun]) x 4[number of cuts]) / (100*[grade factor])) = mins per face
MILL	VERTICAL	EDGE	Rough Machine	(((Height of flat mm / 302[cut width]round up to whole number x 1.25[relaxation factor]) x (Length of flat mm + 455[cutter overrun]) x 3[number of cuts]) / (100*[grade factor])) = mins per face
MILL	VERTICAL	EDGE	Finish Machine	(((Height of flat mm / 302[cut width]round up to whole number x 1.25[relaxation factor]) x (Length of flat mm + 455[cutter overrun]) x 4[number of cuts]) / (100*[grade factor])) = mins per face
MILL	VERTICAL	END	Rough Machine	(((Height of flat mm / 302[cut width]round up to whole number x 1.25[relaxation factor]) x (Width of flat mm + 455[cutter overrun]) x 3[number of cuts]) / (100*[grade factor])) = mins per face
MILL	VERTICAL	END	Finish Machine	(((Height of flat mm / 302[cut width]round up to whole number x 1.25[relaxation factor]) x (Width of flat mm + 455[cutter overrun]) x 4[number of cuts]) / (100*[grade factor])) = mins per face
MILL	HORIZONTAL	FACE	Rough Machine	(((Width of flat mm / 135[cut width]round up to whole number x 1.25[relaxation factor]) x (Length of flat mm + 191[cutter overrun]) x 3[number of cuts]) / (149*[grade factor])) = mins per face
MILL	HORIZONTAL	FACE	Finish Machine	(((Width of flat mm / 135[cut width]round up to whole number x 1.25[relaxation factor]) x (Length of flat mm + 191[cutter overrun]) x 3[number of cuts]) / (149*[grade factor])) = mins per face
MILL	HORIZONTAL	EDGE	Rough Machine	(((Height of flat mm / 135[cut width]round up to whole number x 1.25[relaxation factor]) x (Length of flat mm + 191[cutter overrun]) x 3[number of cuts]) / (149*[grade factor])) = mins per face
MILL	HORIZONTAL	EDGE	Finish Machine	(((Height of flat mm / 135[cut width] round up to whole number x 1.25[relaxation factor]) x (Length of flat mm + 191[cutter overrun]) x 3[number of cuts]) / (149*[grade factor])) = mins per face
MILL	HORIZONTAL	END	Rough Machine	(((Height of flat mm / 135[cut width]round up to whole number x 1.25[relaxation factor]) x (Width of flat mm + 191[cutter overrun]) x 3[number of cuts]) / (149*[grade factor])) = mins per face
MILL	HORIZONTAL	END	Finish Machine	(((Height of flat mm / 135[cut width] round up to whole number x 1.25[relaxation factor]) x (Width of flat mm + 191[cutter overrun]) x 3[number of cuts]) / (149*[grade factor])) = mins per face
MILL	_	SLOT	Rough Machine	(((Width of slot mm[input required] / 27[cut width] round up to whole number x 1.25[relaxation factor]) x (Length of slot mm[input required] + 39[cutter overrun]) x 3[number of cuts]) / (279*[grade factor])) = mins per face
MILL	_	SLOT	Finish Machine	(((Width of slot mm[input required] / 27[cut width]round up to whole number x 1.25[relaxation factor]) x (Length of slot mm[input required] + 39[cutter overrun]) x 4[number of cuts]) / (279*[grade factor])) = mins per face
MILL	_	KEYWAY	Rough Machine	(((Width of keyway mm[input required] / 11[cut width]round up to whole number x 1.25[relaxation factor]) x (Length of keyway mm[input required] + 16[cutter overrun]) x 3[number of cuts]) / (485*[grade factor])) = mins per face
MILL	_	KEYWAY	Finish Machine	(((Width of keyway mm[input required] / 11[cut width]round up to whole number x 1.25[relaxation factor]) x (Length of keyway mm[input required] + 16[cutter overrun]) x 4[number of cuts]) / (485*[grade factor])) = mins per face

MILL	CNC	FACE	Rough Machine	(((Width of flat mm / 170[cut width] round up to whole number x 1.75[relaxation factor]) x (Length of flat mm + 260[cutter overrun]) x 2[number of cuts]) / (280*[grade factor])) = mins per face
MILL	_	CAVITY	Rough Machine	(((Width of cavity mm [input required] / 135[cut width]round up to whole number x 1.25[relaxation factor]) x (Length of cavity mm [input required]+ 191[cutter overrun]) x number of cuts[input required]) / (149*[grade factor])) = mins per face
MILL	_	CHAMFER	Rough Machine	(Length of chamfer mm[input required] + 191[cutter overrun]) x 2[number of cuts]) / (149*[grade factor]) x 1.25[relaxation factor]) = mins per chamfer
TURN	LATHE	DIAMETER FROM RECTANGLE	Rough Machine	*Turn post* (step 1): Length of diameter mm [input required] / (mm per minute [grade factor] / Diameter to be cut (mm)[input required] x 3.142 x [machining index]) [*Time per Rev*] x (((Calculate √ Height mm2 + Width mm2) - Diameter mm[input required]) / 2 (constant) / 8 [*mm depth of cut*] Round up to whole number) [*Number of cuts*] = minutes *Face end* (step 2): ((Diameter [input required] / 2) / (mm per minute [grade factor] / Diameter to be cut (mm)[input required] x 3.142 x [machining index]) [Time per Rev])) x 3 [constant number of cuts]) = mins *Face flats* (step 3): (Calculate √ Height mm2 + Width mm2)[Distance across corners] – diameter (mm) / 2 (constant) / (mm per minute [grade factor] / Diameter to be cut (mm)[input required] x 3.142 x [machining index]) [Time per Rev] x 2[constant] = mins Total mins =((step 1)+(step 2)+(step 3)) X 1.3 [relaxation allowance])
TURN	LATHE	DIAMETER FROM RECTANGLE	Finish Machine	*Turn post* (step 1): Length of diameter mm [input required] / (mm per minute [grade factor] / Diameter to be cut (mm)[input required] x 3.142 x [machining index]) [*Time per Rev*] x ((((Calculate √ Height mm2 + Width mm2) - Diameter mm[input required]) / 2 (constant) / 8 [*mm depth of cut*] Round up to whole number)+1) [*Number of cuts*] = minutes *Face end* (step 2): ((Diameter [input required] / 2) / (mm per minute [grade factor] / Diameter to be cut (mm)[input required] x 3.142 x [machining index]) [Time per Rev])) x 4 [constant number of cuts]) = mins *Face flats* (step 3): (Calculate √ Height mm2 + Width mm2)[Distance across corners] – diameter (mm) / 2 (constant) / (mm per minute [grade factor] / Diameter to be cut (mm)[input required] x 3.142 x [machining index]) [Time per Rev] x 3 [constant] = mins Total mins =((step 1)+(step 2)+(step 3)) X 1.3 [relaxation allowance])
TURN	LATHE	OUTSIDE DIAMETER	Rough Machine	Length of diameter mm [input required] / (mm per minute [grade factor] / Diameter to be cut (mm)[input required] x 3.142 x [machining index]) [*Time per Rev*] x ((Diameter mm [start size] - Diameter mm[input required]) / 2 (constant) / 8 [*mm depth of cut*] Round up to whole number) [*Number of cuts*] = minutes
TURN	LATHE	OUTSIDE DIAMETER	Finish Machine	Length of diameter mm [input required] / (mm per minute [grade factor] / Diameter to be cut (mm)[input required] x 3.142 x [machining index]) [*Time per Rev*] x (((Diameter mm [start size] - Diameter mm[input required]) / 2 (constant) / 8 [*mm depth of cut*] Round up to whole number) + 1) [*Number of cuts*] = minutes
TURN	LATHE	INSIDE DIAMETER	Rough Machine	Length of diameter mm [input required] / (mm per minute [grade factor] / Internal Diameter to be cut (mm)[input required] x 3.142 x [machining index]) [*Time per Rev*] x ((Internal Diameter mm [required size] - Starting Bore Diameter mm[input required]) / 2 (constant) / 8 [*mm depth of cut*] Round up to whole number) [*Number of cuts*] = minutes

TURN	LATHE	INSIDE DIAMETER	Finish Machine	Length of diameter mm [input required] / (mm per minute [grade factor] / Internal Diameter to be cut (mm)[input required] x 3.142 x [machining index]) [*Time per Rev*] x (((Internal Diameter mm [required size] - Starting Bore Diameter mm[input required]) / 2 (constant) / 8 [*mm depth of cut*] Round up to whole number) + 1) [*Number of cuts*] = minutes
TURN	LATHE	END FACE	Rough Machine	((Diameter [input required] / 2) / (mm per minute [grade factor] / Diameter to be cut (mm)[input required] x 3.142 x [machining index]) [Time per Rev])) x 3[constant number of cuts]) = mins
TURN	LATHE	END FACE	Finish Machine	((Diameter [input required] / 2) / (mm per minute [grade factor] / Diameter to be cut (mm)[input required] x 3.142 x [machining index]) [Time per Rev])) x 4 [constant number of cuts]) = mins
TURN	LATHE	STEP FACE	Rough Machine	*Face flats* (step 3): Diameter mm [max size] – diameter mm [min size] / 2 (constant) / (mm per minute [grade factor] / Diameter to be cut (mm)[input required] x 3.142 x [machining index]) [Time per Rev] x 3 [constant] = mins
TURN	LATHE	STEP FACE	Finish Machine	*Face flats* (step 3): Diameter mm [max size] – diameter mm [min size] / 2 (constant) / (mm per minute [grade factor] / Diameter to be cut (mm)[input required] x 3.142 x [machining index]) [Time per Rev] x 4 [constant] = mins
TURN	LATHE	GROOVE	Rough Machine	Length of groove mm [input required] / (mm per minute [grade factor] / Diameter to be cut (mm)[input required] x 3.142 x[machining index]) [*Time per Rev*] x ((Diameter mm [start size-input required] - Diameter mm[input required]) / 2 (constant) / 8 [*mm depth of cut*] Round up to whole number) [*Number of cuts*] = minutes
TURN	LATHE	GROOVE	Finish Machine	Length of groove mm [input required] / (mm per minute [grade factor] / Diameter to be cut (mm)[input required] x 3.142 x [machining index]) [*Time per Rev*] x (((Diameter mm [start size-input required] - Diameter mm[input required]) / 2 (constant) / 8 [*mm depth of cut*] Round up to whole number) + 1) [*Number of cuts*] = minutes
TURN	LATHE	2 DIAMETER FORGING	Rough Machine	*Turn diameter* (step1): Length of diameter mm [input required] / (mm per minute [grade factor] / Diameter to be cut (mm)[input required] x 3.142 x [machining index]) [*Time per Rev*] x ((Diameter mm [start size] - Diameter mm[input required]) / 2 (constant) / 8 [*mm depth of cut*] Round up to whole number) [*Number of cuts*] = minutes
				Face end (step 2): ((Diameter [input required] / 2) / (mm per minute [grade factor] / Diameter to be cut (mm)[input required] x 3.142 x [machining index]) [Time per Rev])) x 3 [constant number of cuts]) = mins *Turn diameter* (step3): Length of diameter mm [input required] / (mm per minute [grade factor] / Diameter to be cut (mm)[input required] x 3.142 x [machining index]) [*Time per Rev*] x ((Diameter mm [start size] - Diameter mm[input required]) / 2 (constant) / 8 [*mm depth of cut*] Round up to whole number) [*Number of cuts*] = minutes *Face flats* (step 4): Diameter mm [Max - input required] – diameter mm [min - input required] / 2 (constant) / (mm per minute [grade factor] / Diameter to be cut (mm)[input required] x 3.142 x [machining index]) [Time per Rev] x 3 [constant] = mins *Face end* (step 5): ((Diameter [input required] / 2) / (mm per minute [grade factor] / Diameter to be cut (mm)[input required] x 3.142 x [machining index]) [Time per Rev])) x 3 [constant number of cuts]) = mins Total mins =((step 1)+(step 2)+(step 3)+(step 4)+(step 5)) X 1.3 [relaxation allowance])
TURN	LATHE	2 DIAMETER FORGING	Finish Machine	*Turn dia*(step1): Length of dia mm [input required] / (mm per minute [grade factor] / Diameter to be cut (mm)[input required] x 3.142 x [machining index]) [*Time per Rev*] x (((Diameter mm [start size] - Diameter mm[input required]) / 2 (constant) / 8 [*mm depth of cut*] Round up to whole number)+1) [*Number of cuts*] = minutes

