PROCESS ASSESSMENT FOR THE EXTENDED ENTERPRISE DURING EARLY PRODUCT DEVELOPMENT USING NOVEL COMPUTATIONAL TECHNIQUES

by

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Abstract

Manufacturing practices have evolved over the last quarter of a century in the light of changes to manufacturing technology and demand. To sustain this growth companies are increasingly focused on better design and quicker time to market, to stay one step ahead of the competition. Expanding technology capabilities have included microcomputers and telecommunications. In particular the Internet has allowed businesses to trade with an extended customer base, resulting in a greater demand and perpetuating the cycle. To mirror this statement, businesses are looking increasingly far and wide for suitable suppliers.

This work identifies a need in the market for an Internet based supplier selection function, during early product development. The development of this work differs significantly from other process selection methods by the use of the Internet to link companies. It has advantages for product development relating to the scope of the opportunities, diversity of possible manufacturing operations and rapid assessment of processes.

In particular the system can be broken down into two main functions, Process Selection (PS) and Factory Selection (FS). The PS method presented enables many processes to be modelled, in multiple organisations for a single product. The Internet is used to gain access to supplier facilities by adopting the same principles as on-line banking, or shopping, for data input and access. The results of these assessments are retained by the system for later analysis. The FS method utilises this data to model and compare supplier attributes, allowing the user to manipulate the data to fit their requirements. Testing of the system has proved encouraging for many operations, including Injection Moulding and CNC Machining.

It can be concluded that the identification of manufacturing operations outside the remit of companies' normal scope will create further opportunities for supplier integration.

To my entire family,

Declaration

I hereby declare that this thesis is a record of undertaken by myself, that it has not been the subject of any previous application for a degree, and that all sources of information have been duly acknowledged.

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I wish to express my sincere thanks to my supervisors, Professor Paul G. Maropoulos and Dr Ian Carpenter, for their advice, guidance and professional dedication throughout this research. Your patience and time spent editing this thesis has been invaluable.

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Notation

Symbol	*Description*	*Units*
M_c	- Manufacturing cost	(£)
V	- Volume	(m^3)
C_m	- Material cost	(£/Kg)
R_c	- Relative cost coefficient	(£/Kg)
P_c	- Processing cost coefficient	-
T	- Processing time	(sec.)
β	- Processing tooling cost	(£)
$\propto$	- Setup time	(£)
N	- Number of operations to be considered	-
f	- Material percentage loss	-
ω_n	- Pro-rated total batch weight	-
R_L	- Relative labour cost	(£)
CD	- Cost associated with design	(£)
CL	- The cost of logistics and transportation	(£)
CI	- The cost of inventory to support product	(£)
D_m	- Material cost per part	(£)
H_n	- Number of tooling changes required for a given quantity	-
Q	- Quantity	-
H_o	- Number of operations between tool and die changes	-
P_a	- Actual production rate for a given operation	(parts/sec.)
P_s	- Ideal production rate for a given operation	(parts/sec.)

S_p	- Number of set-ups required	-
T_p	-Process time per part	(sec.)
T_t	-Tooling time per set-up	(sec.)
I_p	- Internal transportation time per part	(sec.)
V_p	- Total volume of parts	(m^3)
IT_v	- Maximum volume of transportation mode	(m^3)
IT_d	- Internal distance between operations	(m)
IT_s	- Internal transportation velocity	(m/s)
F_r	- Factory cost per part	(£)
T_p	- Total processing time	(sec.)
F_f	- Factory cost rate	(£/hr)
F(x)	- Probability density function of cost, quality and delivery	-
μ	- Distribution mean of result set	-
σ^2	- Variance of result set	-

Chapter One

Introduction

1.1 Background

The desire to manufacture a product to a specific quality, within a designated time frame and to a minimal cost has been the driving force governing product development for a number of years. Over the last few decades Japanese manufacturing techniques and practices have been viewed as the benchmark for production, for the rest of the world.

The need for companies to be more competitive, and hence to survive, has focused their attentions inwards towards their own internal capabilities. The implementation of new manufacturing technology has been aimed towards minimising operating costs, thus streamlining production operations (Savsar, 1996). As companies attempt to reduce costs further, additional pressure is exerted on the extended enterprise to reduce their operating costs and improve quality to retain market share.

To compound the issue of manufacturing competitiveness, there has been a shift away from the general trend of continuous production. The idea that buffer stock may be used to control the demand and supply of products is no longer commonplace. The costs associated with large quantities of Work In Progress (WIP) are outweighed by the drive to streamline the organisation. The name given to this transfer in organisation is Just-In-

Time (JIT) manufacture, whereby the quantity of work processed through the factory is specific to an order. This has meant that suppliers need to be increasingly flexible, to change their product and operation parameters to suit customer requirements. One of the most significant results of this procedure is a reduced time to market (Freeland, 1991). This is achieved by the correct scheduling of operations to ensure that products are dispatched after the final operation. Benefits include lower stock levels and increased operation flexibility. It has been observed that the general trend of companies during the last 10 years has been to move away from vertical integration. That is, non-critical component manufacturing is transferred from in-house facilities to supplier facilities. Thus, it becomes increasingly important for suppliers to meet the customers' deadlines. Due to the JIT philosophy, where a reduced stock control system is operated, shortages result in the failure of an entire production run. A 'Traditional' system would have resulted in a stockpile being utilised whilst a machine was being repaired or replaced.

This thesis aims to develop a manufacturing process selection support system for the extended enterprise, to be adopted during the early design phase of a project. It is proposed that it should be possible for the design engineer to manipulate the manufacturing capabilities of the supply chain. It is further proposed that the design engineer should be able to determine the optimal manufacturing process required to produce a specified design, by considering multiple suppliers.

To facilitate a system for process selection, this work requires information concerning methods for manufacturing process costing, to achieve a model for supplier process selection; internal and external transportation, to model both the movement of material within the factory and between factories; and supplier relationships, to appreciate the complexities of supply chain management.

Ultimately the focus of this work has been greatly overlooked by current research, and it is therefore difficult to be overly critical about much of the research carried out into supply chain management. The broad theme of supply chain management can focus on any particular facet of supply, i.e. transportation flow, production flow, supplier relationships, or globalisation. All of which are of interest to this work, but do not capture the essence of early supplier interaction.

1.2 Product Development

Traditional product development allows the designer a *free hand* in terms of the design of a product. This can cause problems for production engineers who are responsible for transforming the design into a working product. This may not always be possible due to manufacturing constraints. It is at this point that a consultation period between the design and production departments begins. In today's volatile manufacturing environment it is no longer acceptable to protract this process, since valuable lead-time may be wasted. Production engineers are often able to influence the design by informing the design engineers of different manufacturing techniques. Therefore, it is logical to assume that their knowledge should be considered when determining the initial optimal solution for a given problem. Introducing the suppliers into the design process will enable alternative manufacturing operations outside the remit of the manufacturing organisation to be considered. The design and manufacturing elements of a company can no longer be considered as independent entities.

This collaboration refers to the initial outlined problem of company integration and Concurrent Engineering. The *traditional* method of placing an order and then expecting a delivery on a specified date is no longer applicable, based on the time required to develop a manufacturing process or technique. The tendering period a company must wait prior to receiving an order is decreasing. This is due to the necessity of the company to get its product to market more quickly.

1.3 The Importance of Concurrent Engineering

The initial design of a product is the most important phase of its design life cycle. It is considered that approximately 80% of the production costs of a product are determined in the first 20% of its design life cycle (Whitney, 1986). Thus, for this reason the designer should be supplied with the correct manufacturing information from the start of the project. By combining the design phase of the product life cycle with manufacturing knowledge, it is possible to facilitate the design process. Such a process is known as Simultaneous Engineering or Concurrent Engineering (CE).

The *traditional* design process can be described as a set of individual predetermined stages. This *traditional* step-by-step process has certain benefits. For example, it is easier to control and manage a design project, since each phase can be completed prior to the next phase beginning. The main disadvantage of this method is that it can be time consuming and costly. The aim of CE is to formalise and build structure into the design of a product. This is different to the traditional method of 'over-the-wall' manufacture, where the responsibility for the project is passed sequentially between the design and manufacture departments. Many new techniques have been adopted to facilitate CE, including Design for Manufacture and Design for Assembly, which are just two of the most popular techniques. In addition, another possible benefit of such a philosophy is the ability to reduce the time to market. Further, if the product routing has been considered as part of the assembly process, then this may increase the flexibility and agility of the design.

As mentioned above, there is a requirement for clear and concise information to be supplied during the design process. The methodology of CE proposes that by collaborating information between departments and supplier companies, at varying times in the design life cycle, it may be possible to design a product that requires fewer design modifications. This can be achieved by the integration of the supply chain.

1.4 Supplier Relationships

From the discussions above, it should be evident that suppliers play an important role in the design of a new product. The decentralisation of production operations and the minimising of in-house manufacturing fuel this relationship. It is now considered that it is no longer possible to design and build a product efficiently, without the use of external suppliers (Norwood and Mansfield, 1999).

Suppliers can be considered as either, internal or external. Internal suppliers are those suppliers that are related to the same parent company and are used as a central source for a particular operation. For example, Plastic Moulding capabilities that are expensive to purchase may therefore be used by many sources. The external supplier is not related to the factory but can be used to source sub-assembly parts or raw materials.

Recently, significant volumes of work, including that of Evans and Towill (1995), Harland (1995) and Lee and Sasser (1995), have been undertaken into supplier relationships, much of the work has focused upon the production phase of the relationship. This encompasses the Just-In-Time philosophy of product flow, production times and quality. Additionally, a significant proportion of the work considers the economic batch size of a product.

Another area of interest is the relationship formed between the suppliers and customers, regarding design integration. It is apparent that if the CE philosophy is to be widely adopted, then suppliers should be incorporated into the design process. However, the questions remain; what information does the supplier require to generate a factory model? And what information does the customer require from the supplier for process selection?

These issues are extremely delicate, since they may require the transfer of company information, often restricted for commercial security reasons. In modern manufacturing, if smaller companies supply large companies, then the operations performed by a Small to Medium sized Enterprise may constitute a substantial proportion of the supplier's total production capability. Therefore, it is possible for customers in this position to influence the profit margins and batch sizes of the supplier. These factors would be laid out in a contract between the two parties prior to any collaboration.

1.4.1 Requirements of a Supplier Relationship

Any partnership developed between two companies is required to address a number of different issues. From the customer's perspective the issue can be considered as *"to provide a quality service in a specified time"*. This is the *traditional* view, such that little consideration is given to how the supplier should achieve the required objective. The main concern is that the supplier should deliver on time. The relationship has a number or different requirements, these are:

- That both parties are mutually benefiting from the collaboration.
- That realistic objectives are set.
- That trust and security can be gained from the relationship.

If all of these factors can be met then it may be possible for a successful relationship to be formed.

1.5 Supply Chain Classification

To obtain a clear picture of a company's capabilities the identification and analysis of the company's supply chain is required. The supply chain formats can be observed at an abstract level, which is useful since the information can be used to identify material flow between separate factory locations. The advantage of identifying the supply chain formats is that it is possible to determine whether there are any elements of the supply chain that are surplus to requirements, due to duplication of resources. This is a simplification of the problem to be addressed across the entire supply chain. In a 'real world' situation it should be noted that most manufacturing companies have a combination of different supply chain configurations.

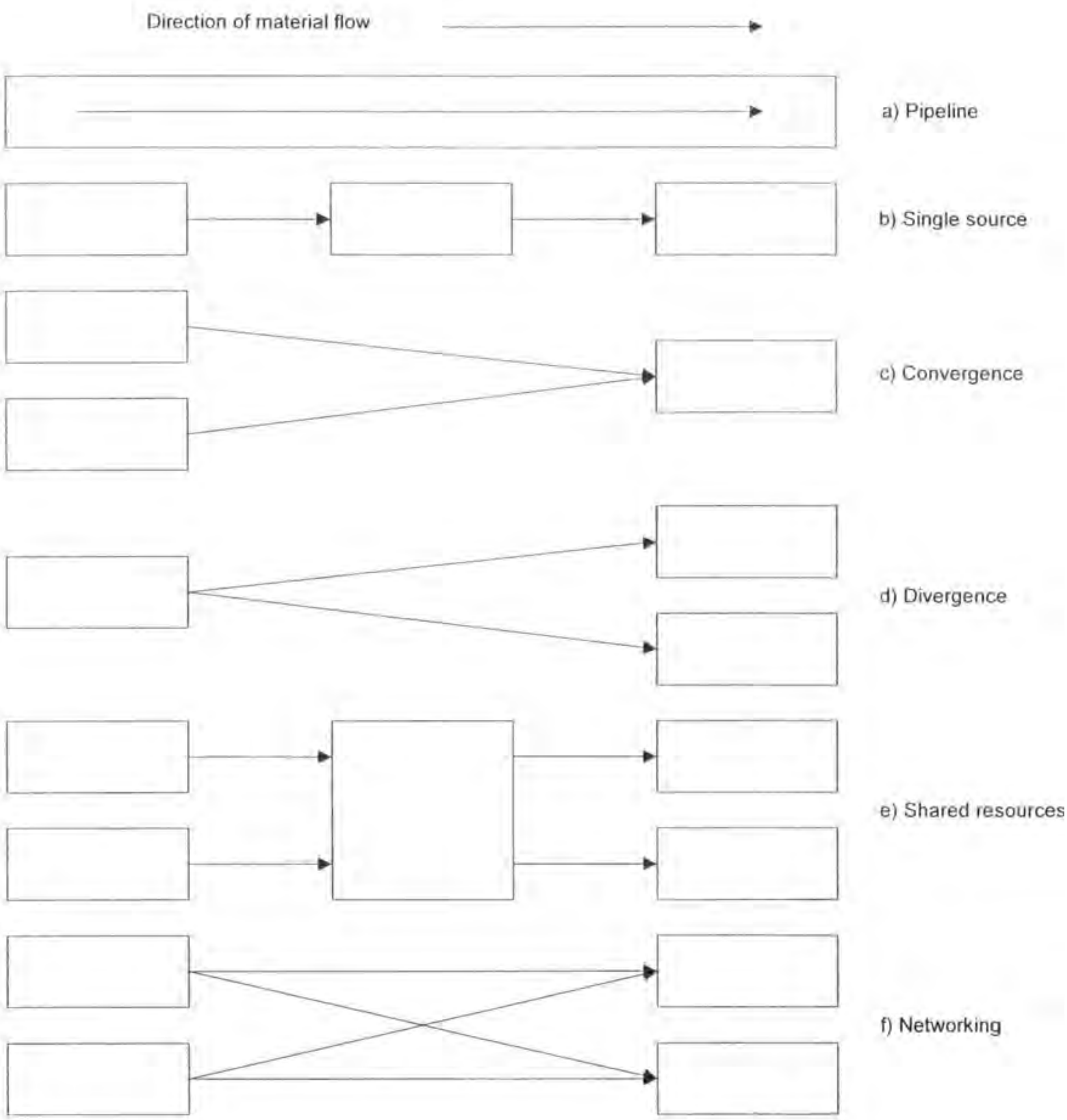

Figure 1. Supply chain configurations (Hoeskra and Romme, 1992).

The basic supply chain formats were developed by Hoeskra and Romme (1992) and are illustrated in Figure 1. Considering Figure 1a, it can be seen that the general format encompassing the entire supply chain is termed a *Pipeline*. This format does not accommodate the flow of information/material between locations. An example of this format would be drive-thru restaurant, whereby placing the order, paying the money and collecting the goods is considered as a single operation. Realistically this is not accurate, since it does not accommodate the supply of raw materials into the operation. The *Pipeline* format can therefore be regarded as an ideal solution and not reflective of a real world operation. The simplest realistic model is the *Single Route* (Figure 1b). The *Single Source* model has both a single entry and exit, but identifies sequential operations within the chain. It is considered that the fast-food restaurant chain operation is an example of this format. All stock is delivered from a *Single Source*, being the parent depot and over the counter service being the only outlet for the operation. However, in real terms the majority of companies supply chains are significantly more complex. The following are examples of complex supply chain configurations. Figure 1c illustrates an example of supplying from many-to-one. This format is referred to as *Convergence*, for example a manufacturer who sources parts from multiple suppliers. Figure 1d illustrates the opposite format, this is supplying from one-to-many, an example of which is a steel mill. Raw material production from the single location is then transferred onto multiple customers. This format is known as *Divergence*. Figure 1e is known as *Shared Resources* or Group Technology that is grouping together of unrelated products and deliveries and the redistribution in different loads of the items. An example of this format would be a transportation depot, where regional loads are grouped together at a single source where they are sorted and later released to different locations. The last of the supply chain configurations is *Networking* (Figure 1f), this relates to suppliers with multiple customers visa-versa. In essence this format might relate to either the real world situation of a manufacturer or retailer, where the products are distributed to multiple customers. From the customer perspective, the multiple suppliers that are required to facilitate the business activities.

It should be stated that the configurations *Shared Resources* and *Networking* can be described as extended combinations of the configurations *Convergence* and *Divergence*. However, in order to correctly model these specific supply chains the model needs to be applied in its general real world format. This allows for a structured integration across the supply chain. Hayes and Wheelwright (1984) claim that companies may justify backward integration, that is, investing in supplier capabilities *"to develop competence in the technology of a critical component, to develop proprietary products, or to stay abreast of technological changes"*.

1.6 Aims and Objectives

The objectives of this research are as follows:

1. To assess previous methods used for the generic process selection problem and outline process selection requirements for the extended enterprise.

2. To develop a manufacturing process data model to accommodate generic manufacturing process information. The manufacturing process families of casting, moulding, machining and fabrication should be represented within the system.

3. To develop methods for Process Selection of the supply chain using the defined manufacturing process data model and to expand the Factory Selection method.

4. To implement the methods for Process Selection. It is proposed that this should include a factory model generation package for developing new factory manufacturing process data models.

5. To evaluate the implemented Process Selection and Factory Selection methods using data gathered from industrial collaboration.

1.7 Thesis Overview

Chapter 2; the literature review presents previous relevant work. The work focuses on the issues of Concurrent Engineering, Product Modelling, Process Planning and Supply Chain Management. Also included is information on production and manufacturing management, scheduling and accountability.

Chapter 3; the system overview chapter is developed to firstly explain the methods and then the program principles of the computer system that has been created to implement the methods. The type of computer software and hardware are also discussed.

Chapter 4; the manufacturing process data generation chapter outlines the process and factory data required for this research. The manufacturing data comprises a framework for data collection and data storage. The factory data includes both internal transportation and overhead details and external transportation considerations.

Chapter 5; the process selection chapter provides an overview of the Process Selection method. The suggested process and resources model is implemented. Further, consideration is given to the external factors governing the supply chain management.

Chapter 6; the factory selection chapter demonstrates the supplier selection problem. The implementation of the manipulation methods is discussed.

Chapter 7; the testing and results chapter presents a methodical overview of the proposed methods. Furthermore, case studies are compiled to demonstrate and confirm the methods using industrial data. A comparison also provides a comparison of software predicted results to industrial data.

Chapter 8; the discussion and conclusions chapter presents a summary of the results and reaffirms the aims and objectives outlined in Chapter 1. An outline for further work proposes both modifications to the given methods and topics of interest raised during this research.

1.8 Summary

It is considered that a large amount of information is required for the successful launch and maintenance of a product. The concept of Concurrent Engineering has been identified as being an influential factor in manufacturing. This in turn has expanded to include the activities of the extended enterprise. Additionally process modelling and product modelling are considered to be of interest, together with the physical transportation problem.

Chapter Two

Literature Review

2.1 *Introduction*

This chapter discusses the literature relating to the integration of manufacturing capabilities across the extended enterprise during early product design. This topic is often missed by current research, relating to product development. Therefore the general themes are required to piece the problem together.

In particular, the topics relating to the requirements of Supply Chain Management (SCM) and the integration of Concurrent Engineering are discussed. To support these focal themes, current methods for Process Selection (PS) and Production Transportation are discussed as being of particular interest. Additionally, Operational Research relating to the implementation of this work, the principles and requirements for software communication and the security of data transfer are discussed. Peripheral topics concerning data handling and management are also included.

2.2 *Supply Chain Management*

Common to all manufacturing companies, regardless of size, type of product or manufacturing process, is the need to control the flow of material from suppliers, through manufacturing to the customers (Stevens, 1989). Traditionally the flow of material has been considered only at an operational level, at best driven by efficiency improvements and cost reduction, at worst abandoned to the demands of a rapidly changing competitive environment.

To gain a competitive advantage, buyers should not rely on the adversarial approach to supplier management. The adversarial approach can be described as 'Over-the-wall', whereby information is passed between divisions but no collaboration exists. Short-term contracts, price-driven negotiations and the threat of future supply are likely to endanger the commitment from suppliers. Good purchasing practice demands that a buyer seek multiple bids from suppliers to be assured of a competitive price. The buyer allocates sufficient orders to suppliers to maintain their interest. While this approach often results in lower purchase prices, it assumes that there are no differences in suppliers' abilities to provide value-added services. Such behaviour does little to encourage long-term co-ordination or co-operation between buyer and supplier. The move away from traditional management has transferred the focus from the prices based criteria to other performance criteria such as quality and delivery.

Historically managers have seen their responsibility lying only within their department or division. Increasingly they now have to look beyond this traditional internal view to accommodate supplier functions. As operations are focused towards defined core abilities there is a move to outsource more materials and services (Harland, 1995). The importance of the extended enterprise to a business has increased. Beyond the immediate supply chain there is an opportunity for strategic benefits to be gained from managing the flow of information and goods between customers and suppliers. When managers have sought to control the product flow they have found that they can obtain speed, dependability, flexibility, cost and quality benefits. In large organisations there may be numerous channels through which goods and services flow. These channels are more generally known as supply chains. A complete supply chain can be viewed as a flow of water; organisations situated closer to the original source are described as 'upstream' and those located closer to the end customer are described as 'downstream'. Purchasing, supply and physical distribution relate only to single elements of the supply chain. Inter-company operations management is more commonly termed supply chain management. Supply chain management is the term adopted to control purchasing and production operations throughout the supply chain. Supply chain management has been developed into a concept with a much broader span of concern and a holistic approach to managing across company boundaries (Inger, 1995). It is recognised that there are substantial benefits to be gained from strategically trying to drive a whole chain in the direction of satisfying the end customer.

Barbuceanu (1997) reports on the use of co-ordination technology to model, design and simulate globally, distributed supply chains. It is shown that supply chains can be naturally modelled, simulated and improved in this way, within a short development time. The hypothesis that was tested is that in general co-ordination technology is adequately efficient for supply chain analysis and design, given that closed form analytical solutions are too difficult for complex multi-tiered structures like supply chains.