				Face end (step 2): ((Diameter [input required] / 2) / (mm per minute [grade factor] / Diameter to be cut (mm)[input required] x 3.142 x [machining index]) [Time per Rev])) x 4 [constant number of cuts]) = mins *Turn diameter* (step3): Length of diameter mm [input required] / (mm per minute [grade factor] / Diameter to be cut (mm)[input required] x 3.142 x [machining index]) [*Time per Rev*] x (((Diameter mm [start size] - Diameter mm[input required]) / 2 (constant) / 8 [*mm depth of cut*] Round up to whole number)+1) [*Number of cuts*] = minutes *Face flats* (step 4): Diameter mm [Max - input required] – diameter mm [min - input required] / 2 (constant) / (mm per minute [grade factor] / Diameter to be cut (mm)[input required] x 3.142 x [machining index]) [Time per Rev] x 4 [constant] = mins *Face end* (step 5): ((Diameter [input required] / 2) / (mm per minute [grade factor] / Diameter to be cut (mm)[input required] x 3.142 x [machining index]) [Time per Rev])) x 4 [constant number of cuts]) = mins Total mins =((step 1)+(step 2)+(step 3)+(step 4)+(step 5)) X 1.3 [relaxation allowance])
TURN	LATHE	3 DIAMETER FORGING	Finish Machine	As above repeating steps 3 and 4 incrementally.
TURN	LATHE	3 DIAMETER FORGING	Rough Machine	As above repeating steps 3 and 4 incrementally.
TURN	LATHE	5 DIAMETER FORGING	Finish Machine	As above repeating steps 3 and 4 incrementally.
TURN	LATHE	5 DIAMETER FORGING	Rough Machine	As above repeating steps 3 and 4 incrementally.
TURN	LATHE	7 DIAMETER FORGING	Finish Machine	As above repeating steps 3 and 4 incrementally.
TURN	LATHE	7 DIAMETER FORGING	Rough Machine	As above repeating steps 3 and 4 incrementally.
TURN	LATHE	OFFSET DIAMETER	Finish Machine	Length of diameter mm [input required] / (mm per minute [grade factor] / Diameter to be cut (mm)[input required] x 3.142 x [machining index]) [*Time per Rev*] x ((Diameter mm [start size] - Diameter mm[input required]) / 2 (constant) / 8 [*mm depth of cut*] Round up to whole number) [*Number of cuts*] = minutes
TURN	LATHE	OFFSET DIAMETER	Rough Machine	Length of diameter mm [input required] / (mm per minute [grade factor] / Diameter to be cut (mm)[input required] x 3.142 x [machining index]) [*Time per Rev*] x (((Diameter mm [start size] - Diameter mm[input required]) / 2 (constant) / 8 [*mm depth of cut*] Round up to whole number) + 1) [*Number of cuts*] = minutes
BORE	-	CENTRE DEEP HOLE	Finish Machine	SUB-CONTRACT ON REQUEST
BORE	-	CENTRE DEEP HOLE	Rough Machine	Length of bore(mm) + 254 [constant] / 1.111 [constant for alloy / carbon steels] = mins per piece
BORE	-	OFFSET DEEP HOLE	Rough Machine	Set up time 7 hours *Bores up to 120mm diameter*: Hole size (mm) x 0.0009 x length of bore (mm) + 5 (mins change over time) = mins per bore *Bores over 120mm diameter*: (120 (mm default pre-bore size) x 0.0009 x length of bore (mm) + 5 (mins change over time)) + (Hole size (mm) x 0.0009 x length of bore (mm) + 20 (mins bar change over time)) = mins per bore
BORE	VERTICAL	INSIDE DIAMETER	Rough Machine	Length of diameter mm [input required] / (mm per minute [grade factor] / Internal Diameter to be cut (mm)[input required] x 3.142 x 0.635 [feed for rough turning]) [*Time per Rev*] x ((Internal Diameter mm [required size] - Starting Bore Diameter mm[input required]) / 2 (constant) / 8 [*mm depth of cut*] Round up to whole number) [*Number of cuts*] = minutes
BORE	VERTICAL	INSIDE DIAMETER	Finish Machine	Length of diameter mm [input required] / (mm per minute [grade factor] / Internal Diameter to be cut (mm)[input required] x 3.142 x 0.635 [feed for rough turning]) [*Time per Rev*] x (((Internal Diameter mm [required size] - Starting Bore Diameter mm[input

				required]) / 2 (constant) / 8 [*mm depth of cut*] Round up to whole number) + 1) [*Number of cuts*] = minutes
BORE	VERTICAL	OUTSIDE DIAMETER	Rough Machine	Length of diameter mm [input required] / (mm per minute [grade factor] / Diameter to be cut (mm)[input required] x 3.142 x 0.635 [feed for rough turning]) [*Time per Rev*] x ((Diameter mm [start size] - Diameter mm[input required]) / 2 (constant) / 8 [*mm depth of cut*] Round up to whole number) [*Number of cuts*] = minutes
BORE	VERTICAL	OUTSIDE DIAMETER	Finish Machine	Length of diameter mm [input required] / (mm per minute [grade factor] / Diameter to be cut (mm)[input required] x 3.142 x 0.635 [feed for rough turning]) [*Time per Rev*] x (((Diameter mm [start size] - Diameter mm[input required]) / 2 (constant) / 8 [*mm depth of cut*] Round up to whole number) + 1) [*Number of cuts*] = minutes
BORE	VERTICAL	END FACE	Rough Machine	((Outside diameter [input required] / 2) / (mm per minute [grade factor] / Inside Diameter (mm)[input required] x 3.142 x 0.635 [feed for rough turning]) [Time per Rev])) x 3[constant number of cuts]) = mins
BORE	VERTICAL	END FACE	Finish Machine	((Outside diameter [input required] / 2) / (mm per minute [grade factor] / Inside diameter(mm)[input required] x 3.142 x 0.635 [feed for rough turning]) [Time per Rev])) x 4 [constant number of cuts]) = mins
BORE	HORIZONTAL	TAPPED HOLE (GUN DRILL)		5 (mins) x hourly rate = cost per hole
BORE	HORIZONTAL	GUN DRILL	Rough Machine	*Set up time 2.75 hours (between 1.5 and 4 hours); Additional settings 45 mins per set; Grinding time 3 to 4 hours* Hole size mm [input required] x 0.00659 x length of bore mm [input required] + 15 (mins changeover) = mins per bore
SAW	RECTANGLE	FACE		([Width mm]x[Length mm])/ cutting variable [mmSq/min from grade matrix] = mins
SAW	RECTANGLE	EDGE		([Height mm]x[Length mm])/ cutting variable [mmSq/min from grade matrix] = mins
SAW	RECTANGLE	END		([Height mm]x[Width mm])/ cutting variable [mmSq/min from grade matrix] = mins
SAW	DIAMETER	FACE		([Diameter mm/2]x[Diameter mm/2] x 3.142)/ cutting variable [mmSq/min from grade matrix] = mins
DRILL	-	PLAIN HOLE		Hole size mm x 0.00377 x depth of hole mm x [grade factor] = mins

Appendix G Process times and costs for feature-based costing

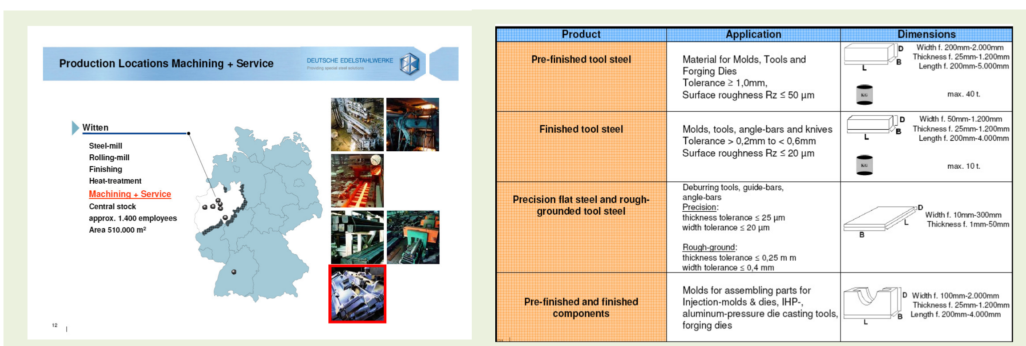
PROCESS			COST £	TIME (mins)
DRILL	M12 TAPED HOLE		8.25	15
DRILL	M24 TAPED HOLE		11	20
DRILL	M36 TAPED HOLE		16.5	30
DRILL	M48 TAPED HOLE		22	40
DRILL	M64 TAPED HOLE		27.5	50
DRILL	TURNING CENTRES		33	60
HEAT TREAT	ANNEAL		£ 0.05 x KG	4320
HEAT TREAT	NORMALIZE		£ 0.05 x KG	2880
HEAT TREAT	QUENCH + TEMPER		£ 0.22 x KG	4320
HEAT TREAT	QUENCH + DOUBLE TEMPER		£ 0.39 x KG	7200
HEAT TREAT	STRESS RELIEVE		£ 0.05 x KG	4320
TESTING	MECHANICAL	TENSILE	32	4320
TESTING	MECHANICAL	TENSILE - ELEVATED TEMP	110	8640
TESTING	MECHANICAL	TENSILE + SUB-AMBIENT IMPACT	70	4320
TESTING	MECHANICAL	TENSILE + IMPACT	70	4320
TESTING	MECHANICAL	IMPACT	38	4320
TESTING	MECHANICAL	HARDNESS	15	4320
TESTING	MECHANICAL	BEND	25	4320
TESTING	MECHANICAL	CARBURISE	180	8640
TESTING	MECHANICAL	CHEMICAL ANALYSIS	65	4320
TESTING	MECHANICAL	GRAIN SIZE	60	4320
TESTING	NONDESTRUCTIVE	ULTRASONIC	12	30
TESTING	NONDESTRUCTIVE	MAGNETIC PARTICLE	24	60
TESTING	NONDESTRUCTIVE	LIQUID PENETRANT	24	60
TESTING	NONDESTRUCTIVE	WATER FLOW + PRESSURE TEST	84	210
INSPECTION	VERIFICATION AND RELEASE		24	60

INSPECTION	DIMENSIONAL REPORT		24	60
LABOUR	FIT BLANKLING PLUGS		48	120
LABOUR	SET UP HORIZONTAL BORER	COMPLEX	198	360
LABOUR	SET UP HORIZONTAL BORER	BREAK DOWN / START UP	49.5	90
LABOUR	SET UP LOCH BORER	RECONFIGURE	216	360
LABOUR	SET UP	TURN	45.75	90
LABOUR	SET UP	MILL	55.5	90
LABOUR	SET UP	BORE	38.4	96
LABOUR	CHANGEOVER	TURN	8	15
LABOUR	CHANGEOVER	MILL	9.25	15
LABOUR	CHANGEOVER	BORE	8	15
LABOUR	FINISHING	STAMPING	10	30
LABOUR	FINISHING	HAND DRESSING	20	60
LABOUR	FINISHING	DEBURRING	20	60
LABOUR	FINISHING	PROTECTIVE COATING	5	15

Appendix H Case study: Deutsche Edelstahlwerke

It was important to establish what could be considered *state of the art* in machined part estimating for medium and large size rolled steel products and open-die steel forgings. A case study was undertaken at Deutsche Edelstahlwerke (DEW): Machining and Service Department, Witten, Germany. The case study involved five one-day workshops conducted over a 10 month period, four of which were in Germany and a fifth which was held in the UK. For the purpose of the project described in this thesis, the DEW facility is be considered to represent the benchmark in functionality for a technology solution to the machined part estimating process at the case study company.

DEW have two major machining facilities in Germany, one in Witten (Figure H.1) and one in Krefeld (Figure H.2). Such is the extent of the machining operations across both sites, that a typical month will produce approximately 800 tonnes of swarf. The value chain for the machining and service department can be seen in Figure H.3.



Product	Application	Dimensions
Pre-finished tool steel	Material for Molds, Tools and Forging Dies Tolerance ≥ 1,0mm, Surface roughness Rz ≤ 50 µm	Width f. 200mm-2.000mm Thickness f. 25mm-1.200mm Length f. 200mm-5.000mm max. 40 t.
Finished tool steel	Molds, tools, angle-bars and knives Tolerance > 0,2mm to < 0,6mm Surface roughness Rz ≤ 20 µm	Width f. 50mm-1.200mm Thickness f. 25mm-1.200mm Length f. 200mm-4.000mm max. 10 t.
Precision flat steel and rough-grounded tool steel	Deburring tools, guide-bars, angle-bars Precision: thickness tolerance ≤ 25 µm width tolerance ≤ 20 µm Rough-ground: thickness tolerance ≤ 0,25 m m width tolerance ≤ 0,4 mm	Width f. 10mm-300mm Thickness f. 1mm-50mm
Pre-finished and finished components	Molds for assembling parts for Injection-molds & dies, IHP-, aluminum-pressure die casting tools, forging dies	Width f. 100mm-2.000mm Thickness f. 25mm-1.200mm Length f. 200mm-4.000mm

Figure H.1. DEW Machining and Service Department, Witten, Germany.

Flat products are machined in Witten, with a monthly capacity for 2000 hours of machining, typically processing 2,200 tonnes per month. The company predominately use CNC machine tools, with 30 machines and 75 operators working a two shift system on flat products. Round products are machined in Krefeld with a similar monthly capacity: 2000 hours / 2,000 tonnes. Again, the company predominately use CNC machine tools, with 40 machines and 75 operators working a two shift system.