2.2.1 Supply chain integration

As manufacturing products become more complex, their design and manufacture demands increasing amounts of resources that are shared between the companies that have entered into the joint venture or commercial agreement (Norwood and Mansfield, 1999). Competition is being typified less by firm versus firm and more by supply chain versus supply chain. Bhattacharya *et al.*, (1996) suggested that a company has to adopt a more proactive approach in order to reach the strategic position that they desire. The degree of supply chain complexity may be determined by the number of inventory's through which materials, semi-finished goods and finished goods have to pass on their path from supplier to the customer. Jones and Clark (1990) described an "Effectiveness framework" designed primarily for first tier suppliers that can influence the rest of the supply chain. It is suggested that other partners may benefit by using the methodology to understand their individual role. There has been a continuing shift in the shape of business structures from vertically and functionally aligned to horizontal, process oriented, and most importantly customer focused (Evans *et al.*, 1995). The role of supply chain management from a system engineering view is also highlighted.

Many companies outsource a wide variety of materials and services. Typically the volume and value of these purchases are increasing an organisation's value, allowing them to concentrate on their *core* functions. There are some underlying objectives of purchasing which are true for all bought materials and services. These have been termed 'the five rights of purchasing'; at the *right price,* for delivery at the *right time,* for goods and services to the *right quality,* in the *right quantity,* from the *right supplier* (Ellram, 1990). These factors can then be related to the departments that are responsible for fulfilling the demand. Purchasing and supply management are recognised terms in business practice for the functions that deal with the operational interface with its supply markets. Physical distribution management is a well-accepted term for managing the operation of supplying immediate customers (Balinski, 1961). Logistics is an extension of physical distribution management and usually refers to the management of materials and information flow from a business through a distribution channel, to end customers.

Increased competition from global competitors, shorter product life cycles and rapidly changing technologies have forced customers to search for suppliers whose expertise and competence can be utilised. In this *quiet revolution*, buyers develop closer, more collaborative ties with fewer suppliers than traditional supply chain's. Companies simultaneously seek supplier input at earlier stages in product development and divulge more long-term information with their suppliers. Spekman (1988) suggested that, "strategic partnerships are increasing". In many industries such as motor and aerospace, collaboration is essential. Eloranta (1995) states that, "*Europe has a desperate need for effective and flexible innovation, improving industrial infrastructure where the most value-added nodes of the supply chains are those in the roles of subcontractors and distributors*". Additionally it was estimated that by responsive customer-driven supply chains the profitability of these chains could be improved drastically. This potential for improvement is based on the reduction of inventory-carrying costs, reduction in indirect and direct labour costs and the increase of sales and sales margins. This can be achieved via better delivery performance at the operative level and reduction in time-to-market at the tactical and strategic levels (Evans *et al.*, 1995).

Ellram (1990) developed additional factors that should be considered in the selection of supply partners. Four categories of additional factors are suggested, financial issues, organisational culture and strategy, technology and a group of miscellaneous factors. It is stated that the issues included in these categories tend to be longer term and more qualitative than factors included in traditional supplier selection models. Also Ellram suggests that these additional factors supplement, rather than replace the more traditional factors in developing strategic partnerships with suppliers.

Field research investigating the relationship between the positions of a company within a supply chain, to 'behaviour' is described by Harland (1995). The study proved that, upstream relationships contained more customer dissatisfaction and more misperceptions about performance than did downstream relationships. Delivery performance was identified as the major cause of these problems. Upstream players appeared to be less customer oriented in their cultures than downstream businesses. In the supply chains, customers were more dissatisfied with delivery performance than any other operation performance dimension. Aderohunmu (1995) shows that a co-operative batching policy, based on cost information exchange between vendors and the buyer, can reduce total cost significantly in the Just-In-Time (JIT) environment. The study showed that joint optimisation of both the vendor and the buyer's operation does not necessarily result in a common lot size. Additionally, Chapman and Carter (1990) and Aditham *et al.*, (1997) showed that strong supplier/customer linkage and fast communication of engineering to the supplier, are very important for efficient just-in-time operation.

2.2.2 Benchmarking

An insight into benchmarking procedure is provided by Lewis and Naim (1995). The critical importance of obtaining aftermarket supply chain excellence is identified. The new customer places greater emphasis on the received service, such as reliability, punctuality and efficiency, in order to rank their satisfaction of the services from their suppliers. It is suggested that the key to providing high levels of customer satisfaction is dependant upon providing what the customer wants (well designed service), when the customer wants it (well delivered service).

Results are described for a benchmarking study performed by Cooper *et al.*, (1995). It is reported that a company's overall new product performance depends on a number of elements relating to the New Product Development (NPD) process. These include the organisation, strategy, culture, climate for innovation and senior management commitment. The study incorporates performance measures of an NPD program including, success rate, percent of sales, profit objectives, technical success, sales and overall success. The conclusion drawn was that the number one driver for performance was a high-quality new product process, followed by a clear and well-communicated new product strategy for the company, along with strategic focus and synergy. Three observations can be made of the functional relationship between profitability and market share. First, small-share businesses are not typically less successful than larger business units. In the service market and the market for raw or semi-finished materials small-share businesses are just as profitable or even more profitable than larger business units. Second, some businesses are 'stuck in the middle', most noticeably in the service market but not in the retail and wholesale markets. Third, very large-share businesses are often less profitable. A critical market share is identified at between 65 and 70 percent. Beyond this the level of the return on investment decreases (Schwalbach, 1991)

The term 'competitive' has been widened to mean more than just the direct comparison with competitors. It is now taken to mean benchmarking to gain competitive advantage (perhaps by comparison with, learning from non-competitive organisations). Small (1995) shows that competitiveness determines our economic freedom and company profitability and begins with clearly identifying the market and responding to demand. Becoming fully competitive is a task demanding total commitment and a holistic approach. Really knowing your customer encompasses the quality of your process, the agility of the organisation, the excellence of the offered product, and global performance.

2.2.3 Agility

An enterprise is considered to be agile, or have agility if, *"it has the ability to thrive in an environment of continuous and unpredictable change"* (Ward, 1994). It is observed that there are many companies that are making agility part of the focus of their strategic business plans. Agility builds from much of the current continuous improvements and lean activity (Sharifi and Zhang, 1999). There is much confusion about the difference between lean and agile. A lean company may be though of as a very productive and cost efficient producer of goods or services. An agile company is primarily characterised as a very fast and efficient learning organisation. Having the ability to produce rapidly upon demand requires a quick and resourceful organisation that is quick and resourceful. It requires short lines of communication and efficient information flow throughout the supply chain (Ligus, 1994).

2.2.3.1 Design for Agile assembly

Design for agile assembly is accomplished by considering operational issues of assembly systems at the early product design stage. Kusiak and He (1996) presented three rules applicable to the design of products for agile assembly from an operational perspective. These rules are intended to support the design of products to meet the requirements of agile manufacturing,

1) Design a product to satisfy the manufacturing operations requirements.

2) Design products to simplify the flow of products in a multi-product assembly line.

3) Design new products compatible with the existing production facilities and product mix.

Jung *et al.*, (1996) provide a primary sketch of the architectural requirements for rapid development of agile manufacturing systems (figure 2.1). There are several aspects of system architecture: control, function, process, information, communication, distribution, development and implementation. The reference architecture is suggested to provide a transparent way to the user when they are establishing the computer integrated manufacturing systems. Perry *et al.*, (1999) described a model for the effective communication and information flow necessary for agile alliances. Information sharing instead of information flow is identified as being of crucial importance to the successful outcome of the program.

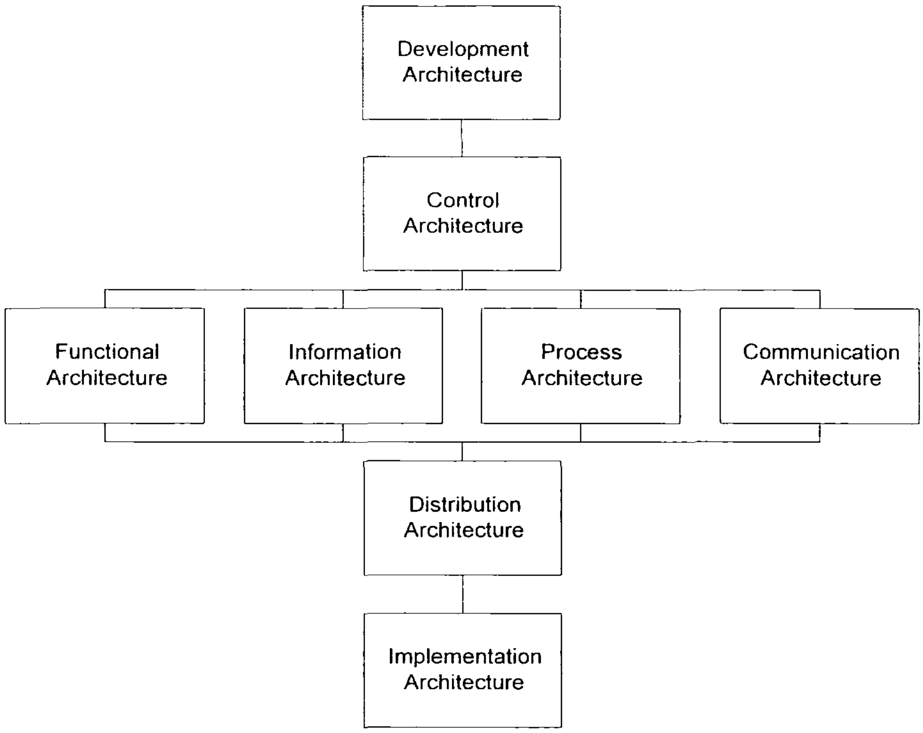

Figure 2.1: Architectural requirements for rapid development of agile manufacturing systems, Jung *et al.*, (1996)

2.2.3.2 Human Factors

The human factors related to the communication and information infrastructure essential to an organisation making the change from traditional to agile product development are summarised by Forsythe (1997). As shown in Table 2.1, an agile enterprise differs greatly from that of traditional enterprise. Forsythe reports that by highlighting human factors issues, and applying the knowledge and skills gained from other domains, there is an opportunity for human factors to assume an important role, positively influencing the future of agile manufacturing.

Table 2.1 General differences between Traditional and Agile Enterprise (Forsythe, 1997)

Traditional Enterprise	**Agile Enterprise**
• Geographical collocation	• Geographical separation
• Solitary work	• Collaborative work
• Sequential information flow	• Parallel information flow

Time is negotiable	Time is critical
Standardisation of technology	Opportunistic technology use
Artefacts relatively static	Artefacts change rapidly
Information flow correlated with organisational structure	Information flow correlated with project structure
Extensive use of hard media	Extensive use of electronic media
Constant, known, internal supplier of information	Diverse, often unknown, external supplier of information
Many indirect lines of communication	Mostly direct lines of communication

2.2.3.3 Enabling technologies

When compared with computer integrated manufacturing, 'agile' manufacturing can be defined as the capability of surviving and prospering in a competitive environment of continuous and unpredictable change be reacting quickly and effectively to changing markets, driven by customer specified products and services (Cho *et al*, 1996). Critical to this success are a few enabling technologies such as Standard for The Exchange of Products (STEP), Concurrent Engineering (CE), Virtual Manufacturing, information and communication infrastructures. Cho reports that manufacturers must put a stress not only on high quality, productivity and reduced costs, but also on the ability to react quickly and effectively to changes in markets, production technologies, and computer and information technologies.

2.2.3.4 Flexibility

The term flexibility means being able to change or adapt manufacturing operations in some way. This may mean changing what the operation does, how it does it, or when it does it. Specifically customers will need the operation to change so that it can provide four types or requirements: product/service flexibility - different products and services, mix flexibility - a wide range or mix of products and services, volume flexibility - different quantities or volumes of products and services, delivery flexibility - different delivery times. Large companies are discovering that size is not always a virtue in today's marketplace. These companies would like to have the flexibility and focus associated with small companies while maintaining the underlying strength of resources of the large company (Calvin, 1995). The identification and leveraging of core capabilities across the business structure are vital to its continuing success. Kasilingam (1996) determined the capacity requirements for flexible manufacturing systems. Additionally Weng (1998) presents a production control policy based on the planned lead-time and the manufacturing capacity requirement. The model provides a vehicle for examining the interrelationships among the production output, the planned lead-time and the actual manufacturing flow time.

Flexibility is becoming a key dimension of firm's competitive priorities. Chen and Chung (1996), takes the first step in investigating the relationship between flexibility measurements and systems performance in the Flexible Manufacturing System environment. Several alternative measures are suggested for the assessment of machine flexibility and routing flexibility. The results indicate that flexibility improves system performance at a decreasing rate, and routing policy as well as operating conditions could have critical effects on the magnitude of performance improvements. Steke and Raman (1995) consider the role of system planning in determining operating flexibility and system performance. It is argued that while the overall flexibility of any system is constrained by decisions made at the system design stage, the realised short-term flexibility depends significantly also upon planning decisions made during pre-production set-up. Different planning objectives lead to different system configurations, and simultaneously yield varying levels of process-oriented flexibility. A classification scheme for different types of flexibility is also presented. This is then used to give an illustrative comparison of conventional and flexible methods. Boyer and Leong (1996) focused on two methods for increasing the flexibility of the manufacturing plant so that production can be varied more easily to match the change in demand. Firstly process flexibility is defined as the ability of a single manufacturing plant to make more than a single product, it is shown that a limited degree of process flexibility is valuable in dealing with variations in demand. Secondly, machine flexibility is defined in terms of a changeover cost. This is measured in terms of the capacity of production that is lost, when a plant must produce more than a single model. Machine flexibility is shown to have a moderating effect on process flexibility, but one that does not necessarily cancel out the benefits of process flexibility.

The performance measures required to induce change in production flexibility are clarified by (Takhashi *et al.*, 1994). The flexibility of production orders in systems as medium range production control systems are studied. By simulating the models, the amplifications of production quantities and inventory levels as flexibility measures for each type of production ordering system are analysed and the flexibility compared

Cho *et al.*, (1997) presents an experimental design developed to determine a combination of robust planning and scheduling rules for an Intelligent Workstation Controller. At the top level is the shop controller that receives orders and their associated manufacturing information, and manage interactions among workstations. The Intelligent Workstation Controller defines and resolves the production control activities necessary to co-ordinate a group of equipment controllers so as to ensure the completion of orders. Specifically, the Intelligent Workstation Controller is responsible for selecting a specific process routing for each part, allocating resources, scheduling and co-ordinating the activities across the equipment, monitoring the progress of activities, detecting and recovering from errors, and preparing reports, Flexible Manufacturing System scheduling strategies are explored further by Lui and MacCarthy (1997). The results showed that the best planning and scheduling strategies are Batch with Minimal Loss and multi-pass techniques for most performance criteria.

2.2.4 Discussion

A diverse range of supply chain management issues has been presented, the most relevant topics being supplier integration, physical distribution, capacity and flexibility. Other reviewed areas have illustrated the broad nature of work relating to supply chain management.

Much of the work relating to supply chain management is strategic, presenting models for a structured supply chain. Illustrating how best to work with, and not dictate to suppliers. It is accepted that cost is not necessarily the only measure of performance. Further, Spekman (1988) stated that the standard terms of cost, quality and delivery are not sufficient for a strategic partnership. Instead including raw materials and components as additional factors. This view is acknowledged, but this cannot realistically be implemented at the conceptual phase of design, where only partial product data is known. For partial product data, the standard terms of cost, quality and delivery would achieve a basis for manufacturing process selection.

Work relating to flexibility presents useful ideas for innovative operational principles and supporting information (Eloranta *et. al.,* 1995). What the work does not address is the question of innovative products and manufacturing solutions, thereby avoiding early product development. It is considered that the early identification of manufacturing processes during product development would add additional flexibility to the operational principles.

Supplier integration goes beyond the purchasing and supply management of a relationship, to also include inventory, logistics infrastructure and materials management. Research has focused on how to either achieve a strategic partnership or classify a strategic partnership (Ellram, 1990 and Harland, 1995). No previous work has addressed the optimisation of supplier capabilities during early product development. In particular focusing on what type of relationship should exist to facilitate data exchange, or what data transfer capabilities are required between suppliers and customers to integrate suppliers.

2.3 Distribution Management

Distribution management or 'the transportation problem' has been modelling in varying forms for many years where considerations for application differ. Much work has been done on the timber industry modelling the transportation of cut timber. Harbel *et al.,* (1997) state, *"On the demand side of the organisation, products and services need to be 'communicated' or moved to the customer. In the case of manufacturing operations, this involves the physical transportation of the goods from the manufacturing operation to the customer".*

2.3.1 Production transportation problem

The Production Transportation Problem (PTP) is a generalisation of the transportation problem, from single supplier and single customer to multiple levels of supply. In PTP not only are the level of shipment from each supplier to each customer of interest, but also the level of supply at each supplier. A production cost is associated with the assignment of supplies to suppliers. The objective function of PTP is the sum of the linear transportation costs and the production costs. There is much literature on the problem of extending the classical, finite number of origins and destinations. This approach has appeared in books such as Anderson and Nash (1987) and there have been many applications in probability and statistics.

The single-customer fixed charge transportation problem is investigated by Herer *et al.*, (1996). Various forms of problems are considered, including the supplier selection problem, the product distribution problem and the process selection problem. Implicit enumeration procedures are developed to solve this problem. These procedures include both domination rules and lower bounds. The methods are tested against pre-existing procedures and thereby demonstrate that problems that are previously computationally intractable can be easily solved. Harbel (1991) presented a branch-bound algorithm for solving a fixed-charge linear programming problem involving identical fixed charges, one equality constraint and explicit bounds on the variables. The motivation for this study is presented in the form of a sawmill problem. For an order assortment of a definite number of planks, to be produced with maximum profit from a given amount of logs of a given length, taking into consideration the costs of set-ups, the qualities of the logs, and the quality of the order assortment. An algorithm is presented for solving the special fixed-charge linear programming problem with identical fixed charges. Additionally Balinski (1961) formulated a fixed-cost transportation problem as an integer program, described some of its special properties, and suggested an approximate method of solution. Cooper and Drebes (1967) propose two heuristic methods to solve the linear programming fixed charge problem. The results indicate that the heuristic methods produce optimal solutions in well over 90% of the problems investigated. Hence it should be of practical significance to practitioners in the field.

Kerantek and Yamasaki (1995) explain that the finite PTP is extended to an infinite one having a countable number of origins and destinations. A constructive approximation procedure is given for obtaining program values arbitrarily close to the infinite program value of the problem. Shi (1995) presents a mathematical model using linear programming to solve the transportation model with multiple criteria and multiple constraint levels. The algorithm is adopted to find the basic feasible solutions. A number of research problems are indicated. From a computational point of view, large-size problems, another problem is constructing contingency plans for each potential solution.

2.3.1.1 The Simplex Method

In the standard form of the linear programming problem, the structural constraints are a system of linear equations. Any solution is a feasible solution to the linear programming problem if it also satisfies the non-negativity constraint, and an optimal solution is one that achieves the objective. It would be an enormous task searching the infinite set for an optimal solution by trial and error (Kortanek and Yamasaki, 1995).

For a given problem with m constraints and n variables, with $m<n$, the total number of possible basic solutions is given as equation 2.1 :

$$C_m^n = \frac{n!}{m!(n-m)!} \tag{2.1}$$

There are therefore at most an infinite number of basic feasible solutions. The simplex method further reduces the scope of the search for an optimal solution by periodically limiting it to the set of basic feasible solutions with 'better' objective function values than the one at the current iteration.

2.3.2 Distribution planning

To achieve high productivity in manufacturing plants and warehouses, an orderly and flexible flow of material is essential. Pirkul and Jayaraman (1996) developed a mixed-integer programming model for the plant and warehouse location, where the objective is to minimise the total transportation and distribution cost and the fixed costs for operating plants and warehouses. The method is used to allocate production between X plants, with Y warehouses and Z customers. The method employed Lagrange relaxation to the model and also a heuristic method. Additionally a decision support system is presented for strategic issues relating to logistics management (Korpela and Tuominen, 1996). It is noted that a typical strategic planning process is periodic and usually lacks the ability to cope with changes in the operating environment. The developed decision support system is based on a hierarchy. The priorities of the elements at each level are determined and these priorities determine the overall priorities of the decision alternatives.

Son (1994) attempts to solve the inherent problems with productivity by an unconventional use of a linear programming method. Accommodation of such strategic factors as manufacturing quality and flexibility are emphasised. It is demonstrated by linear programming based performance analysis that 'manufacturing' strategy can be the most important business strategy of a company. Wan and Levary (1995) described a linear programming based price negotiation procedure for shipping contractors with ocean containers. The procedure incorporated a solution to a linear programming transportation model with results from sensitivity analysis. The procedure described enables shippers to evaluate all possible means of obtaining the lowest adjusted price for a given shipping route in a short period of time.

The frequencies at which several products have to be shipped on a common link to minimise the sum of transportation and inventory costs is dealt with by Speranza and Ukovich (1994). Tyworth and Zeng (1998) and Johansen and Thorstenson (1998) also present methods for estimating the effects of carrier transit-time performance on logistics costs and services. The aim was to find a rule stating when shipments must take place and how products must be loaded on vehicles, to minimise the overall transportation and inventory costs. Models are proposed for both the *total loading* and *partial loading*, where *total loading* is defined as a unit load or complete loads and *partial loading* is said to be a fraction of a *total load.* It is stated that the greater flexibility provided by *partial loading*, although harmful from the point of view of the inventory, may be exploited profitably to improve the effectiveness with which transportation resources are used. Hall and Racer (1995) developed an approximate procedure for determining whether a stop should be served by a private carrier on a local pickup and delivery route, or by a common carrier. Analytical techniques are presented for systems with (1) fixed shipping cycle for all stops with a variable fleet size, (2) fixed shipping cycle for all stops with a fixed fleet size, and (3) variable shipping cycles with a variable fleet size. The cost approximation does not account for specific customer locations and the fact that some stops will be more costly spaced than others. The techniques presented can be used to select fleet size.

2.3.3 Total production control

The main computer integrated manufacture efforts are in flexibility and productivity improvements, but the implementation stresses the technical aspects of the factory integration, and the most flexible production factor, people, are overlooked. Total Production Control (TPC) integrates the main methods and tools for production system analysis and improvement, production system design and production planning and control (Kosturiak *et al.,* 1995). This concept emphasises a preventive aspect to the problem solution in the production process and supports a production manager at three time intervals, past (archive and statistical database), present (shop floor data capture and production process monitoring) and future (simulation and modelling), see figure 2.2.