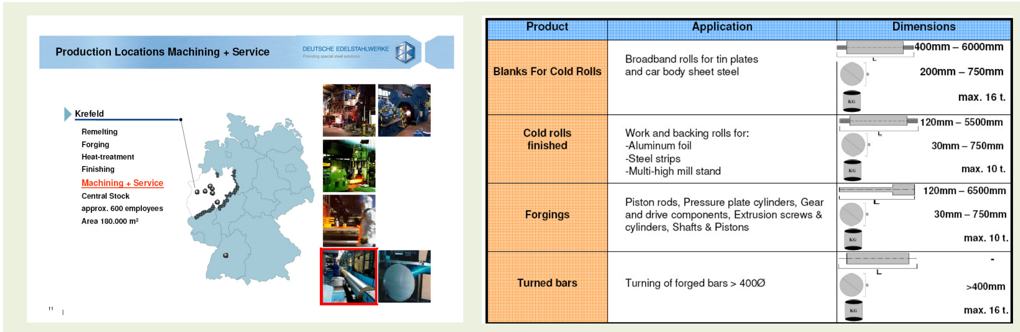


Figure H.2. DEW Machining and Service Department, Krefeld, Germany.

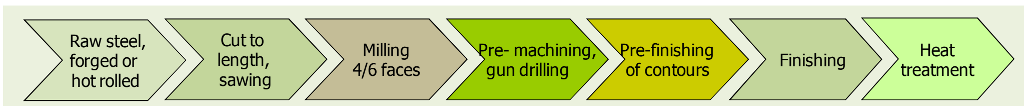


Figure H.3. Value chain at DEW Machining and Service Department.

The process for estimating the time and cost of machining operations is the same at both sites (regardless of there being a clear difference in the products being produced), therefore the case study concentrated on investigating the processes in Witten. Responsibility for estimating lies with the sales team who typically receive between 50 and 100 enquiries per day, and set a target response time of 24 hours maximum. The estimating function comprises (Figure H.4):

- Head of department for Machining and Service.
- Standard products (90% of turnover) – time and cost calculated using SAP estimating tool:
  - 2 estimators responsible for machined bars (random length bars, machined on 4 faces) and precision machined flat sections.
  - 2 estimators (inside sales) responsible for milled plate and machined blocks (6 faces and lifting holes).
  - 2 estimators (outside sales) responsible for milled plate and machined blocks (machined on 6 faces and lifting holes).
- Special products (10% of turnover):
  - 1 estimator responsible for manual estimating, working from engineering drawing.
  - 3 estimators / CAD engineers responsible for managing CADCAM data files (split into two shifts)
- Fine planning:

- 1 planner scheduling priorities (fixed forward production plans for the next 24 to 48 hrs)

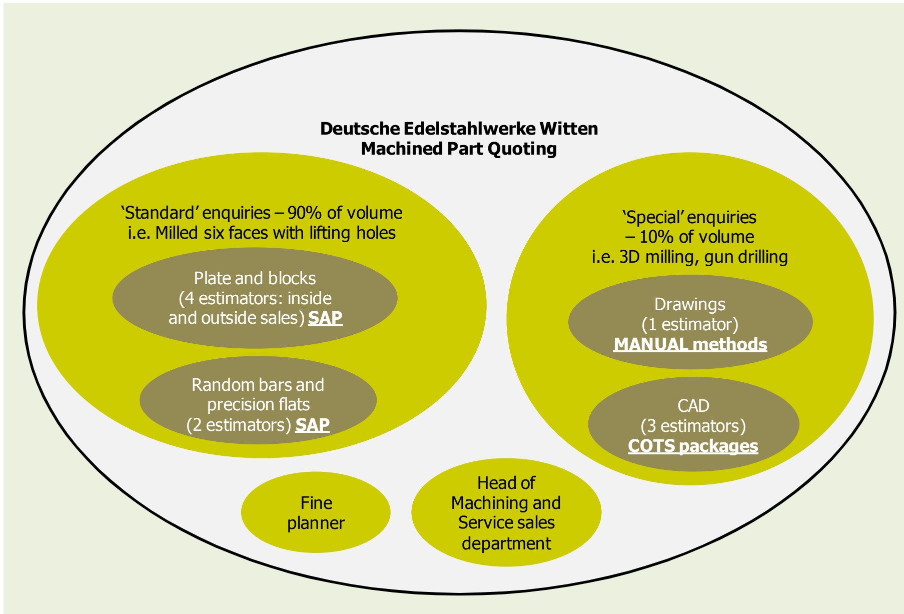


Figure H.4 Systems map for estimating function at DEW Machining and Service Department, Witten.

The company's IT infrastructure provides a LAN interfacing the company wide SAP-ERP platform with both commercial off-the-shelf packages (COTS) and bespoke BDE software used by the machining department (for managing working data between shop floor and management) Figure H.5. SAP provides sales order processing and order management support, COTS packages aid with CAD data handling and 'fine plan' scheduling, which the BDE system provides data on machining operations leading to evaluations of performance and reporting functionality. The IT infrastructure represents a massive investment over a number of years, running into €000,000's, which sets this type of organisation far away from what can be realistically invested in a SME. Such is the sophistication of the whole system it is not practical to describe all features in this thesis, but one example of the complexity is:

- Optical overview of real-time machine utilisation (traffic light system) i.e. monitoring machine activity by electronic sensing of operations e.g. for a milling operation to be classed as being in the 'production' state, both the machining head must be rotating and the machine bed must be traversing. Idle machines are instantly identifiable, as are: machines where operators are logged on to operations but are not in ‘production’; and maintenance / breakdown status.

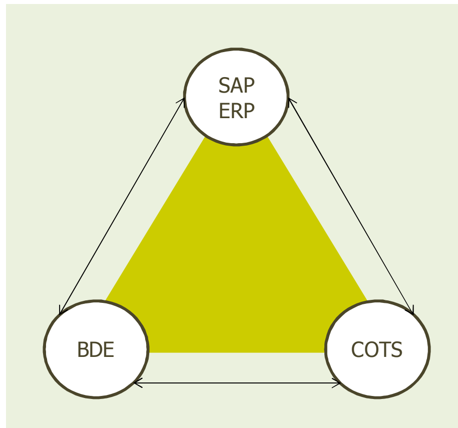


Figure H.5. Main software components

The commercial software utilised is listed below, some of which include of bespoke modifications to their applications developed specifically to address DEW’s requirements (e.g. a ‘quick estimating’ tool in SAP):

- SAP Enterprise Resource Planning
- Actify Spinfire professional
- AHP-Leistand V2.35
- Optimised MS Excel sheets (imported data)
- AutoCAD Mechanical / Inventor 2007
- CATIA V5 R17
- TEBIS CAD/CAM V3.3 Rel. 7
- TEBIS CAD/CAM NC2Achs
- DEPO CAM 2006
- drillCam V 6 840-160
- TopSolid 6.5
- AdCAM NcS V5.9
- EUKLID Design Classic 2001

Interfaces:

- CAD: CAD-exchange files TEBIS-Format (DOS, HPUX etc)
- VDAFS: CAD-exchange files VDA (2.0, DIN66301)

- VDAIS: CAD-exchange files VDA-IGES-SUBSET-type (3.0)
- EXP: CAD-exchange files Catia-Native/Export type (V4.22)
- CADPART: CAD-exchange files Catia-V5-type
- DXF: Exchange files DXF-type
- STEP: Exchange files STEP-type

2D Data:

- DWG: Drawing files AUTOCAD-DWG-type
- DXF: Drawing files DXF-type
- CAT-DRAWING:CAD-exchange files Catia-V5-type
- PLT/HPGL2: Directly plotted in plt.-file goplotte – or drawing HPGL2-type

Standard products amount to 90% of all enquiries and these products comprise of relatively easy to calculate machining operations, for which the SAP sales order platform provides a mechanism for obtaining ‘rough cut’ estimates. These ‘quick estimates’ are accepted as being sufficiently accurate for quotation purposes. Quotes produced using this method generally take less than 10 minutes to complete. The remaining 10% of enquiries require significantly more resources to obtain an accurate estimate. These estimates include calculating complex CNC machining operations using CAD/CAM data files, or the manual interpretation of engineering drawings by an expert estimator.

The salesperson retains the responsibility for ensuring a prompt quotation is provided to the customer, regardless of the estimating method. When the requirements are straightforward, then salesperson uses SAP to obtain both material and machining information; SAP provides a simple drop-down listing of basic machining operations requiring only basic inputs such as material grade and start/finish sizes in order to obtain a rough estimate. On occasions when a more detailed estimating is required, the salesperson refers the enquiry to the appropriate expert estimator. The expert estimator will make the calculation and report back to the salesperson, the salesperson in turn refreshes the quote with the machining costs and lead times.

SAP enables the salesperson to check stock availability across multiple stock locations, along with other relevant information such as material value in €/kg. The salesperson (known as the ‘order manager’) is responsible for all stages of the process from enquiry receipt to despatch of finished product. Compiling an order record for a standard product is a four stage process, known as ‘easy booking’ by the sales staff (Figure H.6):

- Stückliste – ‘inventory’, establishes the material to be used, its starting sizes and costs.
- Arbeitsplan – ‘work plan’, establishes the production route required, specifying machines and times to complete the activities.
- Kalculation – calculates all the costs of production.
- Fertigung – ‘planning order / order reference’ sets the price conditions, delivery commitments and enters into ‘rough cut’ capacity schedule.

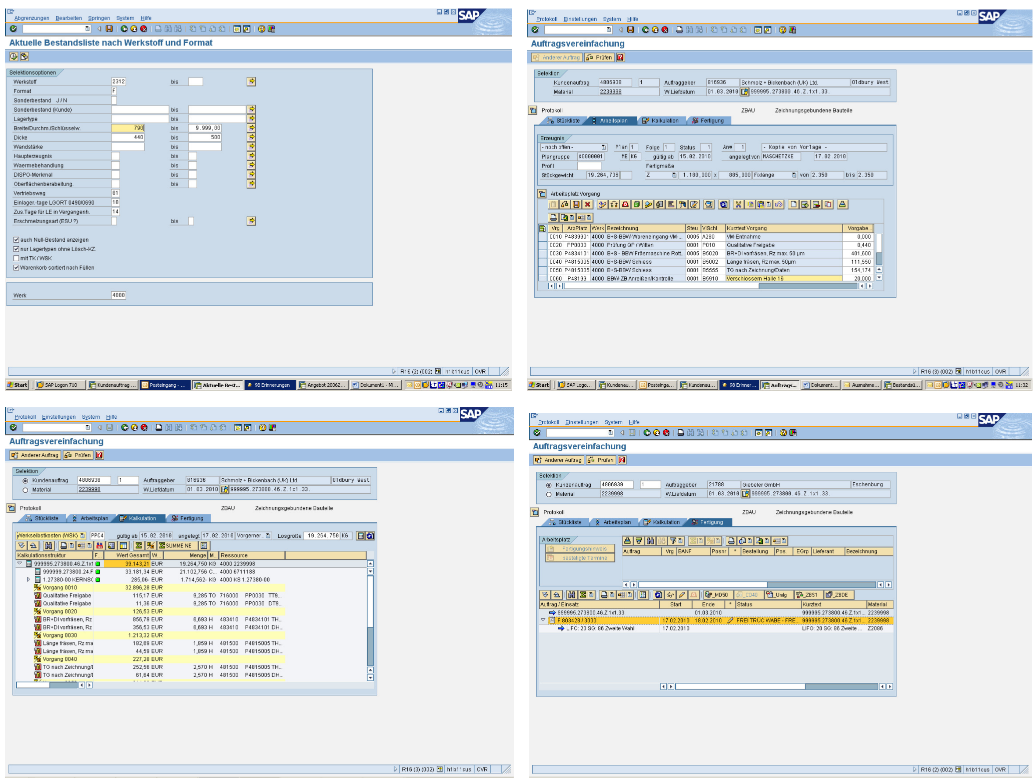


Figure H.6. Producing an order record using SAP four step ‘order simplification’

Therefore cross-boundary communication is essential to ensure effective utilisation of resources and the needs of the customer are met, particularly in terms of delivery (Figure H.7). The order manager uses SAP to establish a ‘rough cut schedule’ in order to state a delivery date to the customer.

Once a work order is raised the responsibility for scheduling the product realisation activities passes to the ‘Fine Planner’, who continuous reviews the priorities for each machine. These priorities are *fixed* for between 24 and 48 hours in advance and the *fine plan list* is communicated to shop floor supervisor electronically, with up-dates every 30 seconds (as the fine plan is continuously modified to optimise resources in real time e.g. delays in workflow, accommodating new top priority orders). DEW strategy is to price material to customer based upon the optimum machining route, if after fine planning an alternative production route is used the difference in cost in absorbed within the machining department.

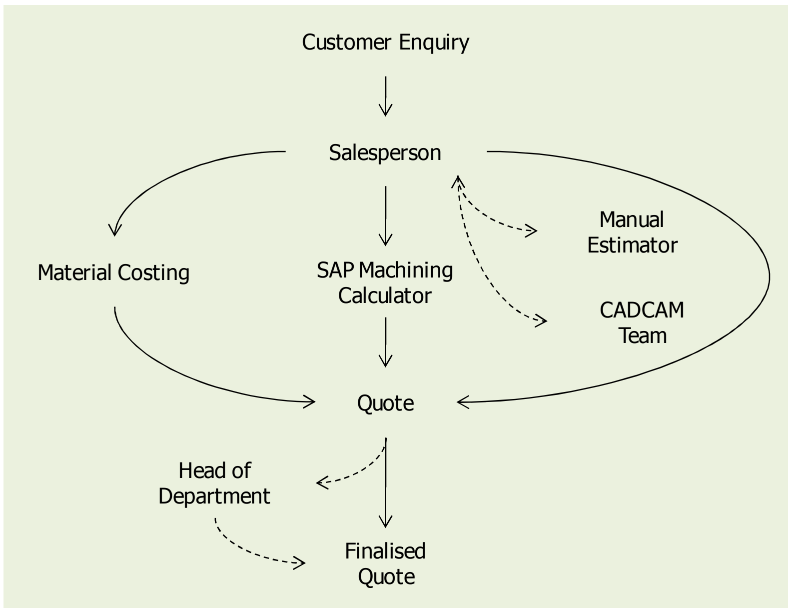


Figure H.7. An activity sequence diagram for estimating at DEW

In today's markets DEW have to retain a high level of flexibility in their machining schedules in order to accommodate urgent customer requirements. Such is the competitiveness in the industry, customers now expect DEW to demonstrate a high degree of agility in their manufacturing operations. Therefore the schedules are continuously changing, with compromises being negotiated between the order manager(s) and the fine planner, indicated in Figure H.8.