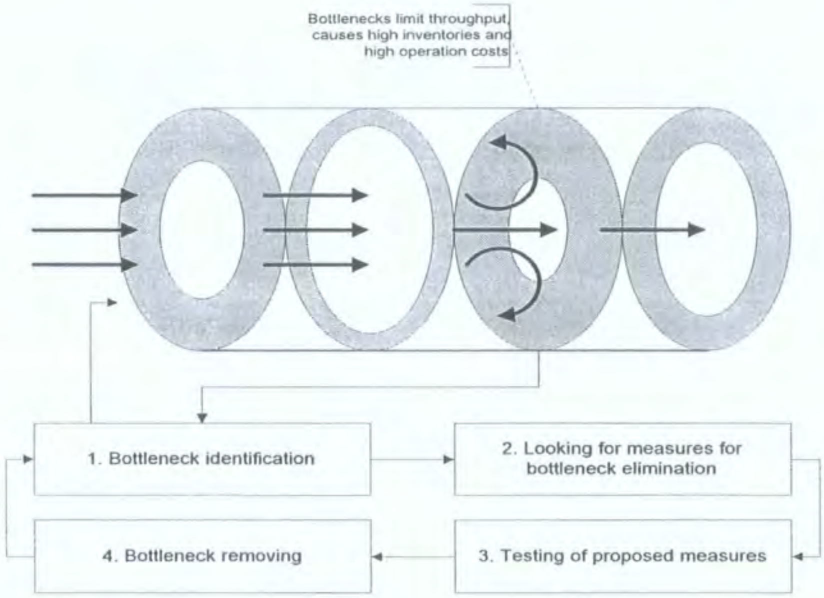

Figure 2.2: Ongoing improvement process (adapted from Kosturiak *et al.,* 1995)

A transport-constrained input-output (IO) and linear programming model is proposed for the purpose of studying the impact of a transportation bottleneck in an economy. In the traditional demand-driven (IO) model, it is implicitly assumed that there are no capacity constraints in the economy (Miller and Blair 1985).

2.3.4 Material handling systems

Since the design of a Material Handling System (MHS) involves large numbers of variables, it is usually accomplished by optimising subsystems in a sequential procedure. Manda and Palekar (1997) reviewed recent research in the design and control of MHS'. Approaches either, assume simple system configurations and determine optimal control policies, or use non-analytical models such as simulation models to evaluate design alternatives.

A method is described for the systematic computer assisted selection of Material Handling Equipment (MHE) (Chu *et al.,* 1995). Where, initially physical requirements are considered for equipment and later economical analysis for each equipment type is performed (see Figure 2.3). Although the MHE system is expert-like it recommends a ranked set of equipment based on user input data.

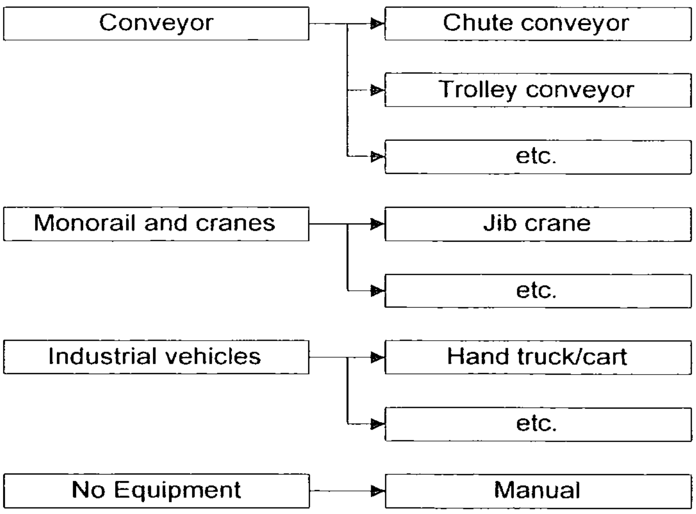

Figure 2.3: Transport equipment subcategorises (Chu et al. 1995)

There are few packages developed specifically for manufacturing planning and control in repetitive contexts. A framework is proposed for the analysis of the characteristics of manufacturing planning and control systems utilised in repetitive contexts (di Toni *et al.*, 1997). The framework describes three basic production control sub-systems, i.e. *planning, inventory control* and *shop floor control.* The proposed model could be useful in diagnosing the correct operating environment. The functions offer daily scheduling capabilities, reduce dependence upon manufacturing order numbers, supply point-of-use material handling support to minimise activity reporting.

Taal and Wortmann (1997) focused on solving the capacity problem by improving capacity planning at the Material Requirements Planning (MRP) level through the integration of MRP and finite capacity planning. This resulted in a planning method for simultaneous capacity and material planning to avoid capacity problems. Buzacott (1997) derives formulae to describe an MRP-controlled system, which is observed continuously. This representation is used to suggest that MRP-type control could be implemented in a distributed manner, with messages passing between stages in the opposite direction to material flow. The messages are related to the occurrence of demand or releases but are advanced in time from the actual demand or release by amounts depending on the lead times.

2.3.5 Internal Transportation

The vehicle routing problem is one of the most important problems in distribution and transportation. A classical technique starts by solving by linear programming relaxation and then uses a branch and bound strategy to find an integer solution to the set-covering problem (Bramel and Simchi-Levi, 1997).

Internal transportation plays a significant role in the capacity constraints of a factory, since the inability to move products efficiently may deter customers. It is therefore beneficial for a new system to utilise this information in any analysis. The factors that are of concern include; at what velocity do products move around the factory? What volumes of products need to be moved to make the process most efficient? What is the cost rate for any given operation?

Previously, there has been a considerable amount of work on the transportation issue. Internal transportation has special requirements relating to the point-to-point capabilities within the factory. The work of Lopez (1993) describes the typical transportation cost from machine x to machine y as:

$$C_{T_{x,y}} = t_{x,y} \times x_T \qquad (2.2)$$

Where, $C_{T_{x,y}}$ is the transportation cost from machine x to machine y, $t_{x,y}$ is the transportation time and x_T the cost rate of transportation equipment. The transportation time is given as a resultant of the distance between the said operations and the velocity of the transportation mode, multiplied be an 'efficiency' factor to accommodate variance in the velocity.

Transportation time is given by:

$$t_{x,y} = \frac{L_{x,y}}{(S_{TR} \times 0.75)} \quad (2.3)$$

Where, $L_{x,y}$ is the distance between process x and process y, S_{TR} the velocity of transportation mode and 0.75 the efficiency factor, to allow for average velocity

The combined transportation cost can therefore be summed as the entry cost of the raw materials, plus the totalled internal cost, plus the exit cost of the final product.

$$C_{B_T} = C_{T_{Entry,1}} + \sum_{i=1}^{m-1} C_{T_{i,j+1}} + C_{T_{m,Exit}} \quad (2.4)$$

Where, C_{B_T} is the combined internal transportation cost, $C_{T_{Entry,1}}$ the initial entry cost, $\sum_{i=1}^{m-1} C_{T_{i,j+1}}$ is the summed internal cost and $C_{T_{m,Exit}}$ the exit cost.

To compound the ideal issue of internal transportation, the actual transportation mode is required to validate the cost per part of the transportation. There are many forms of transportation, both manual and automatic (see Figure 2.3).

The internal transportation cost as defined by the work of Lopez includes the capacity of the mode of transport in any cost calculation. The internal transportation is:

$$I_p = \frac{\dfrac{Q \times V_p}{IT_v}}{Q} * (IT_d * IT_s) \quad (2.5)$$

Where, I_p is the required internal transportation time per part, Q the quantity of parts, V_p the total volume of parts, It_v the maximum volume of transportation mode, IT_d the distance between two processes of process and storage and It_s the internal transportation mode speed.

2.3.6 Strategic transport

The interface between the supplier and an assembly facility was analysed by Hahm and Yano (1995), where direct shipments are made from one to the other. A heuristic procedure to find a Just-in-Time (JIT) schedule was developed in which one production run of each product and a subsequent delivery of these products to the assembly facility occur in each cycle. The objective was to find the cycle duration that minimises the average cost per unit time of transportation, inventory at both the supplier and the assembly facility, and set-up costs at the supplier. An error bound was also developed for the procedure and some insight gained from the analysis was used to explain how delivery schedules could influence the attractiveness of reductions in production set-up costs. Additionally the optimal strategies for the strategic transport model can be found by use of regression modelling (Fowkes *et al.*, 1998).

Brown and Ronen (1997) developed a criteria base for the consolidation process. This criterion base breaks the information into three files, global, plant and order. The global and plant level of information rarely changes. The order file changes for every run and provides data concerning the specific order and run parameters. This technology is already being used by many companies to minimise transportation time.

2.3.7 Discussion

Work relating to the production transportation problem has been researched for many years and has been thoroughly documented. Beyond the logistical problem there is a requirement to understand the different methods of modelling supplier information. Several production transportation models have been presented, looking at the problem from varying angles. Firstly, *fixed cost* or *fixed charge* model and secondly as a *total loading* or *partial loading* model (Tyworth and Zeng 1998, and Johansen and Thorstenson, 1998). There are more complex formats of modelling, looking at multiple sites and products. Much of this work relates to the timber industry, investigating the sorting of a finite number of planks, utilising a limited number of logs of various lengths and taking into account set-up costs and quality (see, Balinski (1991), and Speranza and Ukovich (1994)). The presented work is useful for two reasons; firstly it outlines the optimisation of resources for maximum profit, and secondly, it highlights how optimal loading does not necessarily mean total loading. Since it may be more efficient to partial load a vehicle and alter the transportation frequency to accommodate other production requirements.

It is considered that the requirements of the production transportation problem for this research have been successfully covered by the outlined literature. The Simplex method detailed in many of the cited papers is the basic model for production transportation research (see, Kortanek and Yamasaki, 1995, and Haberl *et al.,* 1991). The Simplex method has been proven to return optimal solutions, for general problems. Whereas it may not necessarily be the most efficient method, it is considered that the results are sufficiently accurate work relating to early process selection. It is not feasible to implement a more sophisticated model, due to a lack of time and the accuracy of the data input.

Additionally, the planning and strategy required to fulfil the production demand is woven into the loading problem. Problems of economic batch size and cycle duration of an operation affect the loading.

2.4 Knowledge Based Systems

Rapid technological progress over the last decade has made Knowledge Based Systems (KBS's) an integral part of large and small organisations efforts to manage their knowledge assets effectively. The KBS is shown to improve productivity levels, increase machine utilisation and increase competitive advantage due to potential benefits, such as, monetary saving and improved quality for training purposes (Kodali, 1997). Generic strategies relate to both the level of knowledge under consideration and the focus of responsibility for the development of the KBS. Different knowledge processing strategies can influence both the management of knowledge within an organisation and the development of the KBS within the organisation (Dutta, 1997). Toh *et al.*, (1998) offers a novel approach for the specification of the information networks needed by small to medium sized enterprises, the approach supports rather than dictates the mode of operation of the business.

Gaines and Shaw (1997) report on the development of tools for knowledge management operating through the web to support knowledge acquisition and representation. The information was overly complex for this research, detailing the origin and format of the work-wide-web. The work did however outline the use of Java as a programming language for write once, read anywhere software development. Adler (1989) argues that the increasing centrality of technology and other forms of knowledge to competitiveness induces long-run changes in both operations management and engineering management. Williams (1994) reports that the world of computing has shifted from centralised *host centric* computing to *network* or *client/server* based computing. This has resulted in more local autonomy or control to the using groups. The key to distributed management is said to be 'Interoperatability'. With various sections of the information system coming from different vendors, the overall need is for these vendors to implement standard interoperable architecture to allow the sharing of management data and control among the different domains within the system.

2.4.1 The Internet and Intranet

The Internet or World-Wide-Web (WWW) serves as a desirable platform for distributed access to information and design tools. Kouzes *et al.*, (1996) reports on the tremendous impact computers have had on science and engineering in the past 50 years. Computer scientists have made progress on several fronts to create and integrate the tools required for internet-based collaboration. Many forms of electronic communication are suggested included, teleconferencing, whiteboard, e-mail, tele-mentoring and web browsers. They predict that collaborator's will be part of our future, *"they will be rich tele-present environments, and that virtual laboratories will proliferate"*. The introduction of support for *forms* on World Wide Web in late 1993 has provided an easily programmable, cross platform graphic-user interface that has become widely used in interactive systems. Chandrakasan (1997), presents a framework that enables distributed web based Computer Aided Design (CAD), in which web based tools can efficiently utilise capabilities of existing hierarchical design tools. Java, with its write once, run anywhere model, changes the basic techniques by which software is designed, developed, and deployed (Hamilton, 1996). Additionally, Rubin (1995) explores the problem of secure distribution of electronic documents in a hostile environment such as the Internet.

The definitions of an Intranet vary widely, but the simplest one is an internal Internet. The Internet, as described earlier is the global network of computer networks that link users worldwide. The underlying technology is the same standard (protocol) as is used for the Internet communication (Lynch, 1997). These technologies are of particular interest to large companies operating at geographical multiple locations.

Virtual Manufacturing (VM) is the name given to an evolving area of research that aims at integrating diverse manufacturing related technologies under a common umbrella, using Virtual Reality (VR) technology. The scope can range from integration of the design sub-functions such as drafting, finite element analysis, and prototyping to integration of all the functions within a manufacturing enterprise (Shukla *et al.*, 1996).

2.4.2 Intelligent manufacture

An intelligent knowledge based system is presented for evaluating Electrochemical Machining in a Concurrent Engineering environment (Amalnik and McGeough, 1996). The product model is specified by a feature-based approach, for further information see chapter 2 section 2.6.4. The attributes of 72 material types and machines are stored in a database. For each design feature, information needed for manufacturing, such as machining cycle time and cost are stored. For the same design specification, machining times are compared and ordered for alternative unconventional processes of Electrochemical Machining and Electro discharge Machining. The results show that knowledge based systems may be used to compare the machining cycle times and costs of alternative processes. It is suggested that product design engineers may use intelligent systems to improve the specification and machine operation conditions, see figure 2.5.

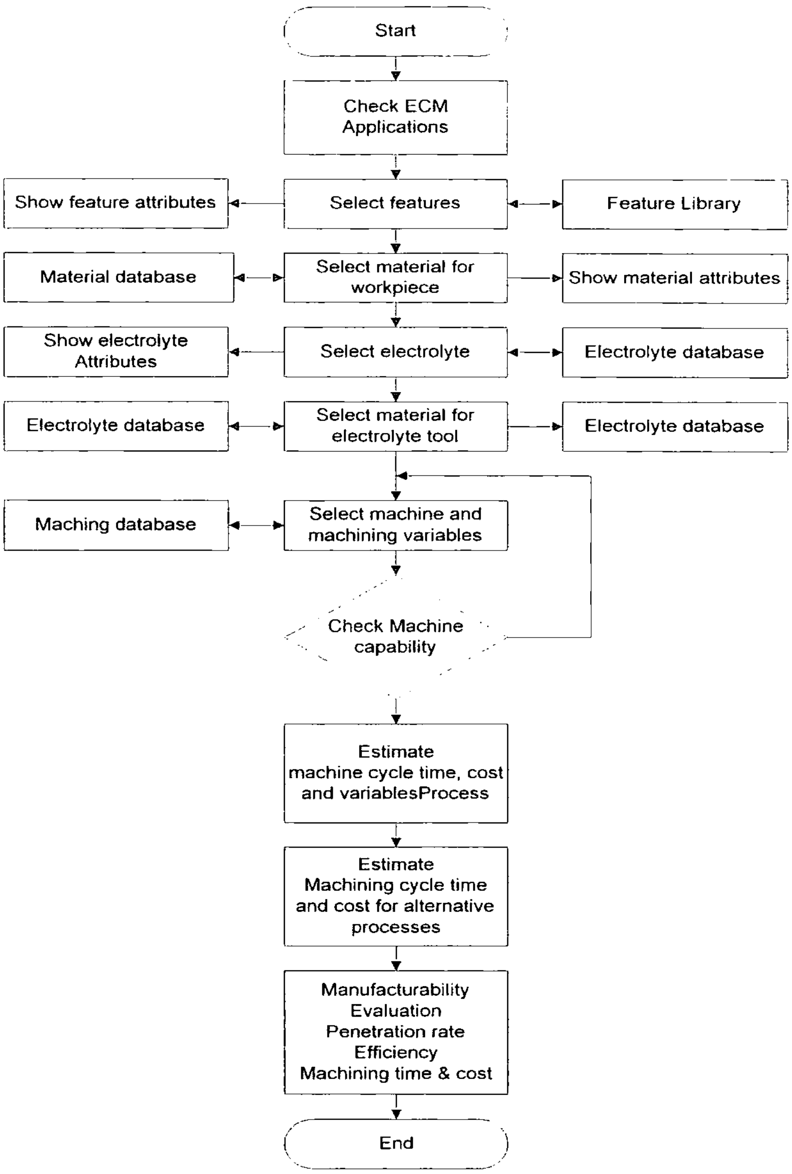

Figure 2.4: Flow-chart of Intelligent Manufacturability (Amalnik and McGeough, 1996)

2.4.3 Discussion

The use of knowledge based systems for manufacturing process data collection and dissemination is presented as being of particular interest for factory manufacturing process data storage. The need to link suppliers to facilitate manufacturing data transfer requires some form of network connection, an Internet connection is the obvious solution. A write once, read anywhere software solution is required to allow suppliers to operate the same software on different computers. Gaines and Shaw (1997) presented Java as a programming language, which is the most commonly referenced solution for Internet programming. Other forms of network solutions have been ignored by this work, since benefits or faults of different programming languages is not the focus of this work.

The intelligent knowledge based system presented by Amalnik and McGeough (1996) utilises a variety of manufacturing data, and is capable of translating feature based design information into process selection data. The work outlines the importance of eliminating personal knowledge and judgement from the product development. This is thought to be a critical view, to maximise the automation of process selection. Additionally this automation increases the speed of assessment and ultimately the flexibility of process selection. The work of Amalnik and McGeough (1996) is however specific to Electrochemical Machining and requires a great depth of information to perform the required tasks. The opportunity to model alternate processes for process comparison has been overlooked by the narrow theme of the work. Similarly, the ability to model external Electrochemical machining has not been included by focusing on detailed internal processing.

2.5 Operational Research

Operations Research or operational management research encompasses many different areas, such as suppliers, manufacturing, warehousing and transportation. Boone et al (1996) presents a review of recent international operations networks research. The study concluded that there is no overall differences found on the topics covering the research methods used between Asia, Europe and North America. Three frameworks exist for the classification of operational networks. Firstly companies that operate internationally are classified on the basis of their strategic capabilities and organisational characteristics. The framework contains four categories; multinational, global, international and trans-national (Bartlett and Ghoshal, 1991). The second framework proposed by Amoake-Gyamoah and Meredith (1989) divides production and operations management research into many categories, these cover areas of interest categorised by Miller and Graham (1981) and Buffa (1980). The third framework is the strategically oriented framework. It delineates manufacturing strategies into a series of structural, infrastructures and integration components.

The growing role of technology in competitiveness is driving parallel changes in management practices (Adler, 1989). Adler sites two trends in management education, "*the growing interest in Production Operations Management and the reliance of traditional approaches in this area*". Decline in competitiveness can be attributed to a wide variety of factors, poor operations management in particular. The very nature of productive techniques is changing in a manner that limits the usefulness of the traditional methods. In particular the impact of information sharing between collaborating companies is considered by D'Amours et al., (1999). Networking strategies are characterised by different levels of shared information, including price and capacity, see chapter 1, section 1.5. Different styles of bidding protocol are used in network manufacturing. Supplying-type bids can be associated as the weakest form of business relationship. "*It is like buying from a catalogue, where products are offered at predetermined prices*". This type of bid limits the transferred information to publicly known price-time packages. The customising-type bid can be associated with a richer form of business relationship. The networking form establishes its needs (time, capacity) and seeks for a maximum set of alternative contractors. Webbing-type bids can be associated with the most integrated network partnership relation. The networking firm establishes its needs and asks for the day-to-day operating characteristics of the contracting firm. With full knowledge of their production abilities, capabilities and pricing functions, the networking firm obtains a maximum level of flexibility.

Strategic technology leveraging is a new approach that requires the re-evaluation of technology strategy in the context of multiple-technology suppliers and partnerships. Most importantly it requires a significant expansion in the role and responsibility of the chief technology officer - to incorporate explicit accountability for creating and capturing the maximum value of technology leveraged through both internal and passive and active suppliers, joint ventures and alliances, acquisitions and licensing (Jonash, 1996). Accountability is more prescriptive than descriptive, it advocates how things should be, rather than how asserting how things are (Parris, 1996). It lives behind the scene as an aid to the design and trouble shooting of management systems. The implementation and practice of these management systems gradually moulds reality in the shape of the model.

2.5.1 Design for X

In recent years the significance of design has been well documented. Many different manufacturing design methods have been identified, from assembly to scheduling. The generic term for this is 'Design for X', where X can be replaced by any of the design methodologies. Whitney (1986) describes how design can lead to over specification. The paper presents a case study to show how a design can require 350 signatures to approve a single part at an automobile company. It states *"According to General Motor's executives 70% of the cost of manufacturing truck transmissions is determined in the design stage. A study at Rolls Royce revealed that design determines 80% of the final production costs"*. Establishing a products design calls for crucial choices about materials made or bought and about how parts will be assembled. In short, design is a strategic activity. It influences flexibility of sales strategies, speed of field repair, and production efficiency.

Design for Manufacture

Many different manufacturing operations can often be used to manufacture a single part. For example, a joint may be constructed from a casting, weld, rivet or bolt. The stresses and strains for each set-up are different. The decision as to the type of process is up to the designer. The use of Concurrent Engineering will enable production engineers to be consulted at this level so that a good balance can be settled between material cost, manufacturing cost and quality levels.

Design for Assembly

Design for assembly is the aim of reducing the number of parts required for a particular part design. This process can be applied to both the material used and also to the chosen operation. By changing the operation there are different capabilities to the design. This has a twofold advantage. Firstly it reduces the complexity of a design and secondly by reducing the number of parts required the production time is also reduced.

Design for Manufacturability

Peters et al. (1995) states *"by accommodating product design, process technology and operations management perspectives, it is possible to achieve the benefits of JIT supply* *with more suppliers"*. The principle is to reduce the variety of inbound materials and create variety close to assembly. The requirement is to have a stable and long-term supplier relationship. The principle to achieve speed and efficiency is to eliminate variety from the inbound flow of materials and create variety in sequence on-line. From a supply chain perspective, the ideal is to eliminate variety in the inbound flow of material. This way, communication with suppliers is simple and straightforward.

In a situation where communication in the supply chain is slow and distorted, the primary concern is to find the means to improve communication, reduce uncertainty and improve control (Neilson *et al.*, 1995). To do this there is a need to accommodate product and process technology considerations with operations management considerations. Taylor (1997) presented and tested new Concurrent Engineering strategies that focused on manufacturing and assembly operations with a global perspective.

Design for Schedulability

Kusiak and He (1994) formulate five design rules aimed at improving schedulability of parts and products. A design rule specifies actions to be considered by the designer in order to satisfy the underlying constraints. The rules are designed for automated manufacturing systems, requiring considerable capital investment and will benefit from the effective utilisation of manufacturing resources through the application of efficient scheduling.

- Minimise the number of machines (*cells*) involved in machining of a part (*product*)
- Assign parts (*products*) to the machining (*assembly*) cells
- Maximise the number of parallel machining or/and assembly operations
- Maximise the number of batches assigned to parallel machines (*stations*)

It is shown that the design of parts and products has a significant impact on the quality of schedules in manufacturing systems. The early consideration of manufacturing operations is identified as a key factor in the allocation of resources.