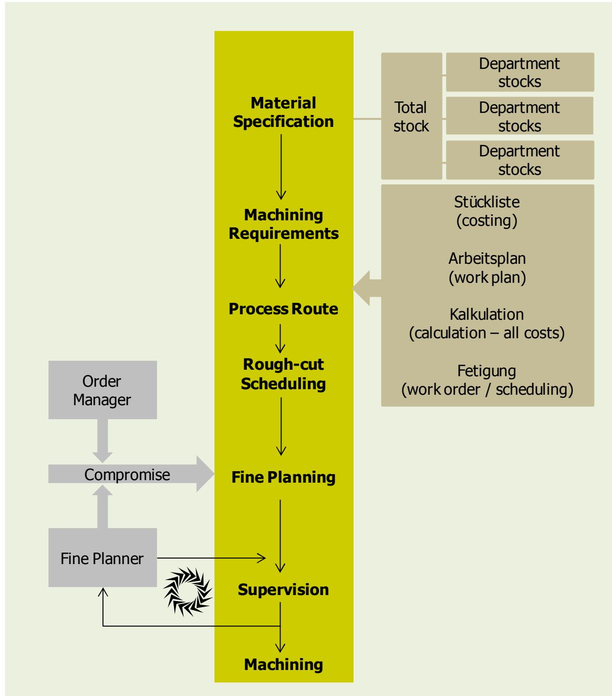


Figure H.8. Process overview for DEW machining

When machining operations are scheduled to commence, process route instructions are issued to the machine operators. These process instructions have bar codes allocated to each operation in the production cycle. Each machine tool is fitted with a PC station and bar code scanner, the machine operator scans the bar code at the start (and finish) of the machining time, and when each operation is complete the operator confirms this via the PC interface to the wider information system. The automatic data collection feature provides SAP with all the necessary information to record actual machining performance for comparison when the estimated times.

When questioned regarding the effectiveness and efficiency of their operations, the Head of Department (Maschetzke, 2010) stated that in his opinion the most significant performance measure for the Machining and Service Department should be 'a comparison of the date on which the order was actually completed against the planned completion date acknowledge to the customer'. For this DEW set the benchmark acceptance level of '90% of all orders completed +/- 1 day of scheduled completion date'. However, strictly in terms of measuring the accuracy of estimating data, it was stated that '+/- 10% is considered good and +/- 5% would be ideal'. When asked how the estimating process at DEW could be improved, Mr. Maschetzke responded with the by the following comments:

- 'Improved data importing from CAD team into SAP quotes. At the moment the order manager must refresh the quote will information from the CAD team, whereas it would be much more efficient if the information could be added to the quote at source.
- Increased flexibility – the system constraints (such as size capacity ranges) are precise and lack the flexibility of a human expert's decision making ability, thus the human expert is considered irreplaceable.
- Reduced complexity in raising quotations i.e. eliminating more 'clicks'.
- Review of the pricing strategy, in terms of both allocation of overhead and standard cost percentage mark-up.'

It had become apparent (in the later workshops) when discussing the requirements for a decision support process for machined part estimating in SMEs, that feature-based costing does offer the opportunity to complete an estimate in much the same way that such a task would be tackled by a human estimator. Furthermore, clear parallels can be drawn to the approach to estimating at DEW, and the individual steps to which their process is decomposed. Having the opportunity to view how such a large machining facility controls its operation also provided insight to just how complex estimating activities are, and it was very interesting to see that even with all the technology at their disposal, DEW still retain the services of a human estimator who spends his entire time manually producing estimates.

However, the most significant insight came from discussions regarding the use of case-based reasoning / analogical reasoning. Whilst DEW built enormous reporting capabilities into their systems, they do not fully realise the potential of this valuable resource. Their sales people discussed how they frequently manually check performance on past orders when there are similarities with a live enquiry, but there is no systemic approach to this. In the final meeting which concluded the case study in February 2010, METALmpe was demonstrated – with particular emphasis on how the application generates a second comparative estimate using case-based reasoning. This created a great deal of interest and the possibilities were discussed at length. In conclusion it was agreed that DEW would make a request to SAP for similar functionality to be built into the SAP system they operate, and that a further workshop would be held in the UK with SAP personnel present to discuss a collaborative partnership project in order for SAP to adopt the CBR functionality.

Appendix I Case study: RAM Machining Ltd

Number of employees:	<9
Estimating hours per week:	<20 hrs
Degree of automation in estimating process:	'Almost entirely manual'
Performance of existing approach to estimating:	'Satisfactory'
Experience of COTS packages:	None
Perception of risk from reliance on 'experts':	'Quite important'

Business:

Subcontract / free-issue machining.

80% production turning bar stock, 20% general milling / turning.

Further information: http://www.rammachining.co.uk

Comments from John Southall:

Q. Would you use the methodology in your organisation?
A. 'No, we are a small company operating in quite a narrow market, which works well with hands on control.'

Q. Please state what you consider to be the major strengths and weaknesses of the methodology?
A. 'Larger companies with a wide range of mostly repeating / similar orders.'

Appendix J Case study: CH Clarke Engineering Ltd

Number of employees:	<49
Estimating hours per week:	<40 hrs
Degree of automation in estimating process:	'Almost entirely manual'
Performance of existing approach to estimating:	'Satisfactory'
Experience of COTS packages:	None
Perception of risk from reliance on 'experts':	'Quite important'

Business:

Subcontract engineer supply machined parts to tier 1 and tier 2 customers.

CNC milling and turning, conventional milling and turning

Further information: http://www.chclarke.com

Comments from Matthew Lowe:

Q. Did you find the methodology applicable to your organization?
A. 'Costing is not black and white. We have to allow for the fudge factor, and also the human element.'

Q. Can you identify potential benefits from applying the methodology?
A. 'Some of our costings would be more methodical.'

Q. Please state what you consider to be the major strengths and weaknesses of the methodology?
A. 'The main strength is that it appears to be an accurate method of costing. The weakness is that it does not look 'friendly'.'

Appendix K Case study: Bishop Engineering Ltd

Number of employees:	<9
Estimating hours per week:	<20 hrs
Degree of automation in estimating process:	‘Almost entirely manual’
Performance of existing approach to estimating:	‘Good’
Experience of COTS packages:	None
Perception of risk from reliance on ‘experts’:	‘Unimportant’

Business:

Small business offering machining services:

Lumsden grinding, vertical milling, horizontal milling, radial drilling.

Owner and manager quoting and machining; with further machine operators.

Further information: http://home.btconnect.com/bishopengineering

Comments from Ben Wake:

‘We have had a think about how we can try and work out a formulae for calculating machining times/costs a lot of times but we could never find an easy way of being consistent because of variables such as material type, material left on prior to machining just to name a few. With pricing steel it is a lot easier as you have the price per tonne and then the sawing time I imagine is pretty consistent, then I assume you can add on extras like transport and additional operations afterwards.

We sort of have a formula for costing top and bottom machining but this really only works on mild steel where you know that the plate is rolled to set, generally quite consistent thicknesses.

What we tend to do is keep a record of prices and then monitor the time things take to machine and fine tune prices as we go along. We put a price in for the first few then monitor the time it took for us to machine them and it didn't work out too bad.

We do have an hourly rate that we aim to make but on some jobs if they make less then our operators will then work multiple machines to try and get the hourly rate right for each operator. We tend to have to do this on regular jobs where we have to price at a rate which is more competitive.

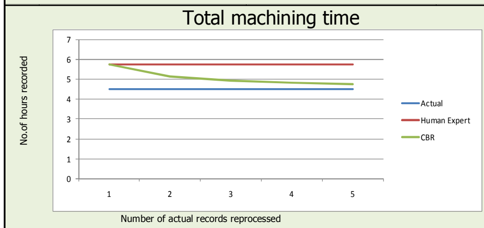
I know it sounds a bit 'stab in the dark' but to be honest it seems to work.’

Q. Did you find the methodology applicable to your organization?
A. ‘The machining we do is not consistent at all and our own general machining knowledge allows us to quote accurately’.

Q. Please rate the likely success of the overall process of the feature-driven case-based estimating methodology.
A. ‘Not worth doing for us, but I feel it would work in other machining processes.’

Appendix L CBR test results: milling operations

Case-based Reasoning Test Results: Sample 970165			
Process route	205	Description	3" SEC BOP Body
Actual times (Ave)	4.50 hrs	Number of parts produced	5
Expert estimate	5.75 hrs	Accuracy of expert Vs ave 'actual' time	+27.78%
CBR estimate (Ave)	4.75 hrs	Accuracy of CBR Vs ave 'actual' time	+5.56%



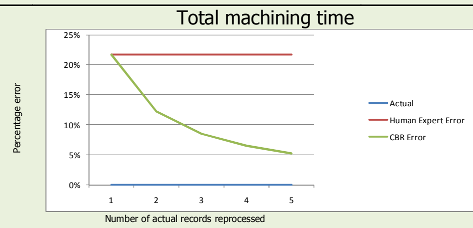
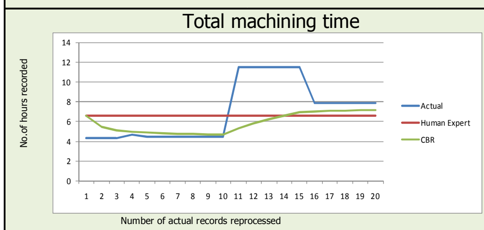


Figure L.1. CBR results for sample 970165: milling operation

Case-based Reasoning Test Results: Sample 980066			
Process route	203	Description	3" DEC BOP Body
Actual times (Ave)	7.08 hrs	Number of parts produced	20
Expert estimate	6.57 hrs	Accuracy of expert Vs ave 'actual' time	-7.2%
CBR estimate (Ave)	5.85 hrs	Accuracy of CBR Vs ave 'actual' time	-17.37%



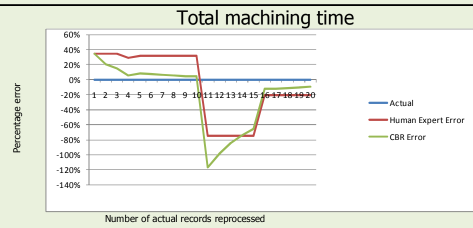
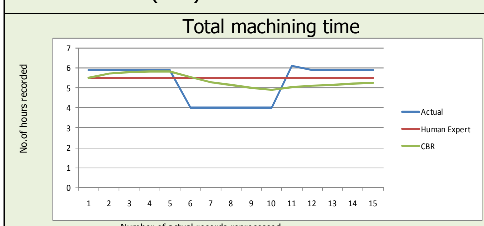


Figure L.2. CBR results for sample 980066: milling operation

Case-based Reasoning Test Results: Sample 970505			
Process route	207	Description	4" SEC BOP Body
Actual times (Ave)	5.28 hrs	Number of parts produced	15
Expert estimate	5.50 hrs	Accuracy of expert Vs ave 'actual' time	-4.17%
CBR estimate (Ave)	5.37 hrs	Accuracy of CBR Vs ave 'actual' time	-1.70%



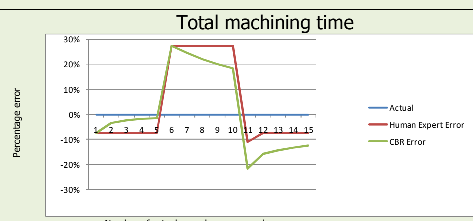
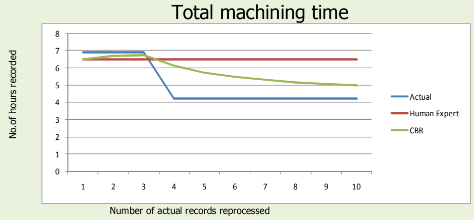


Figure L.3. CBR results for sample 970505: milling operation

Case-based Reasoning Test Results: Sample 980197			
Process route	200	Description	4" DEC BOP Body
Actual times (Ave)	5.00 hrs	Number of parts produced	10
Expert estimate	6.50 hrs	Accuracy of expert Vs ave 'actual' time	+30.00%
CBR estimate (Ave)	5.77 hrs	Accuracy of CBR Vs ave 'actual' time	+15.40%