Design for Supply Chain Management

Lee and Sasser (1995) describe their experience of developing models in which the principles of Design for Supply Chain Management have been implemented for new product development. A wide range of factors was described including manufacturing and logistics costs - that could be used to support the design decision. Product standardisation has become a powerful concept in design for Supply Chain Management, because this design principle often results in higher material and direct manufacturing costs. However, there is a need to use analytical models to quantify the complex impact and benefits of cost drivers like Stock-outs, Factory Layout, Logistics and Inventory.

2.5.2 Sequencing production and inventory control systems

The performance of a production and inventory control system can be improved significantly by managing the situational factors, both internal and external (Yenradee *et al.*, 1995). They suggest an approach to identify the factors that need to be improved by comparing the existing organisational profile of the company with the suitable organisational profile of JIT.

The problem of scheduling in flow-shop and flow-line based Cellular Manufacturing Systems (CMS) is considered by Sridhar and Rajendran (1996). The formulation of timetabling in a flow-line-based CMS is discussed. A genetic algorithm is presented for scheduling in the flow-shop. The proposed algorithm is found to perform well for scheduling in a flow-line-based CMS. Liberopoulos and Caramanis (1997) investigated the optimal set-up change and production control policy for a failure-prone machine to meet constant demand rates. The computational experience is reported for several instances of the problem under different assumptions on holding/backlog costs and set-up change times. The work has significant practical application in the context of hierarchical production planning and control.

Arzi (1995) deals with on-line scheduling in a multi-cell flexible manufacturing system, operating in a produce-to-order environment. A two level Distributed Production Control System is developed and tested through a simulation study. The Distributed Production Control System allows autonomous and simultaneous operation of each cell-controller, utilising only local and short-term information as well as simple heuristic rules. Simulation experiments show that the proposed Distributed Production Control

System achieves good results in throughput, tardiness of orders and WIP inventory level and that it is robust to machine and handling device failure. The real-time production-scheduling problem for multiple-part-type flow shops is studied by Bai and Gershwin (1994). Three classes of activities were considered, operations, failures or repairs, and starvation or blockages. The scheduling objectives were to keep the actual production close to the demand and to reduce the work in progress inventory and cycle time. A three-level hierarchical production control model was developed to regulate production for the manufacturing system.

2.5.3 Just In Time purchasing

It was noted that, most factories have not changed their products or processes for many years and that their managers are comfortable with what they know (Walleigh, 1986). It is observed that in this environment change comes slowly. Walleigh stated *"This inflexibility combined with misperceptions of Just In Time (JIT) keep a lot of executives from using JIT"*.

A survey of JIT purchasing practices in the United States was produced by Freeland (1991). The survey reported that 45% of companies had 'formal' JIT-purchasing programs. Another 22% planned to implement JIT purchasing by 1992. The most significant findings can be summarised as, companies without JIT tended to be more job-shop, make-to-order oriented. The longer JIT had been in place the greater the perceived benefits. Quality is the most important criterion in selecting those parts to be purchased on a JIT basis. The distance between supplier and buyer is an unimportant criterion in selecting a JIT supplier, but is a great impairment to the implementation process. Contract agreements are more inclusive than for non-JIT purchasing. Suppliers are required to carry more safety stock for products not bought by JIT, but little difference exists in ordering and delivering policies between JIT and non-JIT. Buyer-supplier data exchange is more important with JIT.

Economic batch size and work in progress optimisation

There is a direct relationship between the Work in Progress (WIP) and Economic Batch Size. Di Febbraro et al (1994) illustrated a manufacturing system that includes the repetitive production of different products, to apply performance analysis techniques.

The objectives of the related optimisation problems take into account the maximisation of the throughput of the system and the cost of the plant. The overall optimisation shows that the problem can be decomposed into two subsequent mathematical programming problems. The first one is a non-linear continuous mathematical programming problem, whereas the second is an integer linear programming one (Yu, 1997). Particular attention was focused on the optimisation of an aggregate objective, taking into account the system throughput and the manufacturing plant cost. The results presented illustrated that analytical performance tools could be used for the analysis and optimisation of structurally complex manufacturing systems. Additionally Han et al. (1998) presents a Genetic Based Machine Learning (GBML) system for efficient scheduling and control of a job shop. The GBML has the inductive learning ability based on a series of computer simulation experiments to *discover* scheduling heuristics. These heuristics are then used to choose scheduling rules based on a pattern manifested by the job-shop.

Kanban

Savsar (1996) presents the results of a simulation study of a Just-In-Time (JIT) production control system and its performance under different operational conditions. The results of the simulation indicate that fixed order quantity policy is better with respect to throughput rate and average station utilisation, while fixed withdrawal cycle policy is better in reducing total Work In Progress (WIP) levels at all levels of processing time variability and number of different Kanbans allowed at each station. Therefore, an optimum Kanban level must be found with respect to the throughput rate and the total WIP level which are conflicting.

Optimising lot size and set-up

Lee *et al.* (1994) reasons that JIT involves determination of lot size and set-up time reduction so as to increase manufacturing flexibility while minimising the inventory level. The overall trade-off examination revealed that it was not possible to neither reduce tool set-up time to the desired level, nor minimise tool facility idle time. System constraints have a substantial impact by definitively limiting the periphery of solution possibilities, and should be verified with care to ascertain that they are indeed not flexible and not open to prioritisation.

2.5.4 Product definition

Krause *et al.*, (1993), presents an overview of the state-of-the-art and practice of product modelling in terms of product models and process chains. The use of methodologies and modelling tools in manufacturing are reviewed. Factors involved in this review include human organisation, product strategy and information technology. It is stated that product modelling is fast evolving subject, with no common theoretical foundation or agreed implementation strategies. This in turn poses challenges and opportunities for research. In a real environment a combination of these tools may be used to model a complete business environment (Pandya, 1995).

McKay *et al.*, (1986) described the use of advanced product modelling techniques to describe families of products without redundant data. The description of multiple views on a product family, without data redundancy, is a major problem to be overcome when product families are modelled. A solution based on the use of product data sharing to integrate engineering applications is presented. In principle the product variety data is represented in a product model such that both the product family data and the detailed data of particular variants is available for use by computerised product databases. A product family identifies the commonality and differences between the individual products that form a product range. A variant of a product family is an individual product that conforms to the product family. It has all the features that are common to the family and parameter values that are specific to it. A range of products is a set of variants of a single product family.

2.5.5 Discussion

Existing research into operational research forms a key theme to this research. The ability of an organisation to work with the extended enterprise from the initial design conception to production will support supply chain relationships. Design for X has highlighted the differing elements of the design process, and it is considered that the supply chain has a leading part to play in this function (Whitney, 1986). Additionally production optimisation and the varying methods of achieving this have been presented, indicating the topics for consideration when modelling an organisation.

In particular, Design for Supply Chain Management, discussed by Lee and Sasser (1995) evaluated the entire supply chain, assessing the stock levels at different points in the supply chain, and proposed a model for "configure-to-order" of the supply chain structure. This theory reaffirms the idea of supply chain classification described in Chapter 1, section 1.5. Additionally Design for Schedulability (Kusiak and He, (1994)) attempts to consider operational constraints in early design stages of parts and products, to improve manufacturing schedules. The work however omits the utilisation of the supply chain in the proposed design rules, see Chapter 2, section 2.5.1. The involvement of supply chain manufacturing processes would open a new paradigm to this research.

It is suggested that product variety should be eliminated from the inbound supply chain, instead the objective should be to create variety as close to the production line as possible, this can be seen in the automotive industry (Neilson *et al.,* (1995)). This concept is accepted for large production items, where standard products would both reduce the product structure complexity, and more practically, reduce the number of different stock items. However, this idea may also reduce the design optimisation, preferring to remain with what is known, rather than look for better materials, or designs.

2.6 Process Planning

Process planning has been researched for many years and from many different perspectives, see Alting and Zhang (1989) for a detailed survey. It defines in detail the process of transforming raw materials into the desired form. More precisely, process planning can be defined by a sequence of activities. They comprise of mainly, an interpretation of the CAD, a selection of processes and tools, a sequencing of operations, a selection procedure for the given processes and an assessment of the selected processes, based on economic batch data. Many companies have adopted Computer Aided Process Planning (CAPP) as a way to schedule and model these operations.

At a generic level Holmstrom *et al.,* (1997) focused on the principal issue of production control, i.e. to manage the cumulative effects of individually insignificant factors that together contribute to the difficulties of allocating resources efficiently. It was demonstrated in the 1960's by Jay Forrester that certain dynamics exist between firms in supply chains that cause errors, inaccuracies and volatility, and that these increase for operations further upstream in the supply chain.

2.6.1 Computer aided process planning

Modern manufacturing is characterised by low volume, high variety production and close tolerance high quality products. Computer Aided Process Planning (CAPP) is an essential key for achieving computer integrated manufacturing, see figure 2.6. The integration of design, CAPP and Production Planning and Control is becoming essential, especially in a CE environment where many product life cycle factors are of concern. Related issues of quality and evolving standards are also discussed by ElMaraghy *et al.*, (1993).

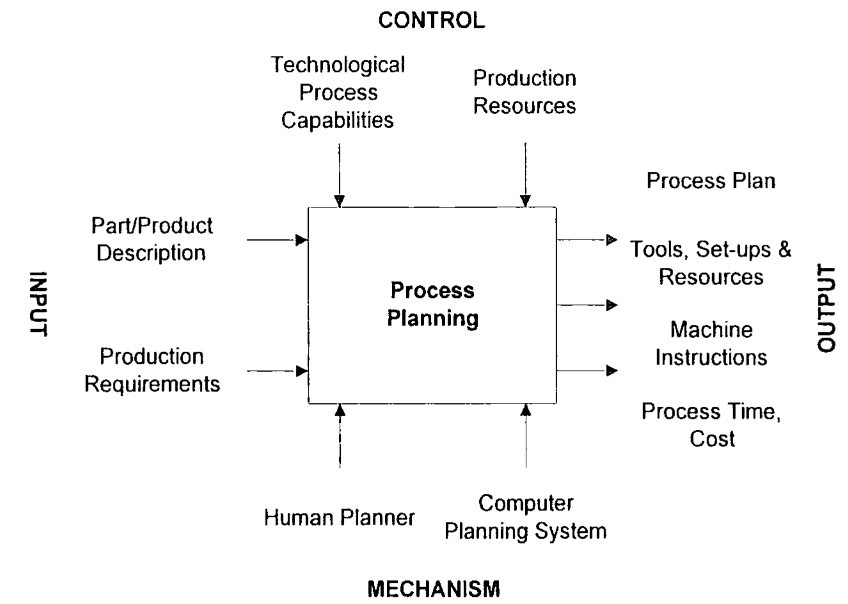

Figure 2.5: Representation of Process Planning Activity (adapted from ElMaraghy *et al.*, 1993).

Many forms of requirement planning exist. By way of process classification a technology index is presented by Kao *et al.*, (1995). The level of technology and management of 15 machinery firms are evaluated. The technology index is constructed from various indicators including those of equipment, employee and technological capability. It was stated that the productivity of the surveyed firms indicated that the management-leader is the group with stronger competitiveness that the machinery firms should consider achieving. A system to aid designers search and evaluate manufacturing processes is described by Leneau and Kristensen (1992). The system enabled the design team to explore alternative manufacturing processes. The procedure searches for a typical component with a shape similar to the desired one, followed by an inspection of the processes that were used to produce it.

Benezhad *et al.*, (1996) presents a mathematical programming model that concurrently encompasses the two areas of capacity planning and aggregate planning. The integrated model incorporates production and workforce planning decisions with equipment procurement decisions. The evaluation is that the integrated model has cost-saving advantages over the individual models.

Early models for capacity planning were based on an infinite planning horizon and unchanging production parameters. Those descriptive models considered a single-product/single-workstation situation and determined the number of required machines (Reed, 1961). The important characteristic the dynamic model presented by Behnezhad and Khosnevis (1988) was the incorporation of inventory build-up and shortage possibilities. Vander *et al.*, (1989) studied the trade-offs between machine investment and machine utilisation.

2.6.2 Aggregate process planning

The majority of prototype and commercial Computer Aided Process Planning (CAPP) systems offer good geometric capability and the operation are frequently based on the definition of features. However it is reported that the advantages of feature based technologies are mainly felt during the detailed design and planning stages. Process planning is predominantly an open-ended problem that accepts many solutions based on the knowledge of the designer (Maropoulos *et al.*, 1998). The method presented satisfies the industrial need for product based manufacture and is compatible with recent developments in the areas of process and product modelling.

Maropoulos (1995) presents a process planning architecture. The architecture consists of three levels, namely aggregate, management and detailed, which are defined according to the stage of the process modelling considerations. The modularity of the architecture will allow the generation of flexible, customised process planning systems to meet specific industrial requirements, enhance the operation of modules at each level and reduce the overall system complexity. Maropoulos (1995a) presents an assessment of research in the areas of tooling technology and management of process modelling. Extensive research work is reported in process modelling for product development, whilst detailed process models are frequently constructed on an ad-hoc basis without any formal analysis regarding data requirements and knowledge representation. Generic process planning research in its present form has been saturated. Applied consolidation research is still required to enhance the current state-of-the-art, particularly in feature-based techniques, and to promote the commercial exploitation of mature technologies. New process planning research should be placed in the integrated product development context, and be compatible with the concept of distributed design (Maropoulos, 1995b).

In the same way that formal system models are used to rationalise the implementations of complex computer systems, formal process models may be used to rationalise system requirements of complex business processes. Minkowitz (1993) examines this by way of a case study in the use of formal modelling to analyse systems requirements for an order fulfilment process. The model suggests information and functional requirements of systems to support the order fulfilment process. Not surprisingly, it identifies the need for order and supply data. A less obvious requirement raised by the model is the need to access key logistics information, such as product and distribution information, to check the legitimacy of orders and supplies.

2.6.3 Process selection

Allen and Swift (1990), illustrates a technique that can be used in early design to for the purpose of manufacturing process selection and costing. The model is logically based on material volume and material processing considerations. The process cost is determined using a basic processing cost and design-dependant relative cost coefficients. Material costs are calculated taking into account the transformation of material to yield the final form. The single process model for manufacturing cost (M_C) can be formulated as :

$$M_C = VC_M + R_C P_C \qquad (2.7)$$

Where, V is the volume of material required in order to produce the component, C_M is the cost of the material per unit volume, P_C is the basic processing cost for an ideal design of component by a specific process and R_C is the relative cost coefficient assigned to a component design.

The analysis was designed primarily to enable the designers to anticipate the cost of manufacture associated with alternative component design solutions, resulting from activities of design for assembly. Bloch *et al.,* (1992) presents a method of performing the cost analysis by taking into account the process yield at each step of the process sequence and how the yield at different steps impacts on the overall cost of the module. This paper outlines the methodology of modelling the process and how to use the outputs from the process models to evaluate the different constituents of the module cost. The cost at each process step is calculated by using inputs from the process model (cost model inputs). Process-based cost modelling has been used for different types of decision-making problems including packaging alternatives, equipment selection and repair strategies.

Originally developed by Allen and Swift (1990) and later adapted by amongst others Esawi (1994). *Shape complexity* refers to a chart method for determining the form of a part design. S*hape complexity* is based on the tubular or prism form, and is process independent. It is however not easily automated. Operator recognition is required for the *shape complexity*, and there allows an element of interpretation. This is not a repeatable process, since the designers' interpretation of an objects complexity may vary slightly. Using the basic theory that there are three basic forms: round, square and thin walled, the analysis is based on the features associated with the base form.

During the early 1990's CAD systems used geometric shapes and designs created primarily by Boolean operations on a set of basic solid forms, and the idea of features did not exist (Joshi and Chang, 1990). A review of *feature recognition* techniques is presented by Joshi and Chang, along with a proposed feature based design as an alternative to *shape complexity*. The proposed *feature recognition* method presents a series of nodes, linked together in different formats to equal a feature. The work is limited to machining features, since features are assumed to be depressions or cavities in a solid billet. This work is also supported by the work of Maropoulos and Bradley

(1997), on aggregate process planning for machining. The work of Maropoulos and Bradley classified an index of machining features, for process selection during embodiment design. However this work extracts features as an entity, with parameters such as length depth or angle.

2.6.4 Discussion

Process planning has been shown to be of particular interest. Individual work by Joshi and Chang (1990), Allen and Swift (1990), and Esawi (1994) has laid out a documented history of process identification. Previous models have proved very successful as cost predictors for manufacturing and fall into two categories, *feature recognition* and *shape complexity*. The *feature recognition* model has been tailored for specific requirements, for example welding or machining. An example of this process cost format can be seen in the work of Maropoulos and Bradley (Maropoulos *et al.*, 1998). *Feature recognition* enables detailed information for each feature, and can therefore be as generic or specific as the data given. With reference to the observed work of Maropoulos and Bradley, this method has been adopted for specific processes, and is focused towards automated process and tool selection. *Feature recognition* enables process models to be compiled with features and feature combinations that are not possible with a given process. An example might be *Blow Moulding*, where internal surface profile features are not possible. Therefore, any specified feature combination, where an internal feature is required would indicate that *Blow Moulding* was not a suitable manufacturing process. To expand this format to consider all manufacturing processes would require an incredible amount of process data, and therefore would result in a slow process assessment.

It was considered not viable to directly adopt either of the previously stated methodologies of *shape complexity* or *feature recognition*, since the outline to this research required both a rapid process cost assessment and an automated assessment. An amalgamation of the knowledge and procedures would be critical in any further developments. It is therefore proposed that *feature recognition* should be adopted to classify the product structure, and process coefficients, identified by shape complexity should be catalogued, stored and used for process assessment. Additionally an investigation is required to determine feature capabilities for a diverse range of manufacturing processes.

2.7 Conclusion

The main topics described in this chapter have discussed the issues relating to the operation and control of the supply chain.

In particular it is proposed that the identification of manufacturing processes during early process selection will add a new paradigm of flexibility to product development. Additionally it is noted that no previous work discusses the role of suppliers during product development, addressing what manufacturing process information is required to assist this process.

The transportation of products both internally and externally has been identified as a key function of the extended enterprise. Factors affecting the loading and frequency of transportation are the economic batch size of the manufacturing process, distance between locations, cost per part, etc. The Simplex method for load/frequency identification is selected, to minimise the complexity of the problem (see, Kortanek and Yamasaki, 1995, and Haberl *et al.,* 1991).

The elimination of personal knowledge and judgement concerning manufacturing processes, is noted as significant for the automation of process selection. It is also noted that operational constraints during process selection improve manufacturing reliability. It is therefore considered that the inclusion of supply chain manufacturing processes during process selection will enable greater choice. Additionally, the adoption of Java as a programming language is considered essential to the ability of the process selection software to operate between companies, across the Internet (D'Amours *et al.,* 1999).

The topic of process planning combines product identification, process classification and process selection. The format of data for the product model is stated as *feature recognition.* This is both the simplest format to automate and is adopted by other members of Durham University, Design for Manufacture Research group. This is the full extent of commonality between this research, and that of the research group.

Chapter Three

System Overview

3.1 Introduction

It has thus far been illustrated that there is a fundamental requirement to model and evaluate the extended enterprise during early product development. It is the focus of this thesis to present a prototype software system to be used during the conceptual design phase of product development, to aid in the process selection decision.

A generic factory selection methodology is developed and tested through the use of this software system that implements the proposed Process Selection (PS) and Factory Selection (FS) methods. This prototype system is an integrated decision support environment that performs automated process and factory assessment. The system is called Supply Chain Oriented Process modelling for Engineering (SCOPE). The data used for this assessment is not live data, and although true at the time of distribution it will undoubtedly become outdated when new data is generated.

It is not the purpose of this work to create a rigorous and fully documented computer aided process planning software system for the extended enterprise. It is recognised that there is great merit in such a system, which would enable the customer to continually re-evaluate the process selection throughout the life of the product. Such a system could be used by the finance department to justify production cost. Typically such systems could be used as a bargaining tool when negotiating costs. Also this would enable the customer to monitor the production of a product, based on the manufacturing operations data. Ideally such a system would use manufacturing operations data, linked to real time data flow.

It is important to note that the development of SCOPE is not the object of this thesis. Rather, the system has been developed in order to evaluate the PS and FS methods that have been applied in its development. This chapter will discuss SCOPE from a system viewpoint, identifying the specifications of the system in terms of the tasks that are required. The structure of the system will then be outlined, describing the main system elements, each of which are detailed in the subsequent chapters.

3.2 Specification of SCOPE

The SCOPE system is a prototype Concurrent Engineering (CE) support software package. The main function of the program is to assist a manufacturing company to assess their supplier capabilities and to aid in the 'make-or-buy' decision. The system enables designers during the conceptual stage of design to generate manufacturing options that include supplier capabilities. It is proposed that the alternate supplier considerations will in turn generate a more informed product design.

This engineering software tool is intended to propose a standard for the transfer of manufacturing process information throughout the Supply Chain (SC). The purpose of the task is to establish a consistent costing method for manufacturing process selection across the SC. At a general level, supplier selection can be stated in basic queries as: 1) What parts are required? 2) Where can they be obtained? Also, 3) What quantity needs to be purchased? These questions address different aspects of the selection procedure. In the *first* question there is no specification of product, only the idea that a product may be required. The identification of a product is the first step in process selection. In the *second* question there is no focus upon a particular supplier. It is considered that many organisations would be able to generate an approved supplier listing to aid the supplier selection. The *third* question relates to the situation after the relevant suppliers have been identified. To pursue an inquiry the order quantity is required. It is proposed that the SCOPE system should follow the above procedure, to identify the product, then to identify the suppliers and finally to assess the individual suppliers.

The literature review on manufacturing process modelling identified the works of Swift and Allen (1990), Esawi (1994) and Taylor (1997) as being of particular interest. The following assessment factors were highlighted by the aforementioned authors as contributing to the product cost; material, labour, tooling, quality, quantity, storage, transportation and factory operating costs. The need to optimise these factors when selecting a supplier can be overridden by intangible management issues such as *customer loyalty* or *customer preference*. It is not proposed to incorporate these issues into the SCOPE software, since they rely mainly on human preference. Alternatively there may be tangible factors such as *quality* or *time* that alter the priority of the supplier selection. It is therefore suggested that any assessment allows for the manipulation of these assessment factors.

The security of any software system is paramount. Suppliers would not be willing to allow company data to be open to a system that could be accessed by unauthorised personnel. During the course of the data collection for the SCOPE system 'Electrolux Outdoor Products' were hesitant about providing hard copies of layout designs or manufacturing process capabilities. Electrolux Outdoor Products, better known for their Flymo range, are a garden product manufacturer producing a wide range of electrical and petrol driven lawn mowers, hedge trimmers, lawn trimmers and garden vacuums. Documentation was required in the form of a verbal agreement that the data would not be passed to any third party, or that the data would be used for any other purpose than this work without the express permission of Electrolux Outdoor Products. It is considered that, for the SCOPE system to operate at a commercial level, a formal documentation process should be adopted to control the access to sensitive information and satisfy supplier fears.

3.3 Functional Description

There is a functional need for SCOPE to support PS, as discussed. This is performed by evaluating the manufacturing operations of suppliers. The SCOPE system is designed to be used by design and development engineers, to explore possible design alternatives. It is therefore considered important to pay careful consideration to the construction of the software to facilitate a user-friendly environment. It is not assumed that the user has a comprehensive knowledge of computing. Information should be presented at the appropriate time in the analysis, such that there is no confusion as to what manufacturing processes are available.

It is reasoned that the SCOPE software should be operable at two levels, P1 and P2 (see, figure 3.1). Firstly the manufacturing process level, where PS is compiled and stored. The SCOPE application connects supplier factories via the Internet, as seen in the box surrounding the supplier factory databases (P1). Approved supplier details, including the computer database links, factory location, personnel contact details and factory overhead rates are stored within the main body of SCOPE. These details are utilised to connect through the internet, to the supplier database. The second level (P2) of SCOPE is Factory Selection (FS), it is possible to operate FS without adding new data.

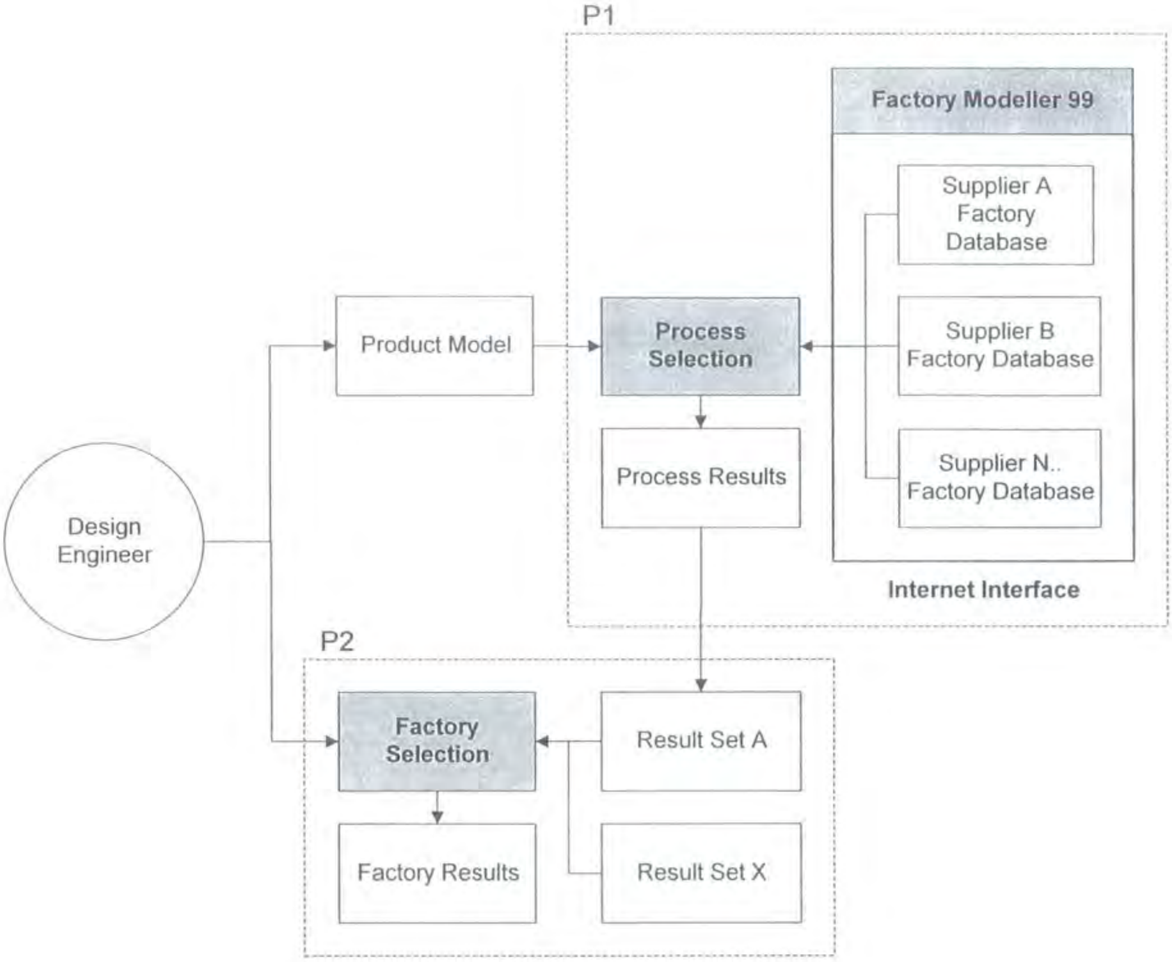

Figure 3.1: SCOPE architecture encompassing the process and factory selection levels

At the PS level (P1, figure 3.1) the product model containing the product data, and the supplier data containing the manufacturing processes are joined. The generated result set can either be saved for later manipulation or discarded, depending upon the user requirements. The PS results are saved at the main factory, as a database containing the highlighted assessment factors. The alternative level of the application is FS (P2, figure 3.1). At this level the stored PS results are retrieved from the computer system and manipulated to identify the most viable options for manufacture. Any number of result sets may be simultaneously accessed for comparison. The method of assessment will be described later in Chapter 6.

Before describing the format of the SCOPE system in detail, it is important to identify the manufacturing process database. The manufacturing process database is the data that is assembled from the supplier factory concerning their factory capabilities. A supplementary software system called Factory Modeller 99 (FM99) has been designed to facilitate this requirement.

3.3.1 Factory Modeller 99

The Factory Modeller 99 (FM99) software is not directly connected to the SCOPE system, in so much as they do not need to run simultaneously. It is proposed that the supplier should run this program to generate the manufacturing processes database. The data is saved into a database running on the PowerJ system. PowerJ is the development tool adopted for this project. The illustrated flowchart (see figure 3.2) outlines the input process for FM99. During the input process of manufacturing data the correct *factory*, *building*, *floor* and *cell* are required to amend the *resource* level, otherwise a duplicate manufacturing process is created at the wrong location. The *resource* refers to an individual manufacturing process, for example an injection moulding device or pedestal drill. It is not possible, for example, to input a *building* or *floor* without first specifying the respective *site* or *building*. This is achieved by applying rules during the programming of FM99 that prevent access to information, unless the correct information is present. The system automatically formats the data into the database, linking each process to the hierarchy of the factory. The hierarchy of the manufacturing process data is discussed in chapter 4. The manufacturing process database can subsequently be accessed by SCOPE. The same system is also used to amend or delete manufacturing process information. Alternatively it is possible to write the database using Microsoft Access, providing that the operator is aware of the database structure. It is then possible to load the Microsoft Access database into the PowerJ Database. It will not therefore be considered during the later discussions of this chapter. The development tools adopted in the construction of FM99 were inherited from the development of SCOPE.

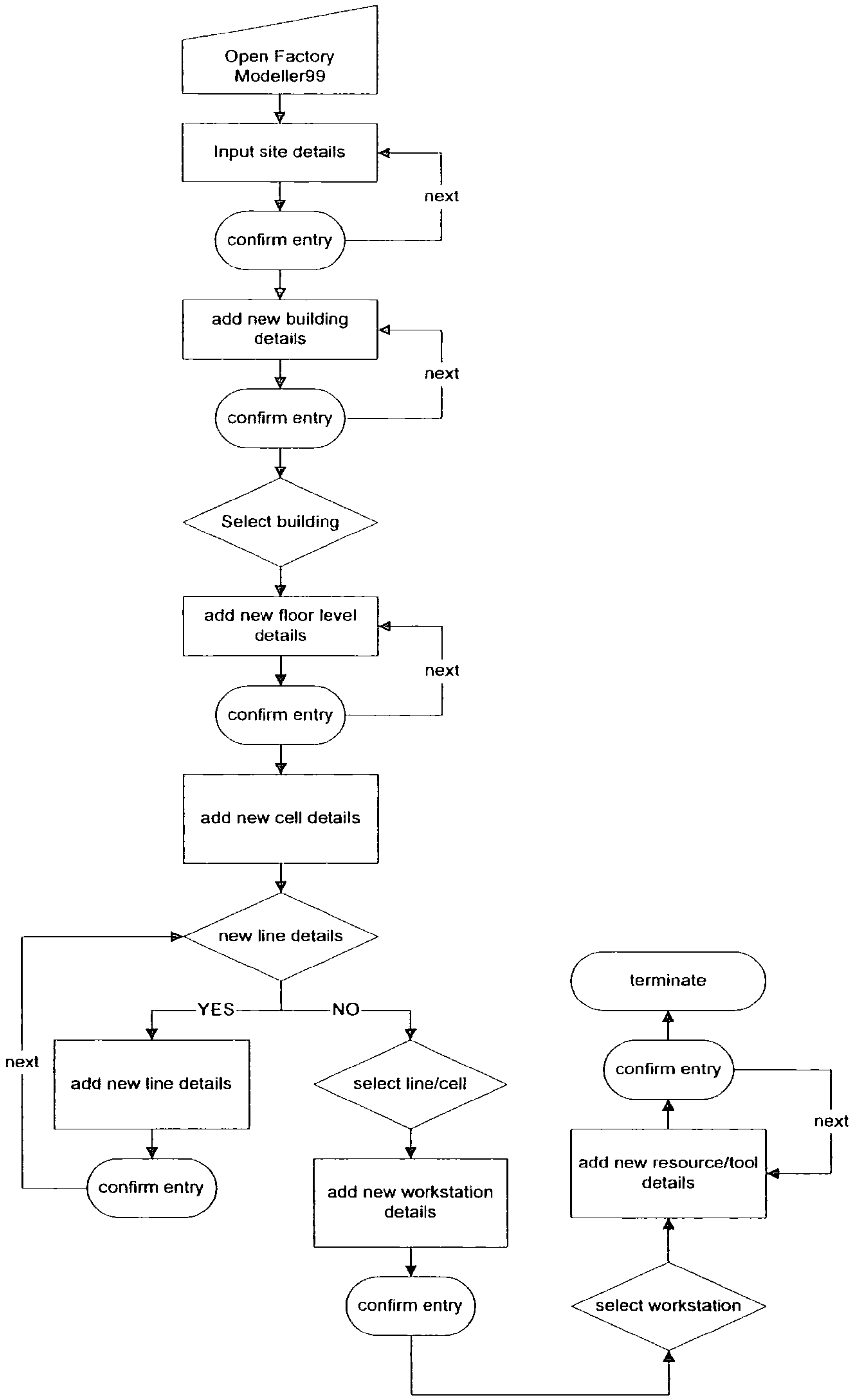

Figure 3.2: FM99 Data Entry Flowchart

3.3.2 Data Amendment in FM99

From the discussion on the specification of FM99 it is stated that manufacturing process data generation is made easy by the FM99 software. Data amendment is also simplified by FM99. This is achieved by highlighting the correct *site*, *building*, *floor* and *cell* for the required 'manufacturing process' *resource*, and then overwriting the information or deleting the entry from the system. Alternatively data amendments can be made using a Microsoft Access database. The information can easily be altered or removed and then saved back into the PowerJ system.

3.4 System Architecture

It has been outlined that the SCOPE system can be operated at two levels. The two levels run separately and have different functions and results. It can be clearly seen in figure 3.1 how the different functions are linked. The SCOPE software has been constructed to allow the operator the maximum freedom to perform separate process selection and factory selection assessment. This is beneficial since there may not be sufficient time to complete a thorough assessment of both individual process selection and the comparative function of factory selection at any given time. The ability to perform separate tasks will allow the user to generate multiple PS result sets and to comprehensively compare the results sets using FS.

3.4.1 Product Model

It has not been the objective of this thesis to propose a novel product model. From the literature review it can be seen that different formats of product model were considered. They were namely the *shape complexity* format, (Bloch, 1992) and (Swift and Allen, 1990) describing the shape of an object in terms of cylindrical and cubic forms, along with combined features. The *feature generation* format (Chang, 1990) and (Bradley, 1997) fragments the design into object features such as profile and face to compile the part. It was considered appropriate to adopt the *feature generation* method for the product model, since this format was already in use by other members of the Design and Manufacturing Research Group (DMRG). Additionally the *feature generation* method was the easiest method to document with the minimum amount of details. The form of the component is easily outlined, detailing each feature dimension and tolerance, a task that would be less efficient for *shape complexity*. For example it is easier to describe a cylinder with an internal thread as exactly that, using *feature generation*, than a complex form being of cylindrical nature with internal features, as would be the case for *shape complexity*. The DMRG method allows synergy between this work and other work into

Assembly Modelling and Aggregate Process Planning. In addition, the feature generation model was readily available for Electrolux Outdoor Products, allowing the method to be easily tested.

The product model needs to be stored in the same PowerJ database as the manufacturing process data, to be accessed by the SCOPE system. However the product model is written as a text file adopting the *feature generation* format used by the DMRG, see Figure 3.3, and then transferred into the PowerJ database. The format refers to the *feature name*, *feature parent*, *feature properties* and the *feature attributes*. An example of a product model can be seen in appendix C. For example, a feature such as a cylinder would have a list of *properties* ranging from length to surface finish. These relate to *values* for the given cylinder. Additionally the cylinder will inherit a *parent* name and that might be a bolt. The bolt in turn may have a *parent* class called a motor, where the motor is the object of the product model. It is possible to operate the PS level of the system without adding new data to the system, providing that suppliers already exist, within the SCOPE register. Product model data is retained in stored PS results.

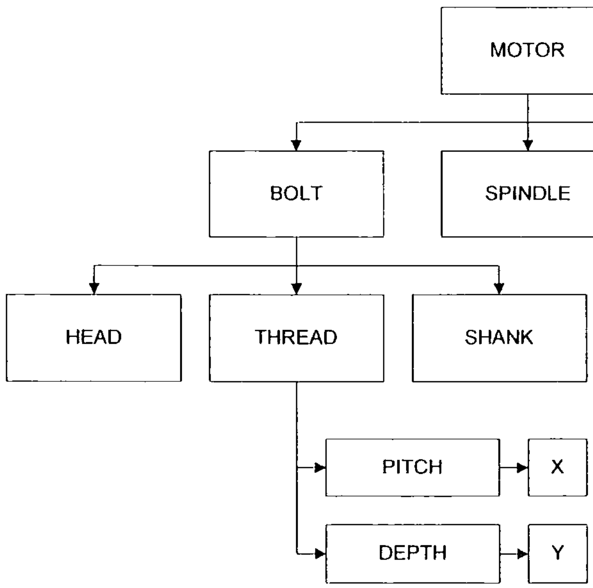

Figure 3.3: Product Model Architecture

3.4.2 Process Model

The ability of the process model to utilise the information of the product model and the diverse manufacturing process data is essential to the generic nature of the system. PS calculations are performed on the basis of both the features supplied by the product model and the supplier information, given in the manufacturing process database. During the PS assessment the manufacturing process data is separated into the fundamental tasks within the organisation, namely process attributes (power, size, materials, etc.), factory attributes (process location, geographical location) and transportation attributes (volume, speed, cost rate). Internal transportation is calculated on the basis of the transportation mode used by the manufacturing operation. Cost is given as the result of the optimal production rate, allowing for tool time and material shortages. The result of the process model are stored a database format on the PowerJ system, and they are utilised in the FS level of SCOPE.

Different levels of manufacturing can be described as primary, secondary and tertiary processing. Primary processes are described as raw material operations where raw material, in the form of a billet, powder, granule or molten liquid is used as the material. These manufacturing operations are generally casting or moulding operations. Alternatively, primary processes for machining consists of rough cutting operations. These operations are used to form the required features. Secondary operations are normally described as finishing operations, such as secondary machining to obtain the required tolerances. Tertiary operations are more difficult to classify, since they have a broad spectrum but they are usually aesthetic or auxiliary operations such as buffing, coating or painting.

3.5 Summary

The data that has been laid out in this chapter has laid out a footprint for the implementation of the proposed PS and FS methods. The development of the FM99 software that is installed at supplier factories will generate a standard format for the manufacturing process data. The adoption of the product model developed by the Design and Manufacture Research Group has standardised the product data input. It should also be noted that the format of the product model presented by Maropoulos *et al.*, (1998) is currently adopted by other members of the research group.

Chapter Four

Manufacturing Process Data Generation

4.1 Introduction

This chapter describes the theories applied within the manufacturing process data generation function of SCOPE. The functions of SCOPE are identified, from the initial selection of the manufacturing process data through to selection of the manufacturing processes. Assessing the suppliers' manufacturing process data creates the process model. The manufacturing process information can then be used to firstly identify, and then calculate optimal utilisation of manufacturing processes. To aid design engineers, multiple process and material combinations should be considered. Computers have been used to aid product development for many years, in particular for product design and assessment. Computer Aided Process Planning (CAPP) and Material Resources Planning (MRP) are software systems that have been adopted as basic requirements for design teams to facilitate Concurrent Engineering (CE). This has resulted in flexibility being built into the design process, thus providing less room for error by designers. Concurrent engineering (CE) is based on the synergy between the design stages of a product and the manufacturing planning stages. CE involves the parallel processing of tasks, enabling groups of people to solve problems simultaneously by drawing on their specific abilities.

4.2 Process Planning

Process planning is a series of decisions that uniquely specify the manufacturing operations required to complete a job. Once the process planner makes a decision concerning either the material or the manufacturing process, it becomes a constraint on all decisions that follow, since the material or the manufacturing process excludes alternate options. It is accepted that these constraints are arbitrary, since they only exist because of the sequence in which the decisions are made; another sequence may result in a different set of constraints. Similarly a decision made at the process selection stage will be a constraint at the factory selection stage. If product data, such as the feasible material or part size, is known during process selection, then benefits may be achieved by utilising the product data during process selection.

Process planning is the first step in the organisation of a manufacturing plan. Certainly without ensuring the feasibility of a process plan, it is pointless preparing production management and production control plans. Conversely, it would not be economical to design process plans that need equipment not presently available within the company that would incur unnecessary expense, or would entail the use of machines that are vital for other manufacturing operations. It is therefore important, for example, to achieve an optimal balance between utilisation of machinery and queuing time of in-process material.

4.2.1 Computer Aided Process Planning

At the most fundamental level, the principle of Computer Aided Process Planning (CAPP) is to utilise the computer technology to assist the process planner with the planning and scheduling of manufacturing operations. This assistance may take varying forms, from a simple record of an operations utilisation, to preparing an automated schedule plan for each manufacturing operation.

The trend in process planning development is to further integrate the two functions of process planning and production planning via software in order to achieve a better understanding of the factory capabilities. The purpose of production control is to supervise the flow of parts on the shop floor in order to maximise the utilisation of production time. Time lost due to long handling transfer periods between manufacturing operations is undesirable. At the same time its purpose is to respect the delivery dates of the product.

4.2.2 Criteria for Process Modelling

A fundamental element of process modelling is the group of process attributes used to establish a criteria base for process assessment. Process attributes, such as power consumption or machine name, explicitly describe the process and its geographical location. The criteria base also needs to differentiate between identical machines within the same factory. The process model must include information on the agility of the process; the cost of the process; the capabilities of the process; the logistics of the process; the key strategic issues and the location and geographical factors. These factors are discussed below.

Agility / Responsiveness

The agility of an organisation is based on its ability to profit from a rapidly changing, continually fragmenting, global market. Often described as a new system of commercial competition, responding to commercial changes ahead of the competition, agility is a successor to the idea that mass production-based manufacture is the ideal strategy. Alternatively, Lean Manufacturing focuses on process efficiency through eliminating manufacturing waste. This differs from agility since the aim of lean manufacture is to maximise the production efficiency of an operation, and the aim of agility to maximise the flexibility of an operation.

Cost Efficiencies

Product plans that are both timely and effective in cost terms are a foundation to profitability. Cost information should be generated to show the source of profit. Cost is not simply incurred, it is designed into the product. The parameters of production method and material type are determined during design, before a single product has been manufactured. By altering these parameters the direct cost of the product is changed. The indirect cost is determined by both marketing and management strategies outside the control of production.

Capacity and Capabilities

The ability to control the planning and introduction of new and existing products is governed by production parameters. The capacity of a factory is limited by both the physical constraints of the facility and by the manufacturing processes available. The capabilities of the manufacturing processes control the production rate. Much work has been done on machine requirement planning and production planning (Minkowitz, 1993; Maropoulos, 1998) since they play a large role in capacity and operations planning in manufacturing. Additionally the control of quality issues during production is essential to gaining customer trust and satisfaction.

Logistics and Geographical Factors

The sourcing possibilities during the make-or-buy decision include suppliers from all geographical locations. For example, if cost is the key issue then the decision to outsource may be influenced by the ability to move manufacture to a more cost effective location. Any benefits of low-cost manufacture may be offset by higher logistics costs - higher transport costs, cost of higher inventory and longer lead times.

Knowledge Management Issues

Knowledge management must be considered as the key strategic process in any knowledge based organisation today. New communications and knowledge sharing technology have dramatically improved the process of acquiring, developing and disseminating knowledge. This knowledge is utilised internally within an organisation, and is also used to communicate with clients and customers. It is now possible to develop knowledge-based products and services faster, to a higher quality, and delivered at a greater value to the customer.

4.3 General Selection of Manufacturing Processes

The requirement to design a part, such that the manufacture is optimised, is termed Design for Manufacture. Manufacturability relates to how readily available the manufacturing processes are. An integral part of Design for Manufacture is the selection of material and process combinations. It is considered that design engineers conceive of parts in terms of processes and materials with which they are most familiar. As a consequence this excludes from consideration process and material combinations that may be preferable. Opportunities for major manufacturing improvements may be lost through such limited selections of manufacturing processes and associated materials in the early stages of design.

The product design cycle is denoted as the period of time between the initial product conception through to production. The decision as to which manufacturing method to adopt is often taken very early in the product design cycle (see, table 4.1). Similarly the most appropriate material is determined early in the product design cycle. Design engineers are neither process planners, responsible for scheduling the manufacturing operations, nor accountants, who rationalise the capital value of manufacturing operations, yet their decisions constrain the process selection. If the production engineer does not agree the selected manufacturing method, then a review of part design should be made to look at more suitable manufacturing methods and materials. Concurrent Engineering proposes that the decision should be mutual and should be taken after discussions between a multi-disciplinary team.

Table 4.1: Initial design considerations

Quantity	The optimal batch size for any manufacturing operation is different. For any given batch size there is an associated set-up cost and time. These factors effect the processing cost for a given operation and are therefore an important consideration.
Complexity of form	The manufacturing capabilities of all manufacturing processes are not equal. The design of any part needs to be compared with each process. For example a part in the form of a cube, would only be feasible with manufacturing processes capable of producing that form.
Material	For any given material there are a number of associated manufacturing operations. For example blow moulding is only possible with plastics. The specification of the material will therefore reduce manufacturing options.