Total machining time



Total machining time

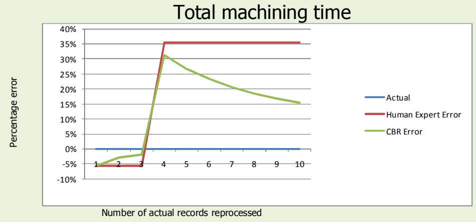
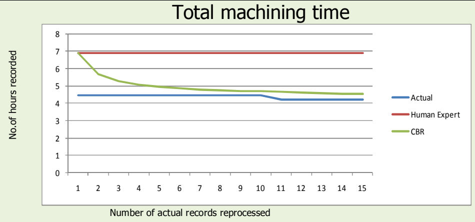


Figure L.4. CBR results for sample 980197: milling operation

Case-based Reasoning Test Results: Sample 970244			
Process route	201	Description	4" TEC BOP Body
Actual times (Ave)	4.37 hrs	Number of parts produced	15
Expert estimate	6.87 hrs	Accuracy of expert Vs ave 'actual' time	+57.21%
CBR estimate (Ave)	4.97 hrs	Accuracy of CBR Vs ave 'actual' time	+13.73%

Total machining time



Total machining time

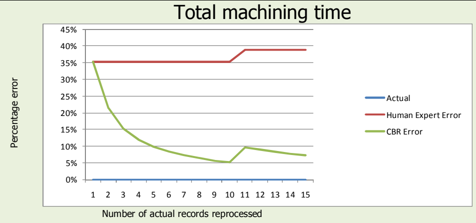
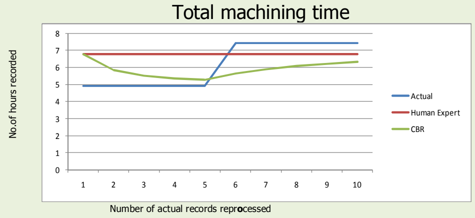


Figure L.5. CBR results for sample 970244: milling operation

Case-based Reasoning Test Results: Sample 970249			
Process route	208	Description	5" DEC BOP Body
Actual times (Ave)	6.15 hrs	Number of parts produced	10
Expert estimate	6.75 hrs	Accuracy of expert Vs ave 'actual' time	+9.76%
CBR estimate (Ave)	5.89 hrs	Accuracy of CBR Vs ave 'actual' time	-4.31%

Total machining time



Total machining time

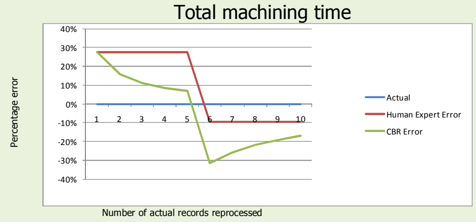
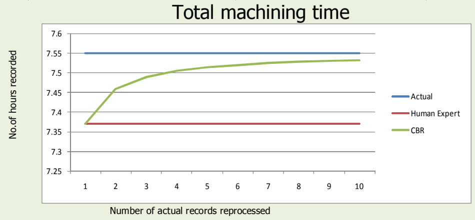


Figure L.6. CBR results for sample 970249: milling operation

Case-based Reasoning Test Results: Sample 970502			
Process route 202		Description 5" TEC BOP Body	
Actual times (Ave)	7.55 hrs	Number of parts produced	10
Expert estimate	7.37 hrs	Accuracy of expert Vs ave 'actual' time	-2.38%
CBR estimate (Ave)	7.50 hrs	Accuracy of CBR Vs ave 'actual' time	-0.66%

Total machining time



Total machining time

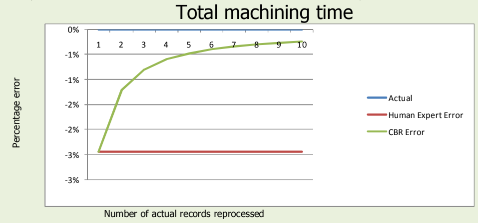


Figure L.7. CBR results for sample 970502: milling operation

Appendix M CBR test results: multiple operations.

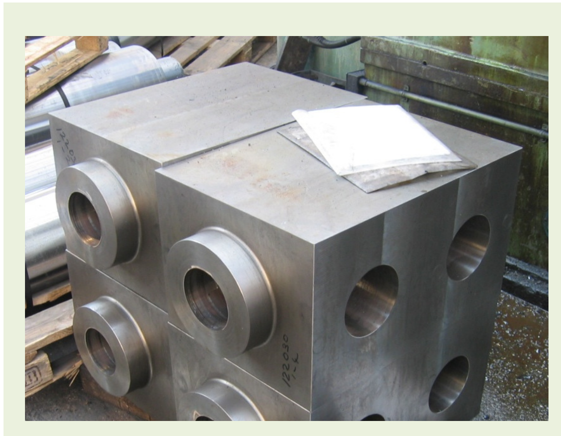


Figure M.1. Product range used in 'multiple operations' CBR tests

Sample No.	Actual time (Average hrs)	Expert estimate (hrs)	CBR estimate (Average hrs)	Accuracy of expert estimate	Accuracy of CBR estimate
1	19.52	22.48	20.09	+15.3%	+2.9%
2	24.01	26.03	24.45	+9.5%	+1.8%
3	24.99	26.85	26.25	+7.4%	+5.0%
4	26.21	26.60	27.87	+1.5%	+6.3%
5	28.82	32.72	29.62	+13.5%	+2.8%
6	30.97	37.75	33.61	+20.6%	+8.5%
7	30.41	32.22	29.94	+6.0%	-1.6%
8	36.29	48.09	37.15	+32.5%	+2.8%
9	46.61	51.98	45.54	+11.5%	-2.3%

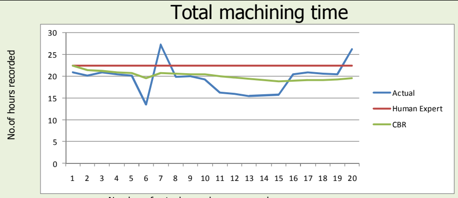
Table M.1. Summary of results (by sample group) for 'multiple operations' CBR tests

Operation	Actual time (hrs)	Expert estimate (hrs)	CBR estimate (hrs)	Accuracy of expert estimate	Accuracy of CBR estimate	Difference (hrs) between CBR and expert estimate
Turning	3816.28	4213.74	3920.02	+10.4%	+2.7%	293.72
Milling	2090.66	2432.70	2212.50	+16.4%	+5.8%	220.20
Cross hole	1539.54	1770.10	1630.88	+14.9%	+5.9%	139.22
Centre bore	3737.68	4049.80	3846.80	+8.3%	+2.9%	203.00
Lifting holes	496.40	622.50	539.36	+25.4%	+8.6%	83.14
Total	**11680.56**	**13088.84**	**12149.56**	**+12.1%**	**+4.0%**	**939.28**

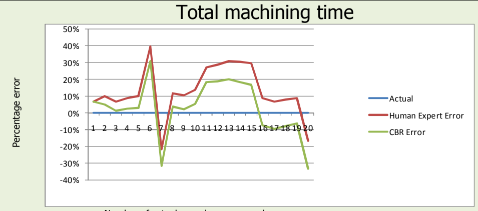
Table M.2. Summary of results (by operation type) for 'multiple operations' CBR tests

Case-based Reasoning Test Results: Sample 1			
Process route	18	Description	3” SEC BOP Body
Actual times (Ave)	19.52 hrs	Number of parts produced	20
Expert estimate	22.48 hrs	Accuracy of expert Vs ave ‘actual’ time	+15.26%
CBR estimate (Ave)	20.09 hrs	Accuracy of CBR Vs ave ‘actual’ time	+2.92%

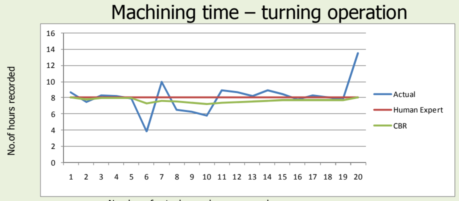
Total machining time



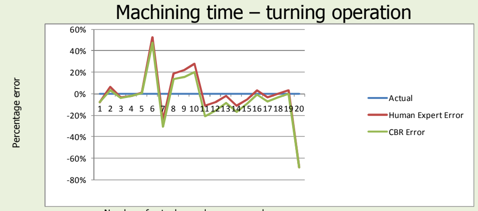
Total machining time



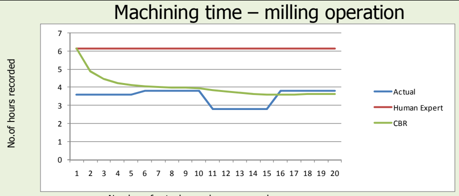
Machining time – turning operation



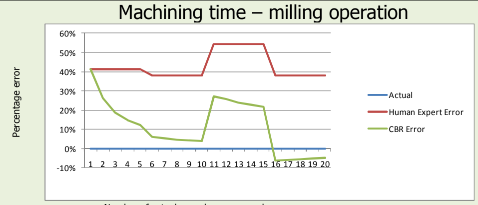
Machining time – turning operation



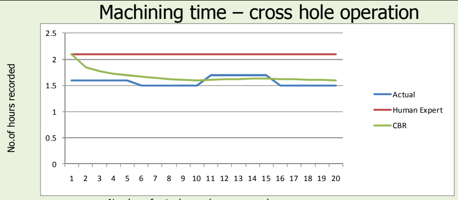
Machining time – milling operation



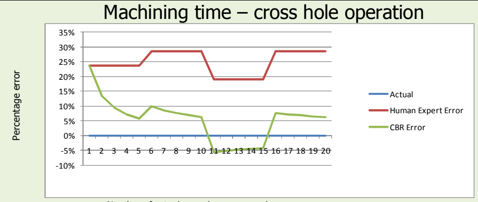
Machining time – milling operation



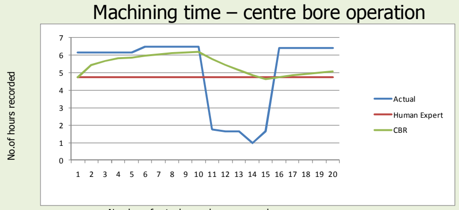
Machining time – cross hole operation



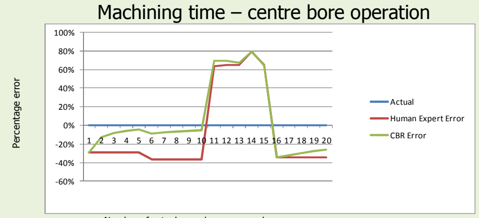
Machining time – cross hole operation



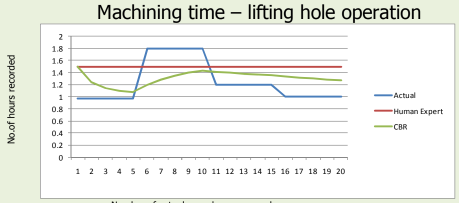
Machining time – centre bore operation



Machining time – centre bore operation



Machining time – lifting hole operation



Machining time – lifting hole operation

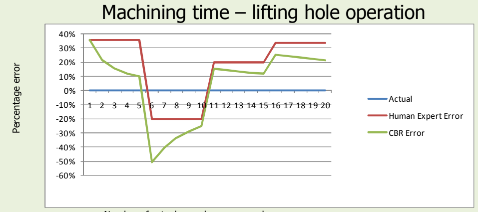
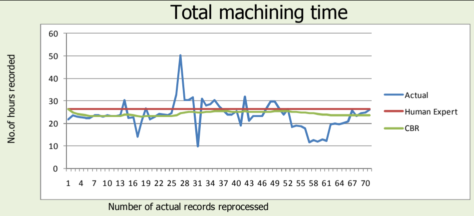


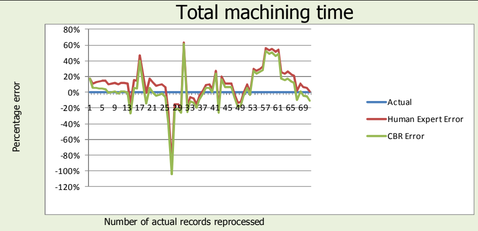
Figure M.2. CBR results for sample 1: multiple operations

Case-based Reasoning Test Results: Sample 2			
Process route	24	Description	3" DEC BOP Body
Actual times (Ave)	24.01 hrs	Number of parts produced	71
Expert estimate	26.03 hrs	Accuracy of expert Vs ave 'actual' time	+9.54%
CBR estimate (Ave)	24.45 hrs	Accuracy of CBR Vs ave 'actual' time	+1.83%