Material thickness	This factor can be important when considering the limitations of machining or casting operations. For example the minimum thickness for a wall section will control whether a casting operation is suitable.
Dimensional accuracy	The dimensional tolerance of a required part is important. It is not feasible to suggest manufacturing operations that do not comply, unless secondary processing is an option. An example may be a casting operation that cannot guarantee accuracy due to shrinkage of the section thickness within the die.
Cost of raw material	It may be possible to gain better dimensional tolerances or dimension accuracy by adopting a different material or manufacturing method. The cost of secondary processing to improve the tolerance will have to be weighed against the benefit of using possibly more expensive materials.
Subsequent processes	As specified above, the dimensional tolerance required by a given operation may require secondary processing to occur. Alternatively secondary or tertiary processing may involve painting or polishing a part.

4.3.1 Material or Process Selection

When designing a part, the general form of a part is confirmed. What is less definitive is the method of manufacture or the material for manufacture. The predetermination of either of these two factors will limit manufacturing options. However, to focus the assessment of a design, a decision on the priority of each design factor is required. By selecting the method of manufacture first, the material options are limited, but the efficiency and cost of the process can be governed. Alternatively by controlling the material first, the method of manufacture is limited. This option controls the material attributes.

It is suggested that the material should be selected before the manufacturing process. This decision is based on the assumption that, when designing a product, the designer has a general idea of which material group a product belongs to. For example this can be plastics, ferrous or non-ferrous metals, or ceramics. The designer suggests the required material, and the SCOPE system suggests the possible manufacturing methods. It should be noted that at the point of process selection, the possible manufacturing methods have not yet been compared to the complexity of the design features.

4.3.2 Manufacturing process data structure

For the purpose of process planning it is essential to identify those attributes of any organisation that will enable an assessment of the processes to be performed. A database is therefore required representing the manufacturing process data, that reflects these attributes. Consideration is required of the structure of any such manufacturing process data model to include both attributes of the factory and its facilities. More importantly, the information that is generated must be applied consistently for all processes and facilities, to reflect supply chain companies.

The problem therefore is to identify those individual attributes of the factory that have the greatest significance over the costing process. These attributes may take many guises from management level, in the form of supplier preference, to machine level, such as the operational cost per hour. Since a wide variety of materials may be considered during the SCOPE assessment, there are more viable manufacturing operations. Many different manufacturing operations should be modelled, to accommodate each of the material groups.

4.4 Factory Layout

It is not the intention of this research to present a novel method for factory layout design. The ability to perform factory layout design requires detailed information on manufactured products and the manufacturing capabilities within a factory, with the intention of projecting efficient workflow. Rather it is the intention of this section to present a novel process identification format to aid process selection.

To organise the process classification the factory layout plan is required, see figure 4.1. Typical factors that influence the factory layout include the practical access of manufacturing processes, for either internal transportation or waste extraction purposes. The logical grouping of operations, for product or process benefits, is seen in figure 4.1 by the separation of 4 cells instead of grouping all operations together. Additionally, space constraints within the organisation may force operations to be grouped together to save floor space, rather than for production benefit. Environmental issues of the factory environment stipulate that personal protective equipment may be required, such as ear protection for working environments where excessive noise is generated. This has the effect of grouping processes to reduce noise in other areas of the factory. Additionally governmental environment policies may relate to vapour pollution where extraction would be required. The power consumption of a factory may also influence the operation locations.

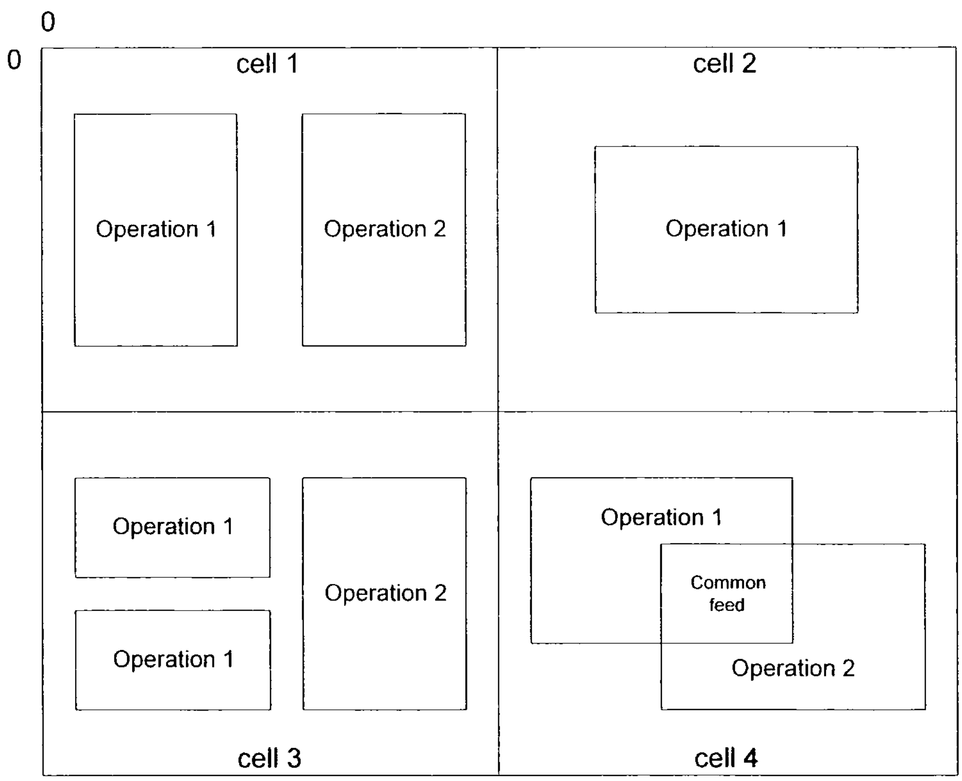

Figure 4.1: Illustration of factory cell layout design

For the purpose of the required process database, the classification should encompass practical production issues concerning layout. As indicated, the grouping of operations within a factory can influence the layout design. This can be either process related or product related. For the purpose of operations identification a hierarchy is required to denote the relation of each operation in relation to all other operations. Other considerations should include transportation considerations, both internally and externally and manufacturing availability, where the availability relates to whether the manufacturing operations is presently being utilised. For manufacturing operations currently used for other business it may not be justified to monitor these facilities, due to the fact that they will not be available for use. Therefore, the availability of an operation is crucial to any assessment.

4.4.1 Factory elements

A number of elements are necessary to constitute a manufacturing facility. The format of this classification has been touched upon; it was indicated that the factory is broken down into a number of elements. The objective therefore should be to present the factory as a selection of units that would enable the SCOPE system to manipulate the information efficiently. From the previous factory layout (Figure 4.1) the factory can be broken down using horizontal and vertical criteria. The horizontal elements combine the site and buildings and the vertical element represent the floors (Figure 4.2).

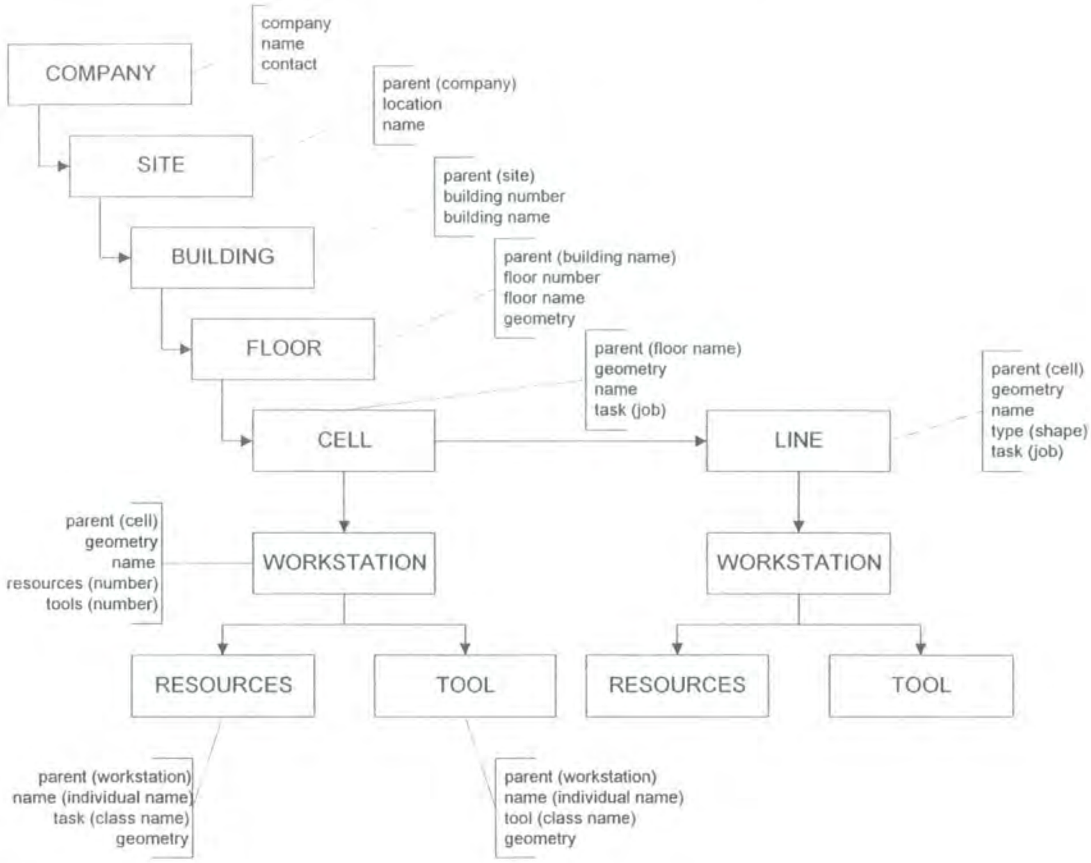

Figure 4.2: Factory model elements

The following section lists each of the resource elements and the possible methods for modelling them within a computer system:

- Site

A site is a location for the production facility, or a depot for the storage of products. This is the root level of the manufacturing process data and is referred to during factory process selection as the reference point for internal transportation. A site is defined as being a single area of production. Any number of activities can be carried out at the site.

- Factory building

Within a site layout, an individual building or factory may be considered for production. Each building has an individual identification and position. A factory can contain any number of operations and floors and can be considered as a single entity or as part of a site analysis.

- Floor

Any factory can be split into any number of different floors. To be able to accurately model internal transportation it is necessary to identify processes that are in the same building are on the same floor or different floors.

- Cell/Line

The cell/line classification consists of two separate levels. The cell level identifies a collection of manufacturing operations. These operations can either be grouped by process or by product. Grouping by manufacturing process may be required to facilitate the access of raw materials or for structural limitations. To group by product is more efficient for process flow, this generally enables reduced internal transportation. The line classification refers to a group of cells that have a common internal transportation and or manufacturing process.

- Workstation

A cell or line contains X number of workstations. A workstation refers to either a single operation (resource or tool), or a group of operations. In practical terms this may be a manual assembly position, where several operations can be carried out at one location.

- Production tool/resource

This is the lowest level of information, where the manufacturing process data is identified. Data is collated in a general format, but is identified as being either a resource (operation) or tool (aid). All data necessary for individual process identification is required at this level.

- Transportation

The transportation mode for the site is classified as being either cellular or factory level. In both instances the option is given to select the mode from a list of options. Differentiation is given to the separate levels of the model to allow for automation or sequencing of operations to occur.

- Labour

Manual operators are classified at the workstation level, relating the operator to the processes within a workstation. The operator is classified under the *tool* heading within production resources, combined with the appropriate cost rate. The reason for this is that an operator is an aid to the process.

4.4.2 Factory Model Structure

The function of the model is to know the location of any operation, within the *site*. Then relate that to other operations within the site, depending on the parameters of the assessment. It is therefore important to have a confirmed structure to the model that allows transference of data. The ground level *site* retains the base geometry and all other levels refer to those Cartesian co-ordinates. Figure 4.3 illustrates the hierarchy of the generated manufacturing process model.

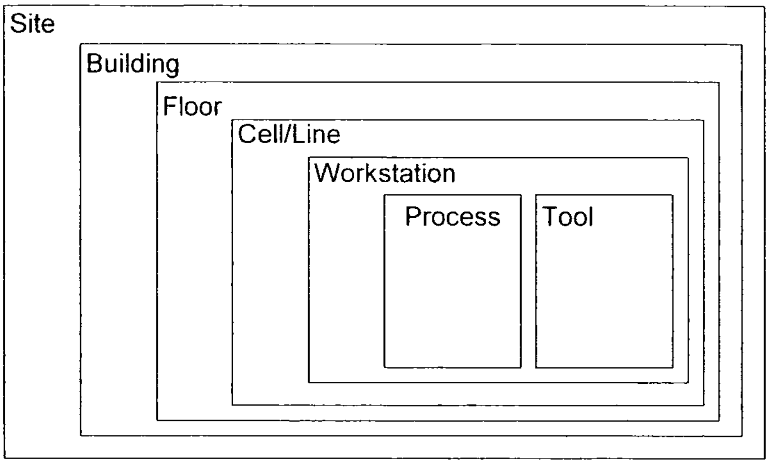

Figure 4.3: Factory model hierarchy

Inheritance is a vitally important factor within the manufacturing process data model. It is a method of reducing the information required for any given assessment by identifying objects in relation to larger entities. As indicated (Figure 4.3) a *Floor* is a subset of *Building*, therefore it may be said that *Floor* is inherits *Building* as an identifier. Later assessment will emphasise the structure of the manufacturing process data model.

4.4.3 Factory model implementation

The *site* information forms the root for the manufacturing process data model. Firstly the site level is used to identify the manufacturing process data model (Table 4.2).

Information concerning the geographical position of the site is used for the manufacturing process data model name, in addition a parent identifier is used to illustrate if this site is part of a larger company.

Table 4.2: Site level implementation

Field type	Field Name
String (site name)	**Name** - Identifier for single site
String (global name)	**Parent** - Identifier for group of factories
String (town/city)	**Location** - Geographical location of site
String (global name + location)	**Database** - Individual site database

The *Building* level inherits the site name as the parent for each specified building (Table 4.3). The additional information given is used to position the building within the confines of the site, for internal transportation reasons.

Table 4.3: Building level implementation

Field type	Field name
String	**Name** - Building identifier within site.
String (site name)	**Parent** - required for inheritance of family structure.
Double (units in fractions of metres)	**X extension** - high level identifier for time and cost calculations.
Double (units in fractions of metres)	**Y extension** - high level identifier for time and cost calculations.
Integer (metres)	**X co-ordinate** - Geographical position within site, required for internal transportation considerations.
Integer (metres)	**Y co-ordinate** - Geographical position within site, required for internal transportation considerations.
Boolean (True/False)	**Availability** - consider building for assessment.
Integer	**Buildings** - Identifier to indicate number of buildings including those not available.

The third level that makes up the factory model is the *Floor* level (Table 4.4). As indicated earlier this level is implemented for buildings that have more than one floor. The information required is much the same as for the factory level as it identifies the location of the floor within the building and the size.

Table 4.4: Floor level implementation

Field type	Field name
String	**Name** - identifier for assessment
String (building name)	**Parent** - required for inheritance of family structure
Double (units in fractions of metres)	**X extension** - high level identifier for time and cost calculations.
Double (units in fractions of metres)	**Y extension** - high level identifier for time and cost calculations.
Integer (metres)	**X co-ordinate** - Geographical position within building, required for internal transportation considerations.
Integer (metres)	**Y co-ordinate** - Geographical position within building, required for internal transportation considerations.
Boolean (True/False)	**Availability** - consider floor for assessment.
Integer	**Floors** - Identifier to indicate number of floors including those not available.

4.4.4 Cell model implementation

At the cellular level, the manufacturing process data model needs to differentiate between those processes that are grouped by process, and those that are grouped by product. The line classification that is adopted as a sub-division of the *cell* where subsequent operations are grouped together is dealt with separately. At the *cell* level the information required enables grouping to be specified, and the *floor* parent is automatically inherited (Table 4.5).

Table 4.5: Cell level implementation

Field type	Field name
String	**Name** - identifier for assessment
String (cell name)	**Parent** - required for inheritance of family structure
Double (units in fractions of metres)	**X extension** - high level identifier for time and cost calculations.
Double (units in fractions of metres)	**Y extension** - high level identifier for time and cost calculations.
Integer (metres)	**X co-ordinate** - Geographical position within floor, required for internal transportation considerations.
Integer (metres)	**Y co-ordinate** - Geographical position within floor, required for internal transportation considerations.
Boolean (True/False)	**Availability** - consider cell for assessment.

Integer	**Cells** - Identifier to indicate number of cells including those not available.

In conjunction with this, the *line* classification identifies the *line* within the *cell* (table 4.6). The information required to form a *line* is the same as that of a *cell*, the benefit being that the main factory is able to define the type of process grouping.

Table 4.6: Line level implementation

Field type	**Field name**
String	**Name** - identifier for assessment
String (cell name)	**Parent** - required for inheritance of family structure
Double (units in fractions of metres)	**X extension** - high level identifier for time and cost calculations.
Double (units in fractions of metres)	**Y extension** - high level identifier for time and cost calculations.
Integer (metres)	**X co-ordinate** - Geographical position within the cell, required for internal transportation considerations.
Integer (metres)	**Y co-ordinate** - Geographical position within the cell, required for internal transportation considerations.
Boolean (True/False)	**Availability** - consider line for assessment.
Integer	**Lines** - Identifier to indicate number of cells including those not available.

4.4.5 Workstation model implementation

Like the *cell* level above there are actually two levels to the implementation. At the *workstation* level, as described earlier, the *workstation* is a collection of *resources* and *tools*. Alternatively it can be a singular *resource* or *tool*. The information contained at this level identifies the position within the cell/line hierarchy and identifies the number of resources and tools within this level (table 4.7). The benefit of identifying the number of resources at this level is to aid the main factory in later assessment.

Table 4.7: Workstation level implementation

Field type	**Field name**
String	**Name** - required for assessment
String (site name)	**Parent** - required for inheritance of family structure
Double (units in fractions of metres)	**X extension** - high level identifier for time and cost calculations.

Double (units in fractions of metres)	**Y extension** - high level identifier for time and cost calculations.
Integer (metres)	**X co-ordinate** - Geographical position within the cell or line, required for internal transportation considerations.
Integer (metres)	**Y co-ordinate** - Geographical position within the cell or line, required for internal transportation considerations.
Boolean (True/False)	**Availability** - consider workstation for assessment.
Integer	**Workstations** - Identifier to indicate number of cells including those not available.

The base level of the classification is the actual resource and tool implementation (table 4.8). The attributes used at this level identify the functional behaviour of the operation in terms of cost rate, standard quality of the operation and production rate of the operation. These are the core values required for assessment. Other information that is required at this level identifies the operation position and availability.

Table 4.8: Resource/Tool level implementation

Field type	**Field name**
String	**Name** - Assigns resources to assessment parameters
String (workstation name)	**Parent** - required for inheritance of family structure
String	**Function** - Numerical value added to general name to uniquely identify resource, in the event that multiple identical resources are within the same workstation.
String	**Company** - Make of manufacturing process
String	**Typeclass** - family class, for example *sand casting*
Integer (metres)	**X co-ordinate** - Geographical position within the cell or line, required for internal transportation considerations.
Integer (metres)	**Y co-ordinate** - Geographical position within the cell or line, required for internal transportation considerations.
Double (units in fractions of metres)	**X extension** - high level identifier for time and cost calculations.
Double (units in fractions of metres)	**Y extension** - high level identifier for time and cost calculations.
Integer	**Power** - Value used for cost assessment (Kw)
Boolean (True/False)	**Availability** - Consider manufacturing process for assessment.
Integer (%)	**Utilisation** - Projected value supplied by user for run-time operation (percentage).
Double (£/hr)	**Cost rate** - Figure used for cost assessment

Double (μm)	**Roughness** - value adopted for tolerance assessment against required finish of product
Integer	**Quality** - Scrap rate value assigned to process.

All information stored is process specific and is required for individual analysis. Each operation inherits from the generated manufacturing process class structure. This structure refers to processes that are related by operation. Initially operations can be split into different families. There are four main families; casting, cutting, forming and fabrication. Each family has subdivisions grouped by type of operation, where each operation is a method of manufacture. Due to the time and resources limitations of this thesis, it has not been possible to compile a comprehensive database of operations. However a full classification of the available manufacturing processes has been included to illustrate the different operations available during assessment.

Casting operations

To start with casting (Figure 4.4), the class structure identifies three main types of casting operation, each of which have different core characteristics. Those operations presently available are highlighted in bold. Permanent mould casting refers to all casting operations that retain a die after use. The mould complexity and quality are less than other forms since moulds have to be aximetric, but production rates are faster. Permanent pattern casting uses a double of the final product as a pattern for an expandable mould. This method is cheap and has good integrity, but production is slow. The third form has expandable mould and pattern; this enables high complexity to be designed into the original mould. Generic considerations for casting refer to the minimum and maximum weight.

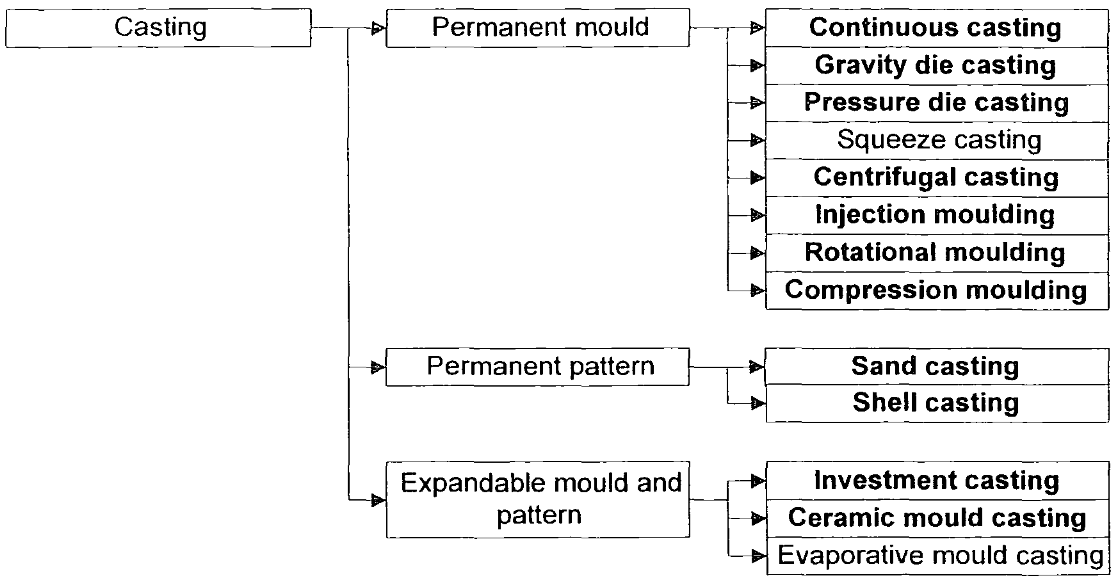

Figure 4.4: Casting hierarchy

Cutting operations

To consider cutting operations (Figure 4.5), the considerations required for cutting analysis are different than other operations. Firstly, the thickness of the material needs to be considered; secondly the volume of the raw material is required. There are two formats of cutting specified, electro machining and mechanical machining. Electrochemical and Electrical discharge machining (as highlighted) have been modelled by this research. Mechanical machining has many sub-categories, including CNC machining, milling and grinding, in addition to the basic formats illustrated. Detailed assessment of mechanical machining operations during design, encompassing tool selection and machining cycle times have been considered within other research, performed by the Design for Manufacture Research Group, and was not therefore closely investigated for this work.

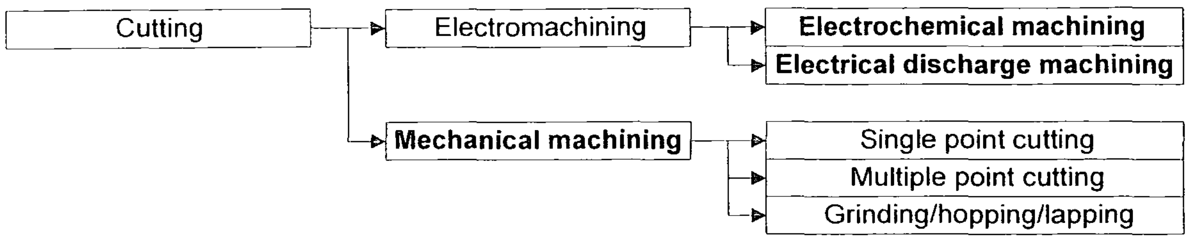

Figure 4.5: Cutting hierarchy

Forming operations

When considering forming operations (Figure 4.6), the initial consideration is for the size of the raw material, and is an operation capable of processing a given volume. Where Sheet Forming operations are used, consideration has to be given to corners and edges since considerable radii have to be allowed during processing. With bulk processes, extra consideration is required during design concerning the strength of a forged part against a cast or mechanical machined operation. The manufacturing processes considered during this research are highlighted in bold.

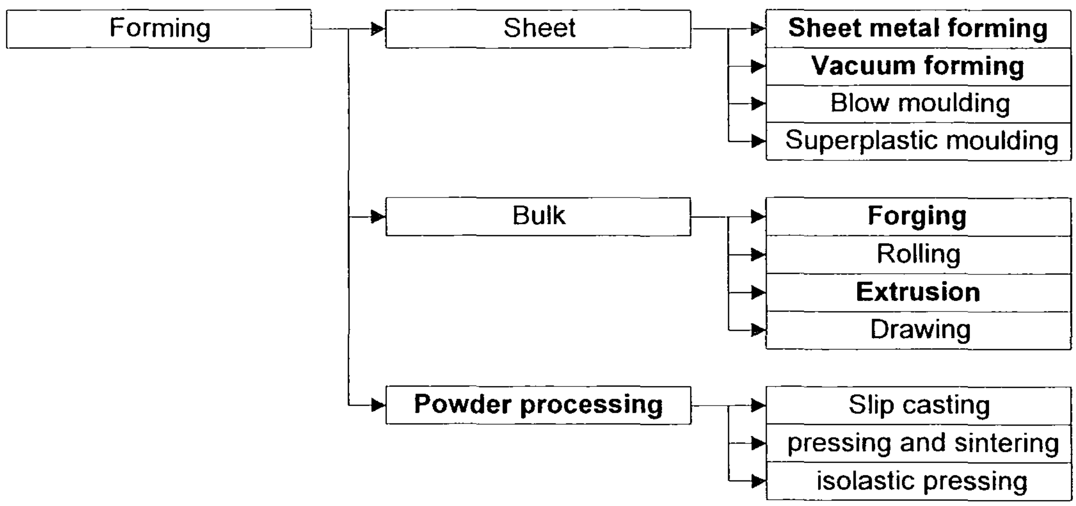

Figure 4.6: Forming hierarchy

Fabrication operations

Assembly operations are complex procedures to model at the conceptual level. A designer may know what a product or part is going to look like. That product can then be modelled through primary processing and secondary processing. However it is difficult to model assembly operations, without first confirming the primary operations and material. Fabrication methods have however been included in this analysis to show what options are available for assembly. Primary assembly methods can be modelled as welding, gluing and joining operations (Figure 4.7), to allow rough assessment. These methods however have not been included as part of this thesis.

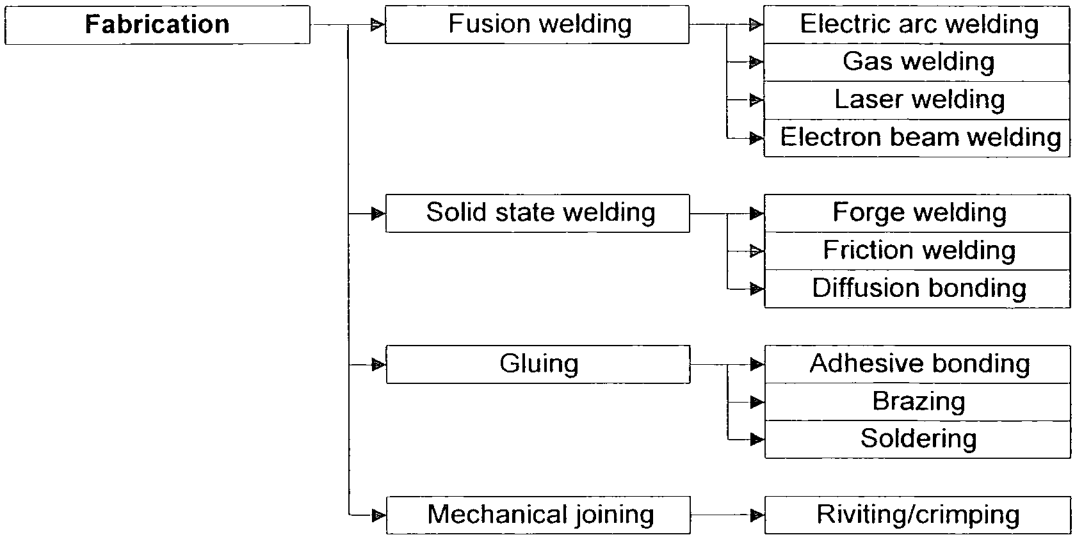

Figure 4.7: Fabrication hierarchy

For any given process, there are several mechanical attributes that are modelled. These include the minimum weight of a casting, moulding or billet to allow operations to be removed from consideration if the material is outside the process limitations. Similarly the maximum weight is used to discriminate the assessment at the opposite end of the scale. These values are not machine specific, and therefore simplify the data to consider. Additional attributes refer to the production of an operation, the tooling cost of a die or mould, the down time required to change a tool and the optimal batch size between tool changes. The permissible material classes for the specific operation are also listed for consideration prior to assessment. A full listing of the operation attributes modelled within this thesis can be found in Appendix A.

In addition to the manufacturing process data models presented, limited data referring to the general capabilities of processes were stored within separate class files. The information stored at this point refers to the optimal batch size, the processing capabilities of the operation and will be discussed further in Chapter 5.

4.5 General Considerations of Outsourcing

The integration of suppliers into the process selection phase of product development greatly increases the process capability options. These options should therefore be embraced as viable alternatives during design. There are many different reasons for using suppliers to outsource components, sub-assemblies and products. The main reasons being that either the required demand is too great for the capabilities of an internal operation, or the process required is not available at the given location. Alternatively processes in-house may already be used for jobs and outsourcing is required to fulfil the demand within the required time period. In any given situation alternative options should be considered.

4.5.1 Supplier Relationships

The relationship between the supplier and customer is a complex and important consideration in supplier selection. The two types of supply chains, internal and external, are explained in chapter 1. Where internal suppliers are considered to be partners or associated companies and external suppliers are considered to be unconnected companies. The main objective of internal and external suppliers is the same, that is, to return a quality product at an agreed process within a set time frame. Close working relationships or collaborations between organisations has been shown to facilitate improved flexibility and performance. The manufacturing process database information requiring supplier details such as operating hours, factory overhead and locations are specified in chapter 5.

4.5.2 Suppliers and Subcontracting

It is the general principle of the SCOPE system to model manufacturing processes within suppliers and subcontracting companies. It is an important element of this research to accept that different suppliers have varying manufacturing capabilities (see figure 4.8), utilising a diverse range of processes and technologies. These companies may vary greatly in size and sophistication, and retain different amounts of data referring to machine capability or performance.

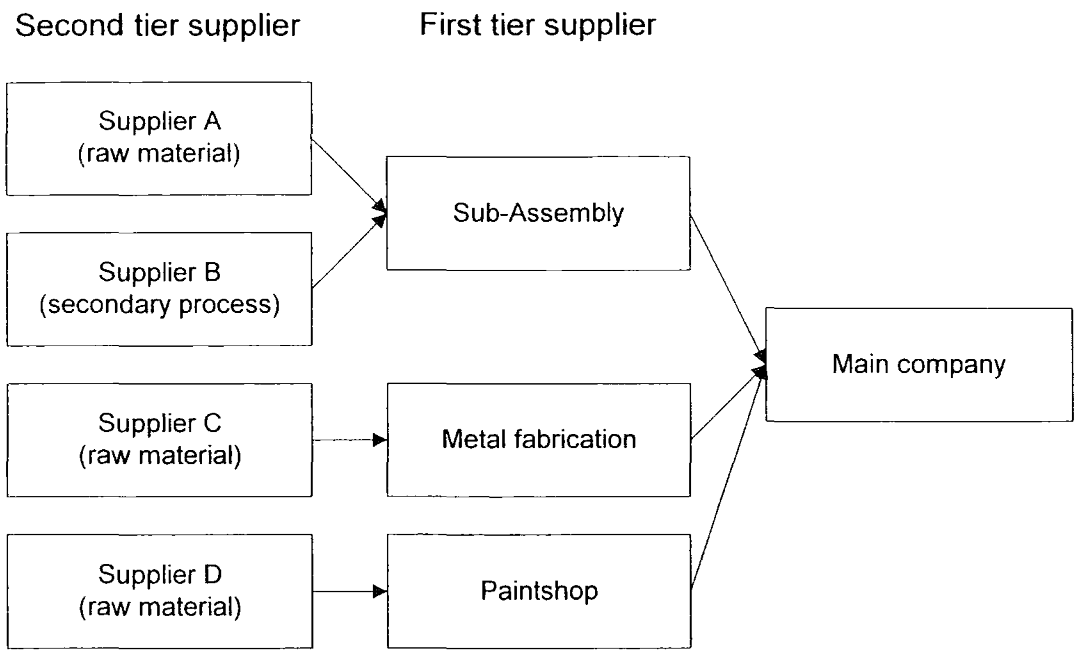

Figure 4.8: Supplier diversification

It is the intention of the manufacturing process database to illustrate a generic approach to accommodate both basic data input and specific manufacturing process details. It is essential that the proposed manufacturing process database be applied consistently at each supplier location. The SCOPE software adopted within this research has been outlined within Chapter 3 and the information required is presented therein.

4.6 Existing Process Cost Methods

Two basic manufacturing process cost models are identified as *feature recognition* and *shape complexity* (see chapter 2 section 2.6.3). Feature recognition separates the component into the individual features that create the form, and shape complexity identifies the approximate form, i.e. cylinder or prism, and by means of a complexity matrix.

The process selection technique follows the basic principles set out in previous work by Taylor, Allen and Swift (1990) and later by Esawi (1994). The principles of process selection are the identification of the raw material, clarification of the basic form of the component and assessment of applicable manufacturing processes. These methods have previously been used for process cost analysis and have been found to have reasonable accuracy for basic process costing (Allen and Swift, 1995). To further this work these methods have been adapted and remodelled to accommodate the data compiled by SCOPE. Additional considerations are given to the external supply chain and those features that make the external model unique.

4.6.1 Limitations of Existing Methods

Previous models have proved very successful as cost predictors for manufacturing. The *Feature recognition* model has been tailored for specific requirements, for example welding or machining. An example of this process cost format can be seen in the work of Maropoulos *et al.*, (1998). Feature recognition enables detailed information for each feature to be stored, and can be as generic or specific as the data given. With reference to the observed work of Maropoulos, this method has been adopted for specific processes, and is focused towards automated process and tool selection. Feature recognition enables process models to be compiled by features. Feature combinations that are not possible by a given manufacturing process are identified. An example might be *Blow Moulding*, where an internal surface profile features is not possible. Therefore, any specified feature combination, where an internal feature is required would indicate that *Blow Moulding* was not a suitable manufacturing process.

Alternatively, models based on the *Shape complexity*, such as tubular or prism forms are process independent, but do not easily facilitate automation. Originally developed by Allen and Swift (1990) and later adapted by amongst others Esawi (1994). *Shape complexity* refers to a chart method for determining the form of a part design. Operator recognition of the *Shape complexity* is required, and although there are quite specific guidelines and descriptions to facilitate *Shape complexity* selection, there still allows an element of interpretation. This in itself is not a repeatable process, since the designers' interpretation of an objects complexity may vary slightly. Using the basic theory that there are three basic forms: round, square and thin walled, the analysis is based on the features associated with the base form.

Part envelope is largely a solid of revolution

Part envelope is largely a prismatic solid

Flat or thin walled section component

A second criteria base for the decision is thus:

Basic Features	Straight forward processing where the operation can be carried out without a change of setting or the need of complex tooling. Parts are usually uniform in cross section
Secondary Features	As above, but where additional processing is necessary or more complex tooling is required
Single axis	This is usually the axis along the components largest dimension, however, in the case of cylindrical or disc shaped components, it is more convenient to consider the axis of revolution as the primary axis
Multi-axis Features	Parts require to be processed in more than a single axis/set-up
Non-uniform Features	Parts require the development of more complex processing techniques/set-up
Complex Forms	Parts need dedicated tooling and the development of specialised processing techniques
Through Features	Features which run along, across or through a component from one end or side to the other

The complexity criteria can therefore be described as single/primary axis, multi axis and complex forms. The minimal amount of required manufacturing process information enables this format to be adopted for rapid process cost assessment, but requires considerable user intervention.

It was considered not viable to directly adopt either of the previously stated methodologies of *Shape complexity* or *Feature recognition*, since the outline to this research specified both a rapid process cost assessment and an automated assessment. Alternatively, an amalgamation of the knowledge and procedures would be critical in any further developments. The information required for analysis is not specific enough for automatic assessment and the variable coefficients are too subjective. However it is important to identify those ideas that have been adopted to formulate the process selection method.

4.7 Process costing

Before describing the main body of the process costing, there are several parameters that should be illustrated. These include the method of shape generation, either shape complexity or feature recognition, and material or process selection. The decision of whether to first specify the material or process will play an important role in the subsequent decision choices. This can be described as the 'chicken or the egg' question, but is required to format the structure of a process selection model. Additionally, external factors that influence the cost of production, including the factory operating cost, external and internal transportation costs.

4.7.1 Costing Elements

The proposed method has a different criteria base from previously stated methods of Swift and Allen (1995), and Taylor (1990). Existing methods have been adapted to model internal processes, where detailed process information is available, the internal capabilities are known. Additional consideration needs to be given to other factory factors that will influence the cost of a part. These can be summarised as:

- The operating cost for a given operation.

- The economic batch size for a particular manufacturing process
- The external transportation batch size and transportation frequency necessary to fulfil the demand.
- The internal cellular level transportation cost and time
- The internal factory level transportation cost and time
- The generic operating costs associated with the factory

As explained in Chapter 2, section 2.4.1, linear programming techniques were adopted to compile the costing for process selection. This in turn required the factors that compiled to form the costing method to be separated. This included material costing, process costing and transportation costing. Material costing was the first element

$$M_C = D_M \times V \times R_C \qquad (4.1)$$

Where, M_C is the material cost per part (£), D_M the density of the chosen material (kg/m^3), V the volume of the required form (m^3) and R_C is the material cost (£/kg) multiplied by the waste coefficient (dimensionless) to give the actual cost (£/kg).

This format allowed material density to be adopted as the controlling factor, and consequently material cost is calculated by the standard kilogram rate. The volume is obtained from the required product model, which quotes the volume as a standard rod, cylinder or prism. Consequently, material cost-rate is quoted in each format since there are small discrepancies between the costs of material in raw material form. The complete materials database adopted within SCOPE is detailed in Appendix B.

After the parameters of application have been set it is time to consider the actual processing cost. To determine the actual processing cost it is first important to determine the variables required for the result. Questions like, *what is the number of required parts?* Significantly influence the calculated cost. Also what are the capabilities of the selected processes?

The *hot size* batch refers to the optimal number of batches suggested for a specific process and the required quantity. This value is based on the number of parts which can be produced per set-up or tooling change. By dividing the quantity by the *hot size* (H_o) (see equation 4.2), required number of set-ups is given. If the quantity does not divide equally between set-up and tooling batch sizes then an additional set-up or tooling change would be required to accommodate the surplus. An integer is added to the equation to ensure that the hot size is equal or greater than one.

$$H_n = \left(\frac{Q}{H_o} \right) + 1 \tag{4.2}$$

Where, H_n is the number of tooling changes required for a given quantity. The number is rounded up to the next integer value, Q is the quantity of required parts and H_o the number of operations between tool or die changes. The addition of one is required to increment the number of number of batches, since the integer value of H_n is always taken.

The actual production rate relates to the optimal production rate, as indicated by the process, and relates this to the required features. Depending on the process family and the required features, the production rate is manipulated to reflect realistic conditions. Production rate, P_a (parts/sec.), is given by:

$$P_a = \frac{P_s}{H_n} \tag{4.3}$$

Where, P_s is the ideal production rate (parts/sec.) for the process and H_n the number of set-ups required for a given quantity.

The production time required per process per part can be calculated as follows:

$$T_p = \frac{1}{P_a} + \left(\frac{H_n \times T_t}{Q} \right) \tag{4.4}$$

Where, T_p is the required process time per part (sec.), Q the quantity of parts, P_a the actual production rate (parts/sec.), H_n the number of required batches and T_t the tooling time for each set-up (sec.).

To consider this as the actual factory time would be unrealistic. Additional consideration needs to be given to internal transportation. To do this, firstly the mode of transportation needs to be considered. Any mode has a given cubic capacity for load, and a transportation time and cost rate associated with its progress. Equation 4.5 therefore expresses the internal transportation time considerations per part.

$$I_p = \frac{V_P}{IT_V} \times \frac{IT_D}{IT_S} \tag{4.5}$$

Where, I_p is the required internal transportation time per part (sec.), V_p the total volume of parts (m^3), IT_v the maximum volume of transportation mode (m^3), IT_d the distance between two processes of process and storage (m), and IT_s the internal transportation mode speed (m/s).

The principal factors required for process costing are almost complete. The final consideration is the factory operating cost. This consists of the operating overheads i.e. heating, lighting and paperwork, and the profit margin.

Tooling costs are the costs involved in making the tools, dies, moulds, patterns and special jigs and fixtures necessary for manufacturing a product or component. The tooling cost is greatly influenced by the selected production process. For example, if a part is to be made by casting, the tooling costs for die-casting is higher than for sand casting. Similarly, the tooling cost in machining or grinding is much lower than that for powder metallurgy forging, or extrusion. In machining operations, carbide tools are more expensive than high-speed steel tools, but tool life is longer. If a part is to be manufactured by spinning, the tooling costs for conventional spinning is much lower than for power spinning. Tooling for rubber forming processes is less expensive than that for male-and-female sets used for drawing and stamping of sheet metals. High tooling costs on the other hand, can be justified for high-volume production of a single item. As stated previously, the expected life of tools and dies and their obsolescence because of product changes, are also important considerations.

Fixed costs include the costs of power, fuel, taxes on real estate, rent, and insurance, and capital, including depreciation and interest. The company has to pay these costs regardless of whether or not it made a particular product. Thus, fixed costs are not sensitive to production volume. Capital costs represent the capital investment in land, buildings, machinery, and equipment and represent major expenses for most manufacturing factories.

The factory cost per part is expressed in equation 4.6.

$$F_r = (T_p + I_p) \times F_f \tag{4.6}$$

Where, F_r is the factory cost per part (£), T_p the total processing time per part (sec.), I_p the internal transportation time per part (sec.), F_f *the* standard factory cost rate (£/sec.)

The processing cost as shown in Equation 4.7 can therefore be described as the accumulated material and process attribute costs.

$$C_p = M_c + F_r \tag{4.7}$$

Where, C_p is calculated cost per part (£), M_c is the total material cost per part (£), F_r the total factory cost per part.

The presented process costing considers the process at the factory level, and does not consider external transportation considerations.

4.7.2 State of the Art manufacturing operations

When considering existing manufacturing operations, it is important to explore all manufacturing options. To extend this principle further, the idea that it is possible to add new technologies to an existing facility would add a new paradigm to a factory. The ability to perform "what-if" scenarios would then be possible, utilising the existing operation and new processes. The fundamental idea would be to indicate what the effects of new processes and technologies would be on the production rate, cost rate and utilisation of a factory. Hypothetically, this information could then be used to negotiate future customer contracts, based on the proviso that the supplier was to adopt the new technology.

The concept of attaining a distributed supplier network of factory data is a novel element of this research. It is possible to accommodate this idea into the schematic of the SCOPE system by integrating a function to allow the addition of new processes into the final analysis. This function will require process manufacturers to publish individual process characteristics on a designated web site, for the SCOPE system to view. Practically this is not manageable with the given time and resources, SCOPE will allow the manual input of process characteristics during assessment.

4.8 Summary

It is proposed that the data generation and process selection method outlined within this chapter will enable operations within the extended enterprise to be modelled using generic process data, during the early design phase of product development. The novelty laid out in section 4.7 has highlighted that existing methods for process planning and selection have been limited to a singular factory process or group of processes. The extensions to this theory have included the evaluation of different transportation modes within the factory, and the evaluation of external transportation. The cost models presented are therefore specific to the SCOPE system.

The information required for process selection within the SCOPE system has been presented herein. A process classification has been identified and described, and the supplementary information required for analysis confirmed.

Chapter Five

Process Selection

5.1 Introduction

The previous chapters explained the background information required for Process Selection (PS). This information included the manufacturing process data generated and stored at the supplier locations, and the computational system designed to facilitate the implementation of PS. This chapter presents the proposed PS methodology for suppliers' manufacturing operations. To do this the PS function is separated into functional tasks. Looking at the individual data manipulation steps, the process can be separated into three functions, 1) access the product model and store the data, 2) connect to the supplier manufacturing process database and format their data, and 3) combine this data for assessment. Additionally previous relevant work is referenced during this chapter to validate both the data used and to confirm the focus of this research. The use of PS will add an extra paradigm to early design considerations.