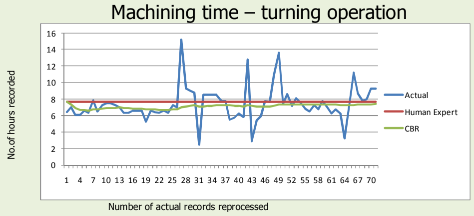
Total machining time



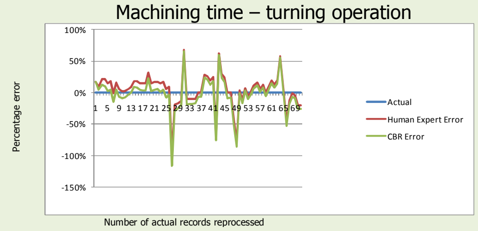
Total machining time



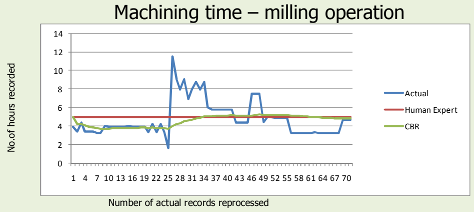
Machining time – turning operation



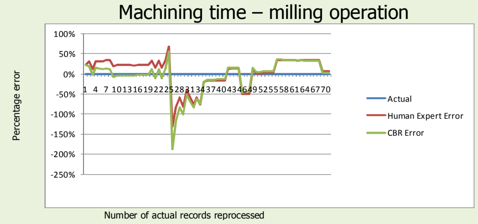
Machining time – turning operation



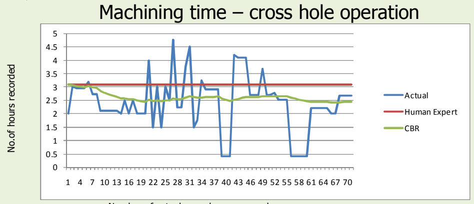
Machining time – milling operation



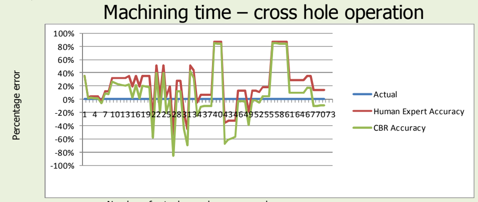
Machining time – milling operation



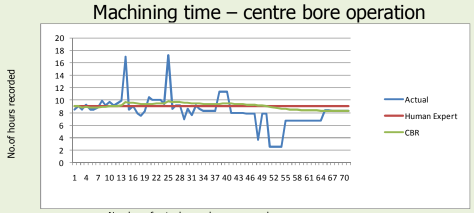
Machining time – cross hole operation



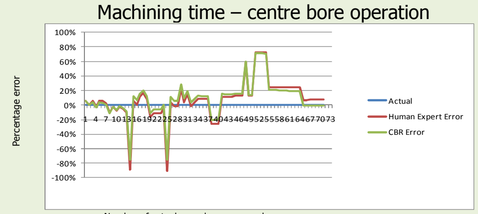
Machining time – cross hole operation



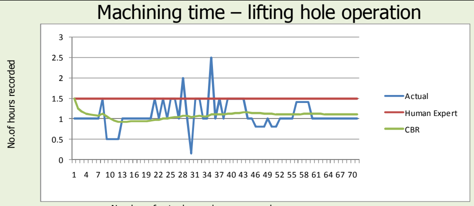
Machining time – centre bore operation



Machining time – centre bore operation



Machining time – lifting hole operation

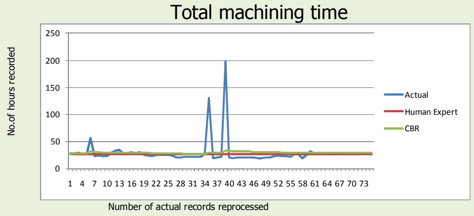


Machining time – lifting hole operation

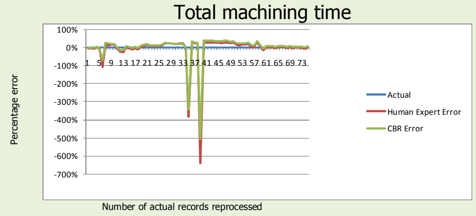
Figure M.3. CBR results for sample 2: multiple operations

Case-based Reasoning Test Results: Sample 3			
Process route 25		Description 3" TEC BOP Body	
Actual times (Ave)	24.99 hrs	Number of parts produced	75
Expert estimate	26.85 hrs	Accuracy of expert Vs ave 'actual' time	+7.44%
CBR estimate (Ave)	26.25 hrs	Accuracy of CBR Vs ave 'actual' time	+5.04%

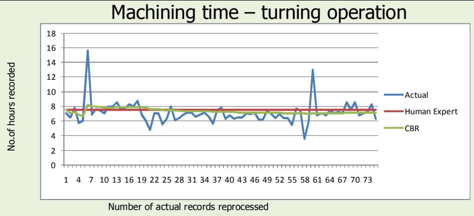
Total machining time



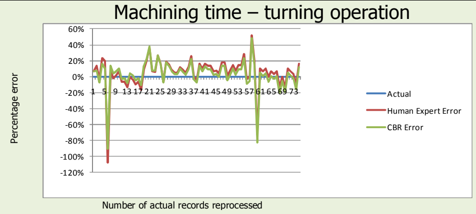
Total machining time



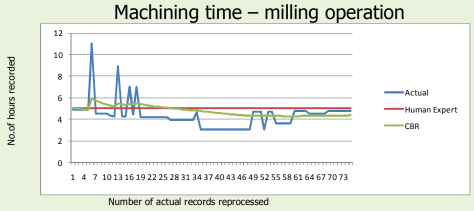
Machining time – turning operation



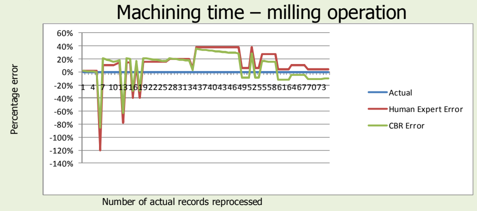
Machining time – turning operation



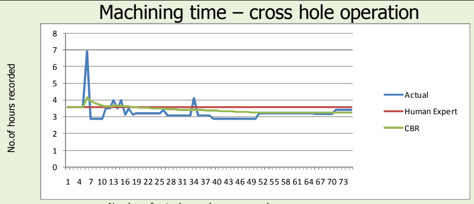
Machining time – milling operation



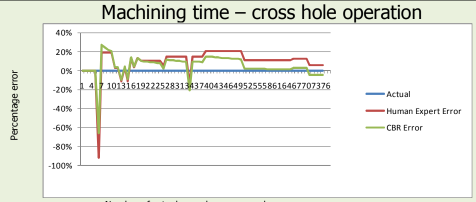
Machining time – milling operation



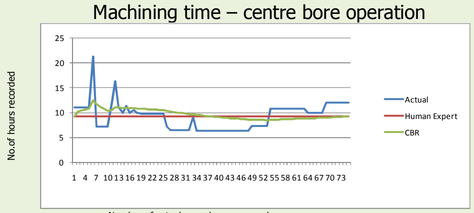
Machining time – cross hole operation



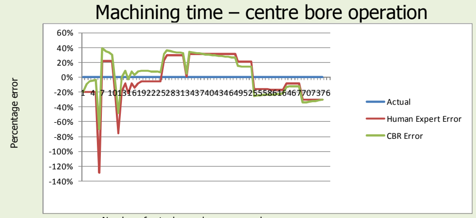
Machining time – cross hole operation



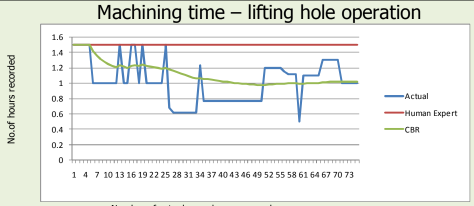
Machining time – centre bore operation



Machining time – centre bore operation



Machining time – lifting hole operation



Machining time – lifting hole operation

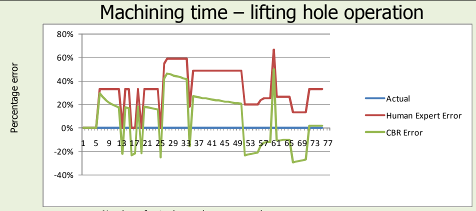
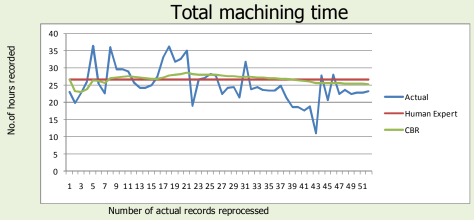


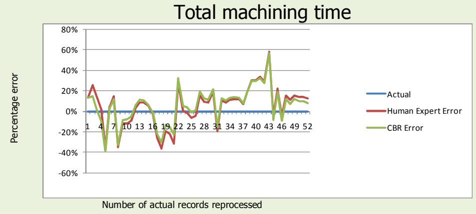
Figure M.4. CBR results for sample 3: multiple operations

Case-based Reasoning Test Results: Sample 4			
Process route	27	Description	4" SEC BOP Body
Actual times (Ave)	26.21 hrs	Number of parts produced	52
Expert estimate	26.60 hrs	Accuracy of expert Vs ave 'actual' time	+1.49%
CBR estimate (Ave)	27.87 hrs	Accuracy of CBR Vs ave 'actual' time	+6.33%

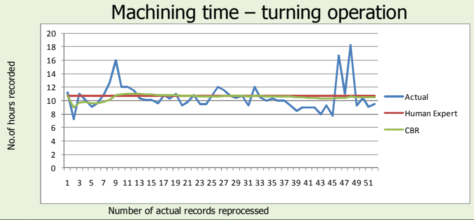
Total machining time



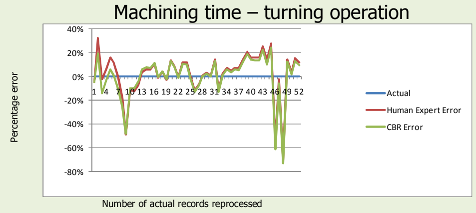
Total machining time



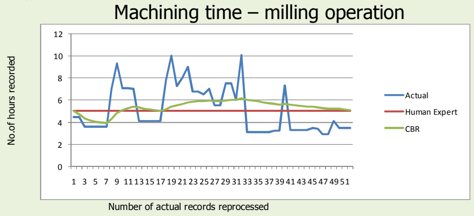
Machining time – turning operation



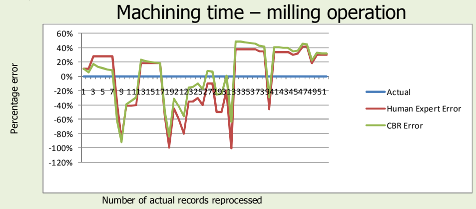
Machining time – turning operation



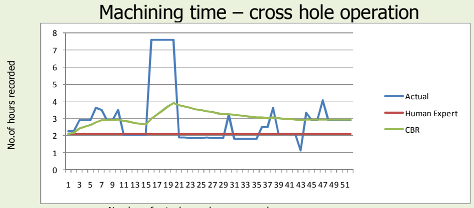
Machining time – milling operation



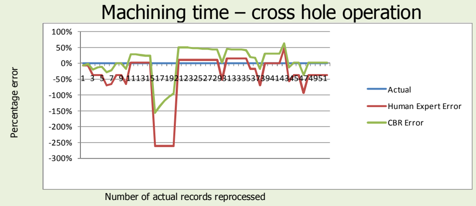
Machining time – milling operation



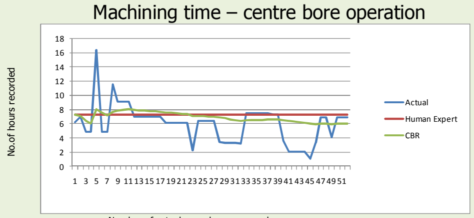
Machining time – cross hole operation



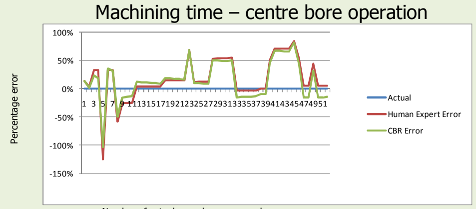
Machining time – cross hole operation



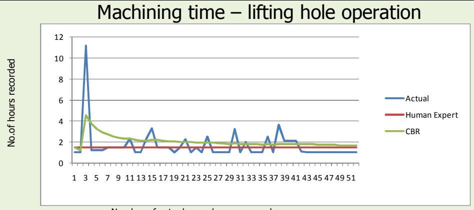
Machining time – centre bore operation



Machining time – centre bore operation



Machining time – lifting hole operation



Machining time – lifting hole operation

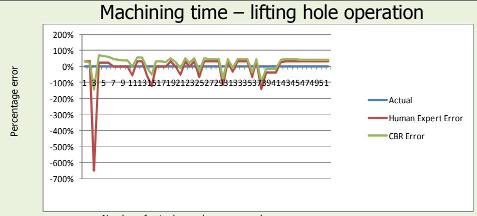
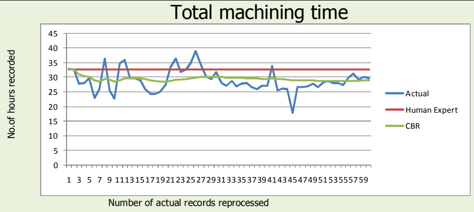


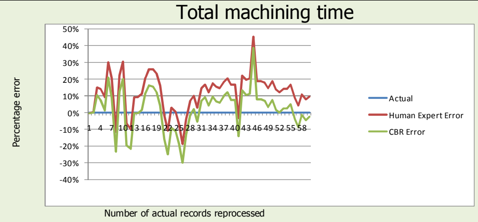
Figure M.5. CBR results for sample 4: multiple operations

Case-based Reasoning Test Results: Sample 5			
Process route	28	Description	4" DEC BOP Body
Actual times (Ave)	28.82 hrs	Number of parts produced	60
Expert estimate	32.72 hrs	Accuracy of expert Vs ave 'actual' time	+13.53%
CBR estimate (Ave)	29.62 hrs	Accuracy of CBR Vs ave 'actual' time	+2.78%

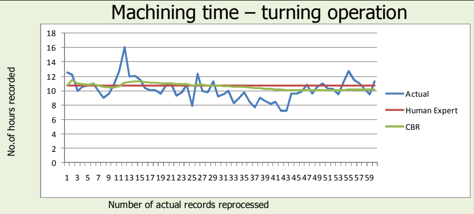
Total machining time



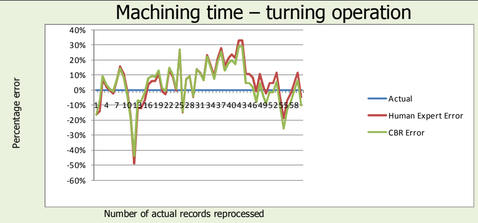
Total machining time



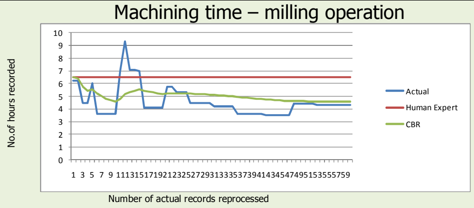
Machining time – turning operation



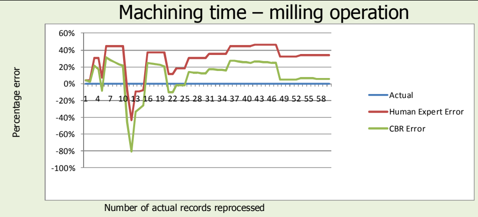
Machining time – turning operation



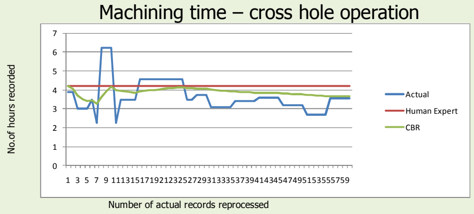
Machining time – milling operation



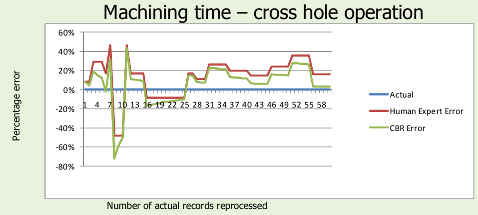
Machining time – milling operation



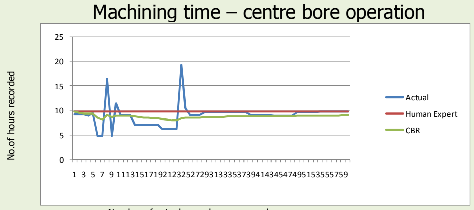
Machining time – cross hole operation



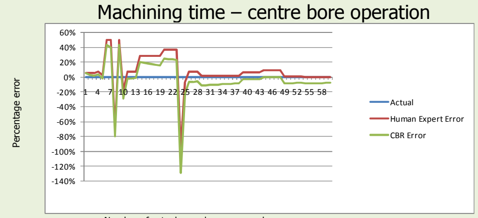
Machining time – cross hole operation



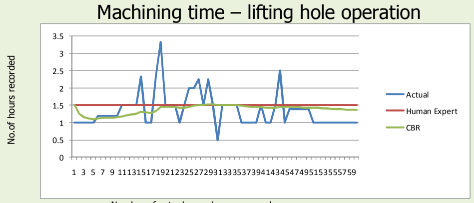
Machining time – centre bore operation



Machining time – centre bore operation



Machining time – lifting hole operation



Machining time – lifting hole operation

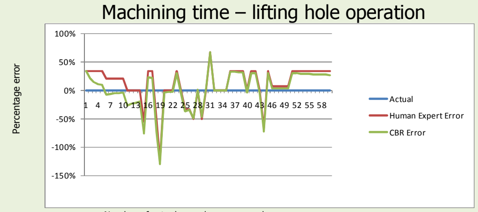
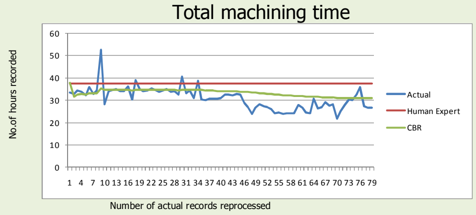


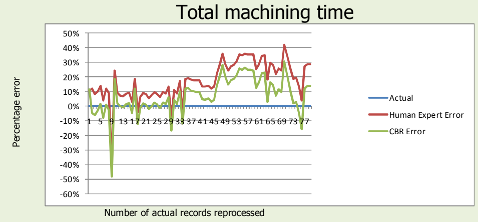
Figure M.6. CBR results for sample 5: multiple operations

Case-based Reasoning Test Results: Sample 6			
Process route	20	Description	4" TEC BOP Body
Actual times (Ave)	30.97 hrs	Number of parts produced	79
Expert estimate	37.75 hrs	Accuracy of expert Vs ave 'actual' time	+20.62%
CBR estimate (Ave)	33.61 hrs	Accuracy of CBR Vs ave 'actual' time	+8.54%

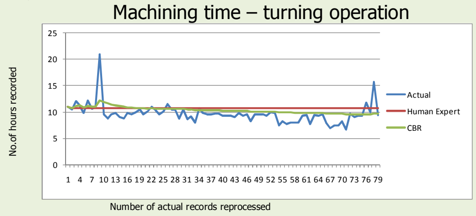
Total machining time



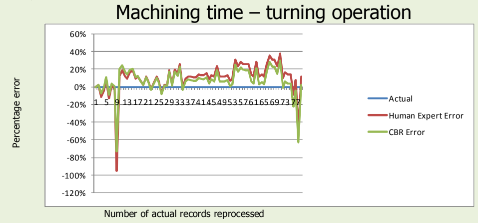
Total machining time



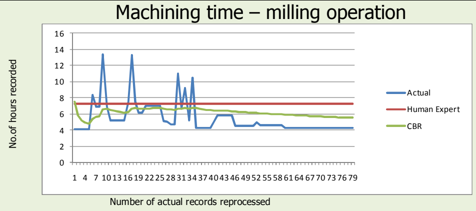
Machining time – turning operation



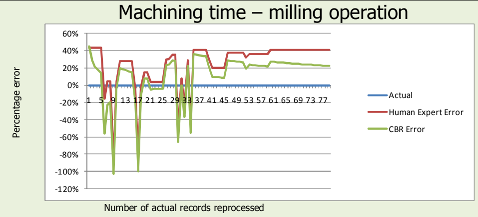
Machining time – turning operation



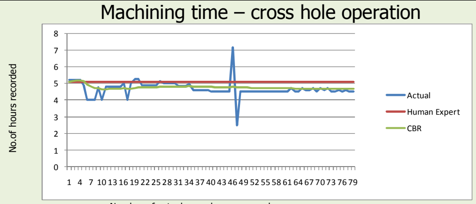
Machining time – milling operation



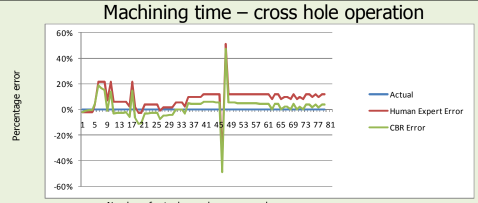
Machining time – milling operation



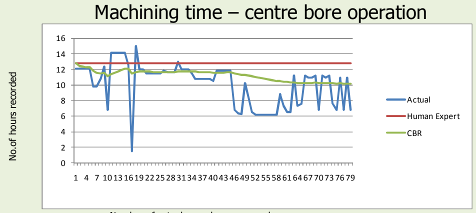
Machining time – cross hole operation



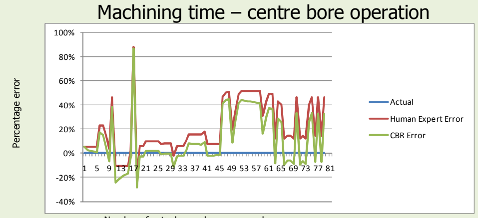
Machining time – cross hole operation



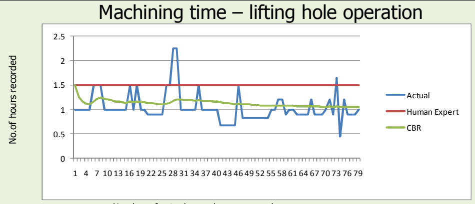
Machining time – centre bore operation



Machining time – centre bore operation



Machining time – lifting hole operation



Machining time – lifting hole operation

Figure M.7. CBR results for sample 6: multiple operations

Case-based Reasoning Test Results: Sample 7			
Process route 21		Description 5" SEC BOP Body	
Actual times (Ave)	30.41 hrs	Number of parts produced	20
Expert estimate	32.22 hrs	Accuracy of expert Vs ave 'actual' time	+5.95%
CBR estimate (Ave)	29.94 hrs	Accuracy of CBR Vs ave 'actual' time	-1.55%

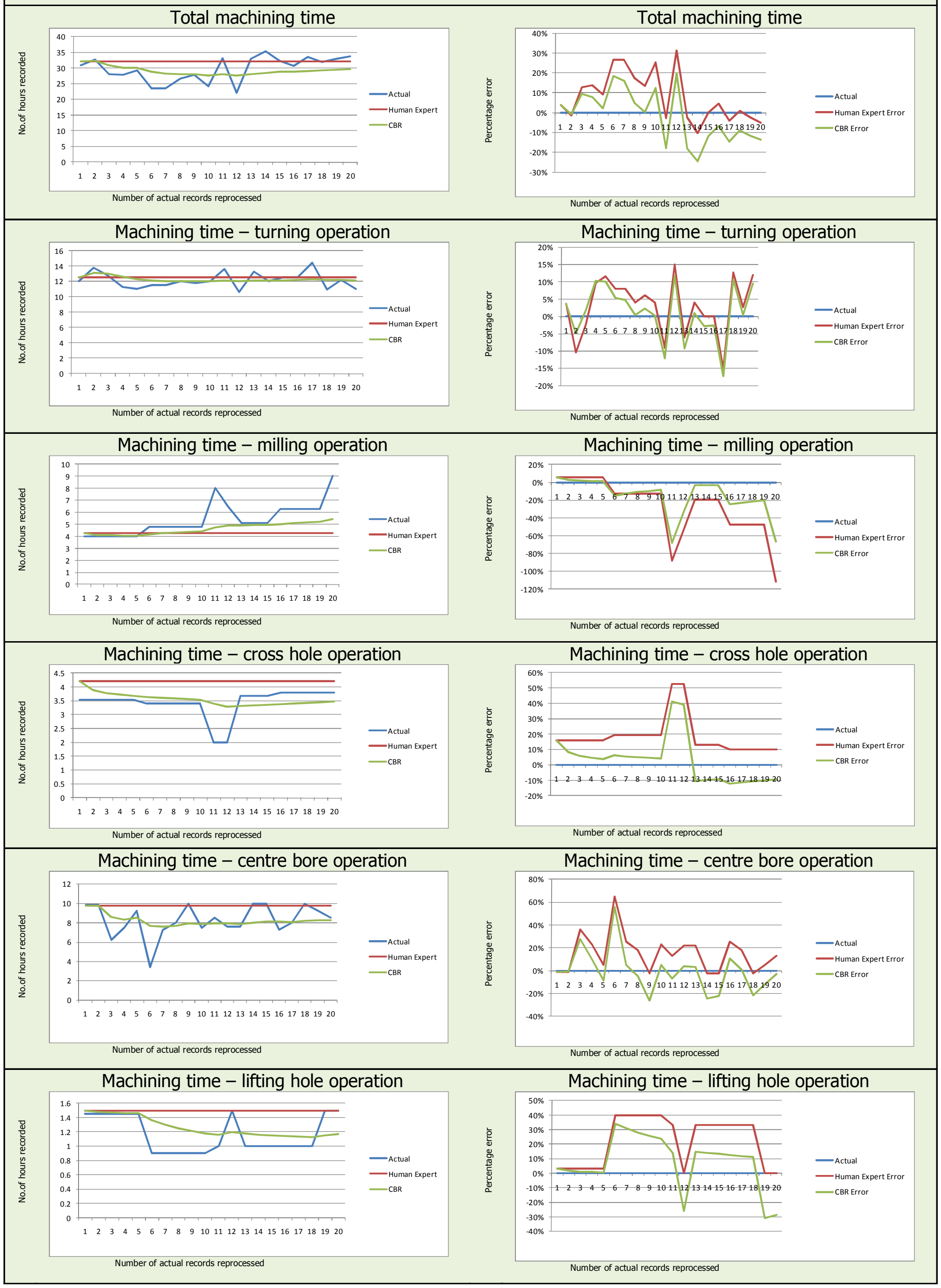
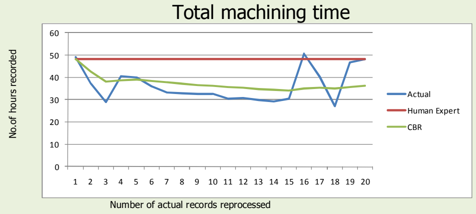


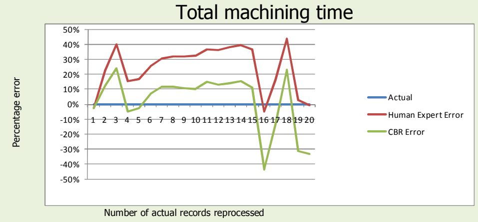
Figure M.8. CBR results for sample 7: multiple operations

Case-based Reasoning Test Results: Sample 8			
Process route 22		Description	5" DEC BOP Body
Actual times (Ave)	36.29 hrs	Number of parts produced	20
Expert estimate	48.09 hrs	Accuracy of expert Vs ave 'actual' time	+32.52%
CBR estimate (Ave)	37.15 hrs	Accuracy of CBR Vs ave 'actual' time	+2.37%

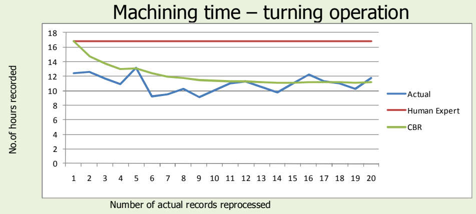
Total machining time



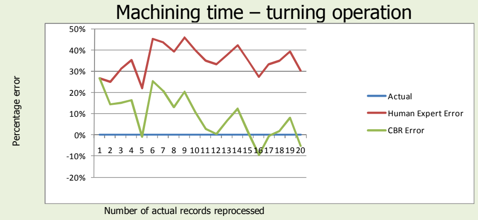
Total machining time



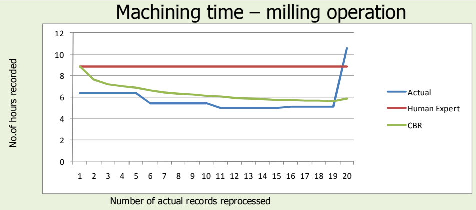
Machining time – turning operation



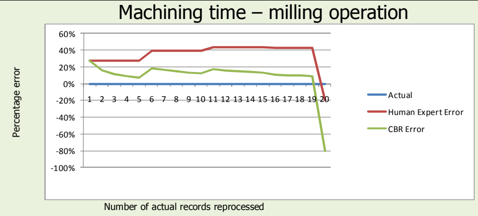
Machining time – turning operation



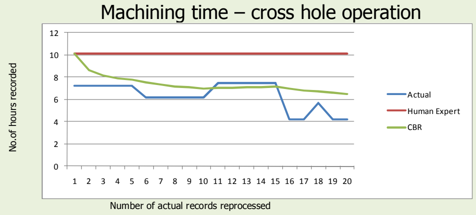
Machining time – milling operation



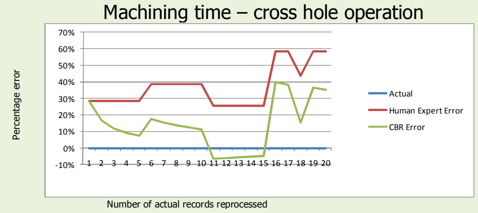
Machining time – milling operation



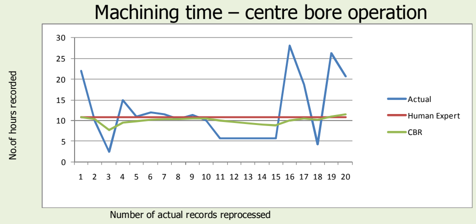
Machining time – cross hole operation



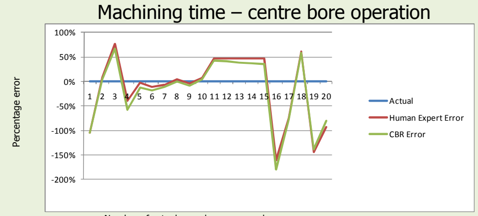
Machining time – cross hole operation



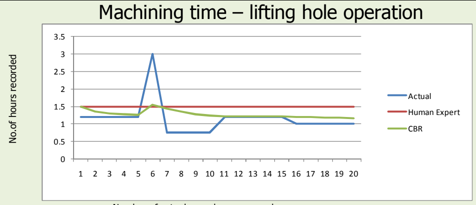
Machining time – centre bore operation



Machining time – centre bore operation



Machining time – lifting hole operation



Machining time – lifting hole operation

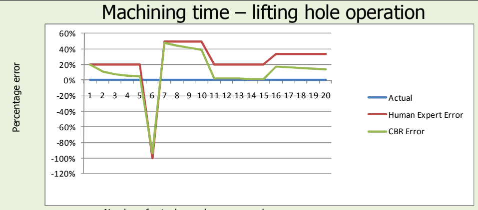
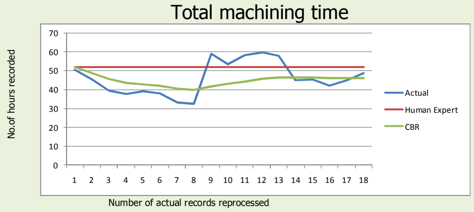


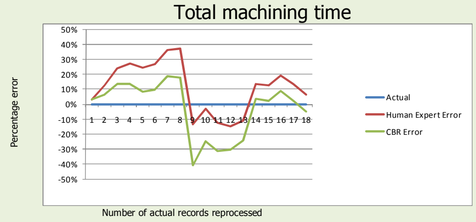
Figure M.9. CBR results for sample 8: multiple operations

Case-based Reasoning Test Results: Sample 9			
Process route	29	Description	5" TEC BOP Body
Actual times (Ave)	46.61 hrs	Number of parts produced	18
Expert estimate	51.98 hrs	Accuracy of expert Vs ave 'actual' time	+11.52%
CBR estimate (Ave)	45.54 hrs	Accuracy of CBR Vs ave 'actual' time	-2.30%

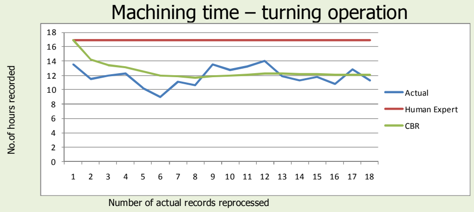
Total machining time



Total machining time



Machining time – turning operation



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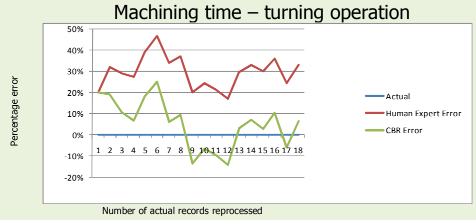
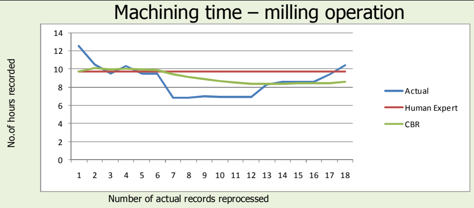


Machining time – milling operation



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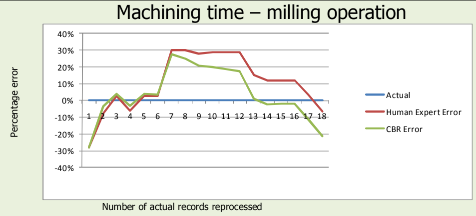
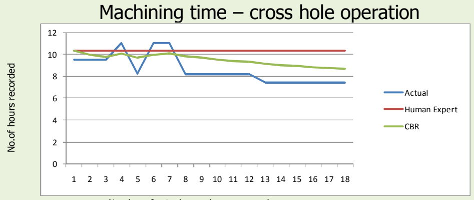
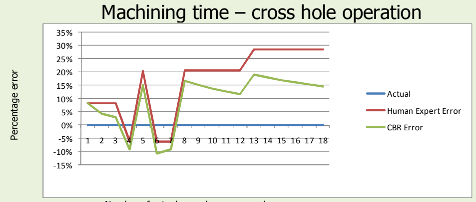


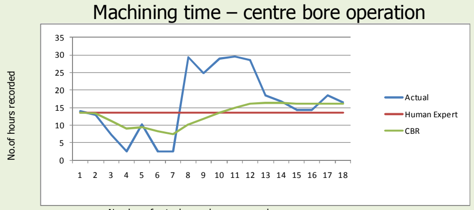
Machining time – cross hole operation



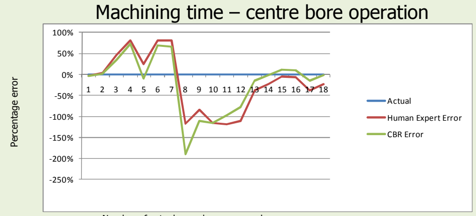
Machining time – cross hole operation



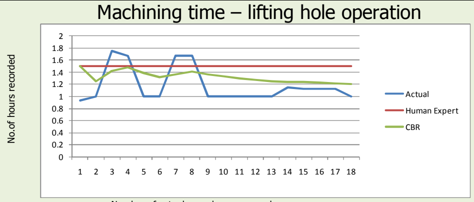
Machining time – centre bore operation



Machining time – centre bore operation



Machining time – lifting hole operation



Machining time – lifting hole operation

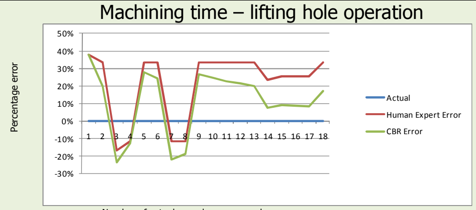


Figure M.10. CBR results for sample 9: multiple operations

Appendix N Mapping METALmpe processes to thesis sections

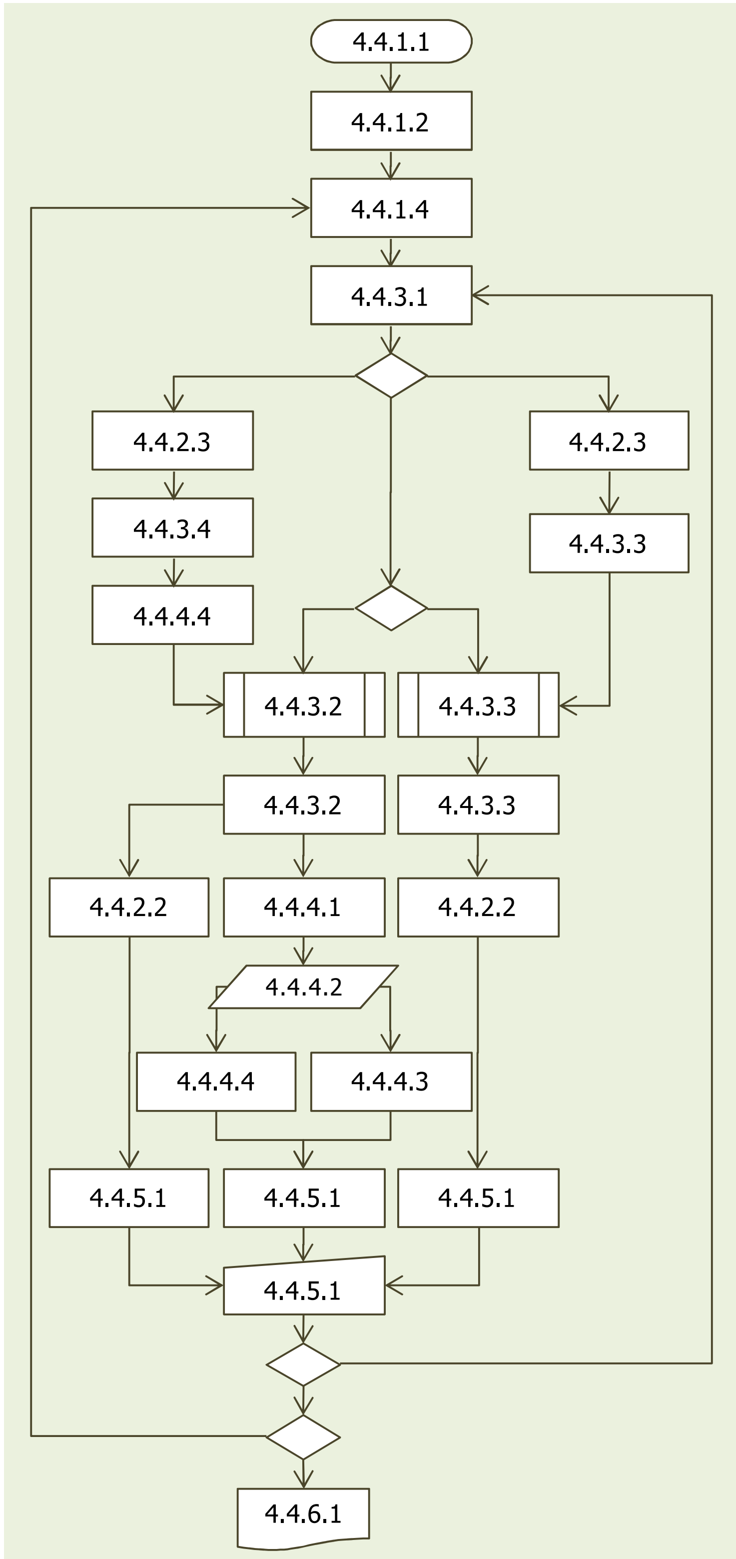


Figure N.1. Mapping METALmpe processes to thesis sections