5.2 Product model specification

A product model is the generated product data model, used to describe the physical properties of a specified product. In particular, a product model stores geometrical and functional information about a product. Information stored is restricted to the geometrical domain and material type.

Product data differs in quality of information as well as in quantity of detail from conceptual to detailed design. In conceptual design, decisions are made between alternative function structures that could meet the specification of the product. This determines a basic list of components and their principle attributes. It is neither possible nor desirable at this stage to produce a geometrical representation of the part, since this will depend on factors yet to be considered. At this stage, however, the developer should be able to make some assessment of the relative manufacturability of alternative conceptual design options, in order to select the most appropriate.

In embodiment design, the component or the product is designed in more detail by mapping the functional requirements of the product onto particular features of the component. The key functional dimensions of the component are identified as parameters in the product model and the desired values are determined. At this stage it becomes possible to produce a schematic representation of the component geometry. Further, there is a requirement for the assessment of the manufacturability of the component and identification of production processes.

A key specification for early design consideration is that PS is a generic technology, intended to be applicable to a wide variety of manufacturing processes. The specification has been used to develop the operating procedure of the software. Other specifications are:

Early Design	The model must be developed to operate during conceptual design.
Variable detail	The system must be designed to operate with the minimal amount of data, normally consisting of product volume, material, and basic geometry.
Process identification	Each process must be identified during analysis to allow for routing methods to be applied
Resource selection	The system must be able to identify individual resources for

	assessment, and mark these processes such that their details can be retained for factory analysis
Sequencing	The process planning function must be able to identify the order of operation of primary and secondary processes

The product model is required for PS assessment. The product model is loaded into SCOPE before the assessment can commence. The information stored within the product model contains all information relating to the identity and physical assembly of the product, and takes the following form.

Table 5.1: Process attribute specification

Field	Purpose
Product name	The general name of the product is stored as an identifier during assessment. For a product containing more than one component the product name is essentially the 'family' or 'root' name.
Order number	This is the specific order number associated with the product, and is a unique identifier for the component, stored at the root level.
Component name	This is the name of the specific component to be modelled, unlike the product name, the component name identifies the
Required features	These are the features required to form the required component; multiple features are stored.
Required set-up	For every feature there is an associated set-up. For machining operations the set-up equals the total required tool changeovers. For non-machining operations where all features are created simultaneously the set-up time is taken as one, since the operation is a single shot operation.
Required tolerance	Similar to the set-up, the tolerance associated with an

	individual feature is stored. There are therefore multiple tolerance settings.
Order quantity	The number of parts required for a single assembly is stored in the product model. The operator suggests the actual manufacturing requirement during assessment.
Material	The material is required during process cost assessment to determine the raw material cost per component. Each component of the assembly identifies its own material.
Part geometry	The geometry refers to the initial billet or mass of material prior to processing. This information is required for each identified material, and is required to determine the most appropriate raw material cost.
Viable processes	The viable processes are those operations identified by the SCOPE system, in relation to the identified material. For example, if thermoplastic were identified as the required material, then casting operations would not be suggested. This information is required to identify those suppliers whom have the relevant manufacturing processes.

After the product model has been loaded into the system the next step is to decide which factory to model against the data. This function is possible by opening a connection to the supplier factory.

5.2.1 Assembly representation

At the basic level, the product model can be considered as a set of interacting components. Simple products may consist of just a single component, whilst complex products consist of many levels of sub-assemblies and can include many components. An important feature of the product model is the ability to represent the logical grouping of product components into assemblies and sub-assemblies. At this level, the product model resembles the product Bill of Materials. When representing assemblies, the method of fixture must be stored. The product model recognises that assemblies may be created by temporary fastening processes, or by permanent joining processes such as welding or the use of adhesives. Connections between components are represented using assembly features relations, described in addition to the features.

5.2.2 Component representation

When seeking to represent the product design in conceptual design stages, it is important to recognise that the design will have many undetermined aspects. Design theory suggests that the best designs are achieved when each decision is left as late in the process as possible since this imposes the minimum number of constraints for each subsequent decision. This leads to the identification of two requirements of the process selection model:

- A flexible product model which allows the design to be changed easily
- A model which can represent conceptual designs and detailed designs with the same object constraints

5.3 Process selection functionality

The PS functionality describes the requirements of SCOPE, focusing on presenting PS as a capability for early design consideration. The architectural outline for the SCOPE system can be seen in chapter 3, see section 3.3. From the specification it is possible to develop the functional description of the algorithm for PS. The algorithm must transfer the product model data, and analyse each described feature. Following the data encapsulation the algorithm should assess all of the suppliers' manufacturing processes against the product data and form a list of possible manufacturing processes. The PS algorithm may produce a number of alternative manufacturing options depending upon the level of assessment used. In summary, the level of assessment is the limiting factor in PS, where a constraint is put on the manufacturing processes available for evaluation. The level of assessment is set to only include manufacturing processes within a given area. For example, this area can be set to include the whole factory site or a single workstation.

To facilitate the user, PS is operable in two formats; either automatic or manual process selection (see figure 5.1). Automatic process selection is designed to automatically assess and order manufacturing processes, based on the assessment criteria given. The results are then classified and stores for further work. Manual process selection requires the user to be familiar with both the capabilities of the SCOPE system and the manufacturing processes available. Specific manufacturing processes are highlighted to perform each task required by the given product model. Similarly, the results are stored in the same format as the automatic process selection for later manipulation.

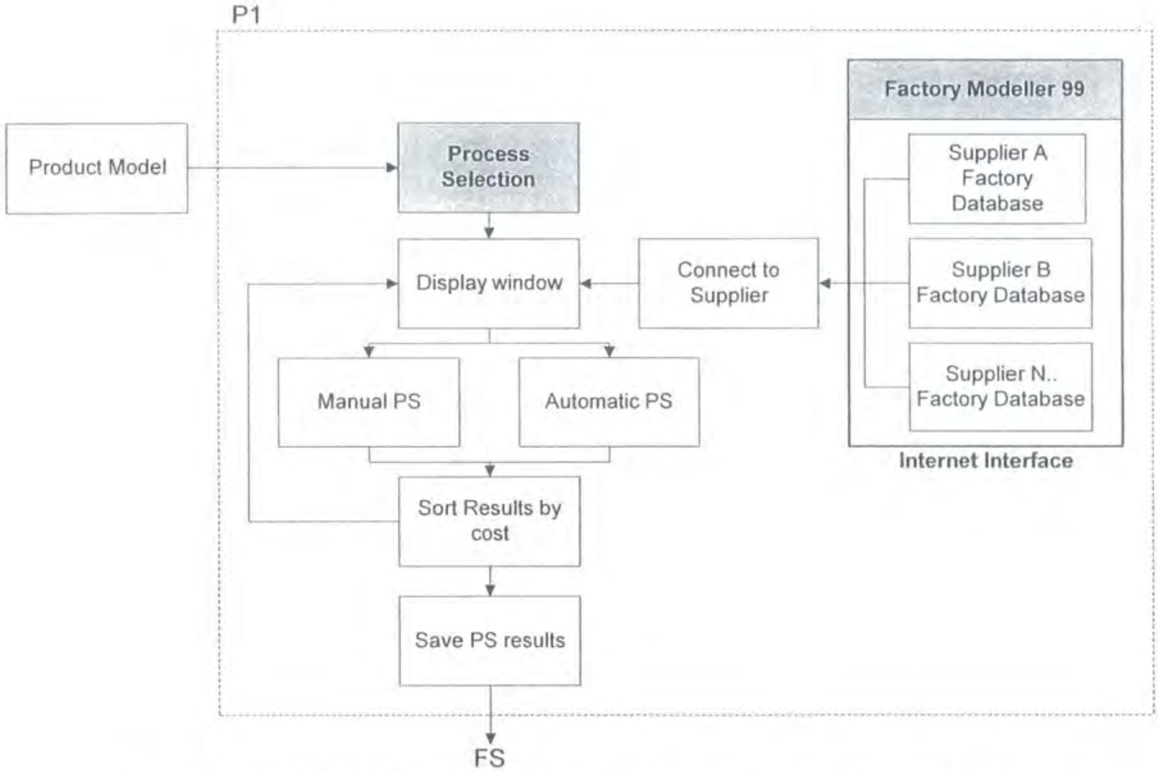

Figure 5.1: PS Overview, including *manual* and *automatic* process selection

At each stage of the algorithm where important selections are made, the user should be able to view the alternatives that are available and the choices made by the system. The main tasks of process route generation are detailed in the following sections.

5.3.1 Product model selection

Before any analysis can be carried out, the required product model data is collated and stored, using the Factory Modeller 99 software. The information is stored within the Powersoft PowerJ database. It has not been the intention of this research to propose a new product model architecture. Moreover it has been the intention to show how the product model integrated within PS can be used in conjunction with existing work on Aggregate Process Planning (APP) developed by the Design Manufacturing Research Group. The product model produced to accompany the APP work is a relational database of information. The hierarchical format of this model is explained in chapter 3, section 3.4. The APP is developed for specific manufacturing processes such as machining or welding, generating sufficient data to produce product routings and timings. The required product model as justified by the APP methodology is inherited as the prerequisite for PS.

5.3.2 Material selection

It has not been the focus of this work to integrate a comprehensive materials database into this research. Empirical material data is available from many sources, i.e. textbooks and raw material distributors, and this can be incorporated into a materials database. The required attributes are similar to those used in alternative process costing methods, such as Allen and Swift (1990), regarding material density and cost. The cost is specified to be a linear relationship between density and cost. The cost is based on values quoted by leading raw material manufacturers, for example Baco, Multi Metals and Corus for metals.

This research has created a materials database of materials suitable for the available manufacturing processes. A complete listing of the included materials can be found in Appendix B.

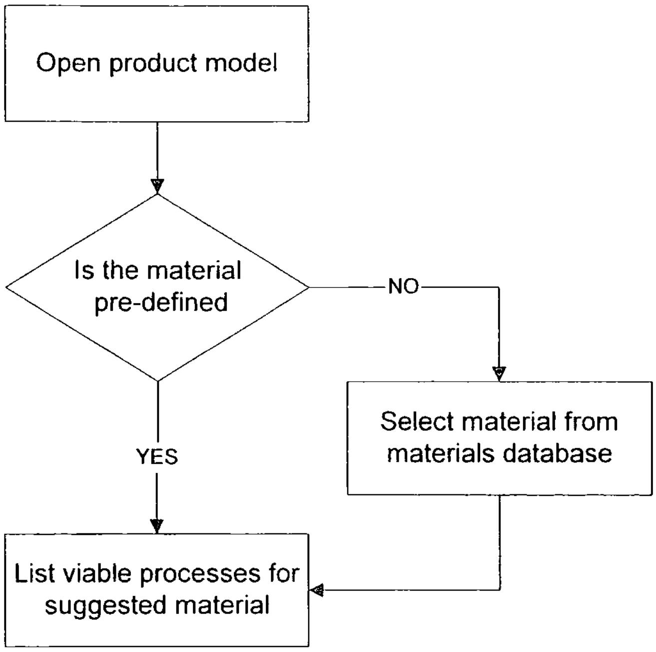

Figure 5.2: Material selection algorithm

Upon selecting the material a list of manufacturing operations are provided. These indicate those manufacturing operations approved for assessment for the specified material (Figure 5.2). The manufacturing approval is guided by manufacturing process data, stating manufacturing methods for any material. The material and manufacturing method combinations are inserted into the materials database during development. Suitable manufacturing methods are therefore obtained from the materials database after material selection. New manufacturing methods or materials are added by amending the database, as described in chapter 3, section 3.3.2. At this point in the assessment the required features have not been compared with the suggested processes, neither a supplier connection established to view what actual processes are available.

5.3.3 Manufacturing process selection

To initiate the SCOPE software a password is required. Initially the system administrator should be responsible for distributing access to SCOPE. After following the *Login* and product model generation sequence, supplier access can be started. The system requirements have been laid out in Chapter 2, section 2.4.3. After establishing a connection with the supplier factory, it is now possible to view the available manufacturing processes (see, figure 5.3).

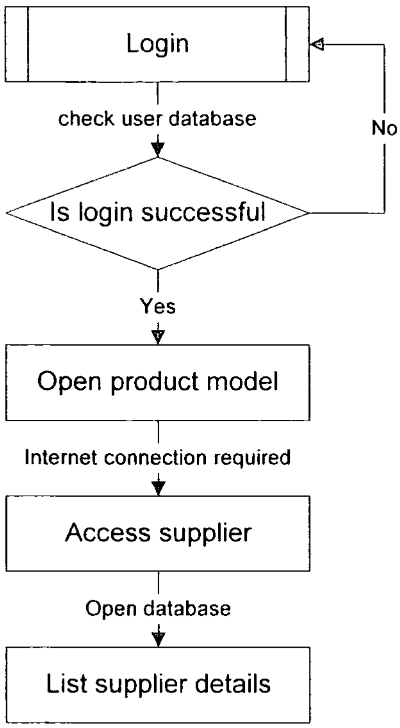

Figure 5.3: Manufacturing process data generation

Available manufacturing processes belonging to the supplier are illustrated, however they are not necessarily feasible. At this stage in the selection process, the manufacturing processes have not been ordered by any form of sort algorithm and therefore will not necessarily comply with the required roughness and quality constraints stipulated by the product model. The information that is known refers to the process Typeclass. The Typeclass is the parent name of the process; an example of this is sand casting, which is the parent Typeclass for any specific sand casting operation.

5.3.4 Task verification

Task verification is required for those primary processes that do not initially comply with the all requirements of the product model. Consideration is given to the primary processes, to check the feature suitability, quality and roughness capabilities. If the primary process capabilities are not sufficient then secondary operations should be suggested to fulfil the requirements. An option that is given to the user allows the scope of the operation to be altered depending on the user preference. This is done by restricting the factory level view of the assessment. The factory levels for the associated processes can be applied at five different levels:

Site	Any process combination within the same site
Building	Only those process combinations that are within the same building
Floor	Any process combination upon the same floor
Cell	Any process combination within the same cell/line
Workstation	Only those process combinations that are contained within the same workstation

For example, by setting this parameter to equal *floor*, the assessment would only include primary operations, or combinations of primary and secondary operations that are on the same floor. The object of this function is to give the user the ability to reduce internal transportation, since a large proportion of the time spent in a factory is wasted, either by internal transportation or stockpiling during manufacture.

5.4 Manual process selection

Manual process selection is the individual selection of manufacturing processes for the required features, as specified by the product model. The method relies on the knowledge of the design engineer to make an informed decision concerning the combination of processes. This method does not comply with the '*process scope*' principle indicated earlier, where the level of assessment is governed by the scope of application, since the method relies on the correct selection of manufacturing processes.

5.4.1 Manual process option generation

It is the purpose of the manual selection technique to allow full access to the supplier's factory, and full control over which features are proposed for each machine. Due to the nature of the assessment the designer would require a working knowledge of process capabilities, but if features are suggested for unsuitable processes then the software should highlight this fact.

All supplier resources are indicated prior to assessment, but those resources that are not viable are indicated as being void. In addition, the factory availability at each level governs whether the information is displayed. For example, if a 'cell' has been indicated as being unavailable, then the workstation resources within that cell will not be illustrated. This function allows the customer to work with those processes that are available.

5.4.2 Manual process selection functionality

Manual selection functionality allows specific resources to be assigned to each feature. Machines are selected directly and their sequence is fixed for the following assessment. Required process information is specified within the class hierarchy (see chapter 3, section 3.4). At each of the factory levels *site, building, floor, cell/line* and *workstation*, the available manufacturing processes are identified by a Boolean (yes/no) flag (see chapter 4, section 4.4.1). Initially the *building* level is indicated to the user, this lists all buildings within the given supplier *site*. Upon specifying a building, the *floors* contained within that building are shown. Consequently by specifying a particular *floor*, the available *cells* are shown. This progression also applies to the *line* level, and *workstation* level. At the *workstation* level the user has control over which manufacturing processes are applied to a given feature.

The function operates by identifying the number of required features, and available manufacturing processes. When the user assigns manufacturing processes to required features a list of the combinations is compiled. Before the assessment is performed SCOPE inspects the given combinations to check for both feature duplication and operation commonality. For features that require secondary machining to attain the required quality, the user selects a second manufacturing operation that achieves that quality level. For example, the user is able to select a single feature and request a casting operation. It is feasible to suggest that a rough casting is produced, and secondary operations are required. Secondary operations, such as milling or machining add detail, additionally a polishing operation may be utilised to finish the part. The *Typeclass* for the casting operation (e.g. sand, shell, gravity die, etc.) retains a list of features feasible for any given operation. These features are then compared to ensure that there are no conflicts in the requested operations. The user is informed if a conflict occurs.

5.5 Automatic process selection

Unlike manual selection, the automatic process selection method does not allow the user to manually indicate which features are associated with specified processes. Consideration is given to those manufacturing processes that fulfil the requirements of the given product model and constraints of the factory.

5.5.1 Automatic process option generation

By using the automatic process selection method the user is able to generate multiple results for the selected product model. A heuristic approach has been adopted for process generation. All combinations that fall within both the *process scope* and assessment criteria will be assessed.

As with the manual selection, only those processes that are available at the time of assessment are included in the analysis. Before assessment commences the supplier capabilities are separated into three divisions, primary for all casting, moulding and forming operations, secondary for all machining operations and tertiary for all finishing operations such as polishing and buffing. It has been the intention of this thesis to focus the attention on the primary processes, but consideration has been given to secondary processes.

5.5.2 Automatic process selection functionality

The level of assessment controls the number of manufacturing operations available to the assessment. The level of assessment indicates whether the PS includes all manufacturing operations across the *site*, or only within a single *building*, or on a single *floor* and so on to only include those manufacturing processes in a single *workstation*. Once the scope of the assessment has been set, the selection function is then able to model the selected processes. Before any assessment has been performed the suggested processes are those that fit the process family classes designated by the product model (figure 5.4). Those processes that do not comply with the required tolerances and quality will be discarded from the assessment.

If all processes within the supplier *site* are selected, then the assessment may take a considerable period of time to check and verify if the manufacturing combinations adheres to the to product model quality, process features and tolerances. It is, however, possible for the operator to specify the preferred number of presented results, the automatic sequencing and ordering methods then uses this limit to present only the optimal results.

5.5.3 Automatic sequencing

Unlike the manual selection process, the automatic sequencing is carried out by the system. It is reasoned that primary processes occur before secondary processes, and this rule is applied throughout the sequencing. For primary processes that fulfil the product model requirements this is a simple process of assigning internal transportation to the processes. For primary processes that do not comply with the product model requirements, secondary processes are suggested to fulfil the requirement. If this is the case then the secondary process' capabilities have to be assessed against those of the product model. This in turn confirms if the required combination is viable.

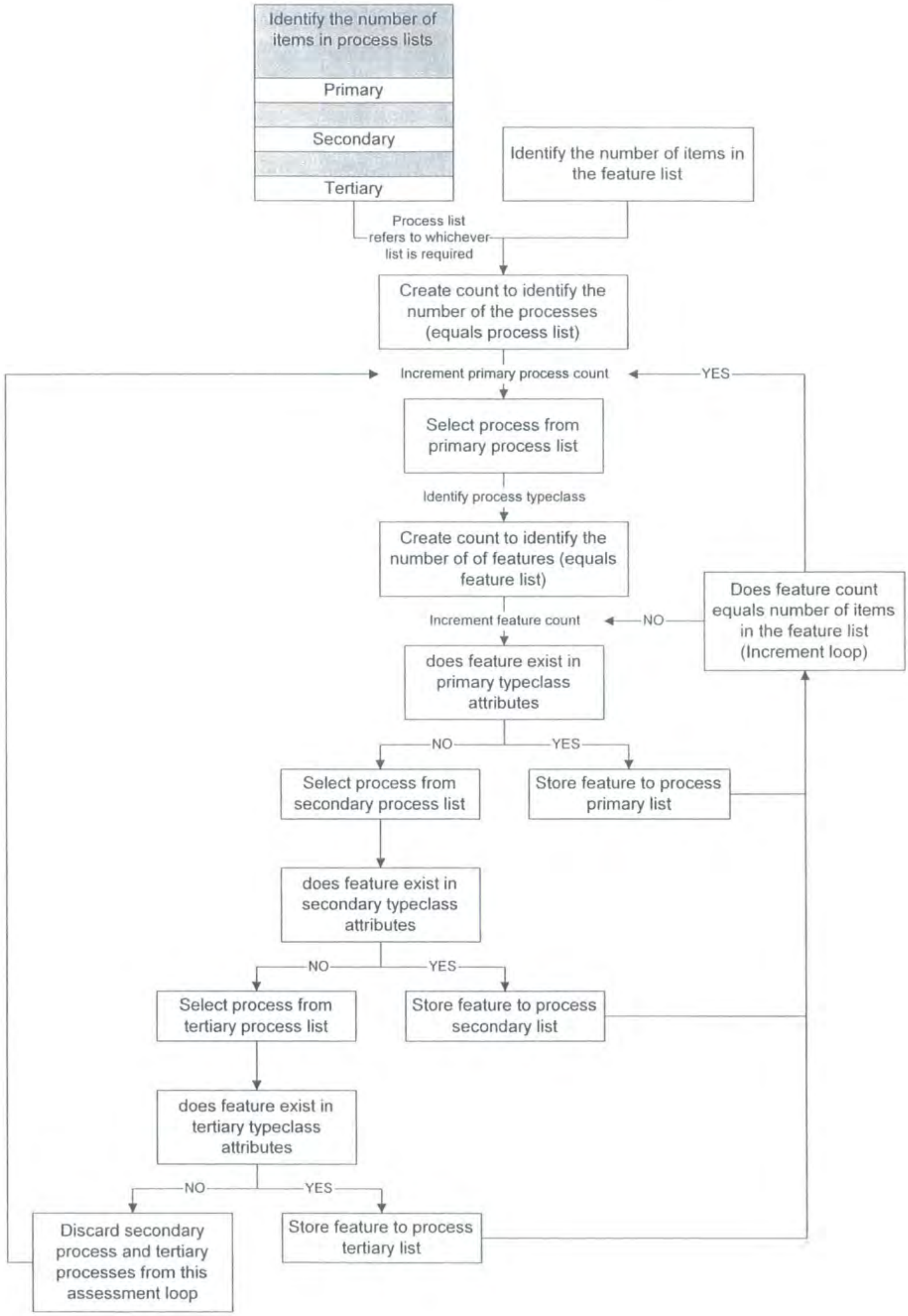

Figure 5.4: Automatic process selection algorithm

5.5.4 Automatic order method

The order method has been developed to optimise the generated manufacturing process result set. The method illustrated in figure 5.5 does not specify the function using the method. The method deletes the existing result set from view, and scrolls through the new result set for the minimum value. The algorithm is then recycled in ascending order. If two results are giving the same cost value, then it is the result that is encountered first that is given priority in the result classification. The number of results presented is specified by the operator (see chapter 5, section 5.5.2).

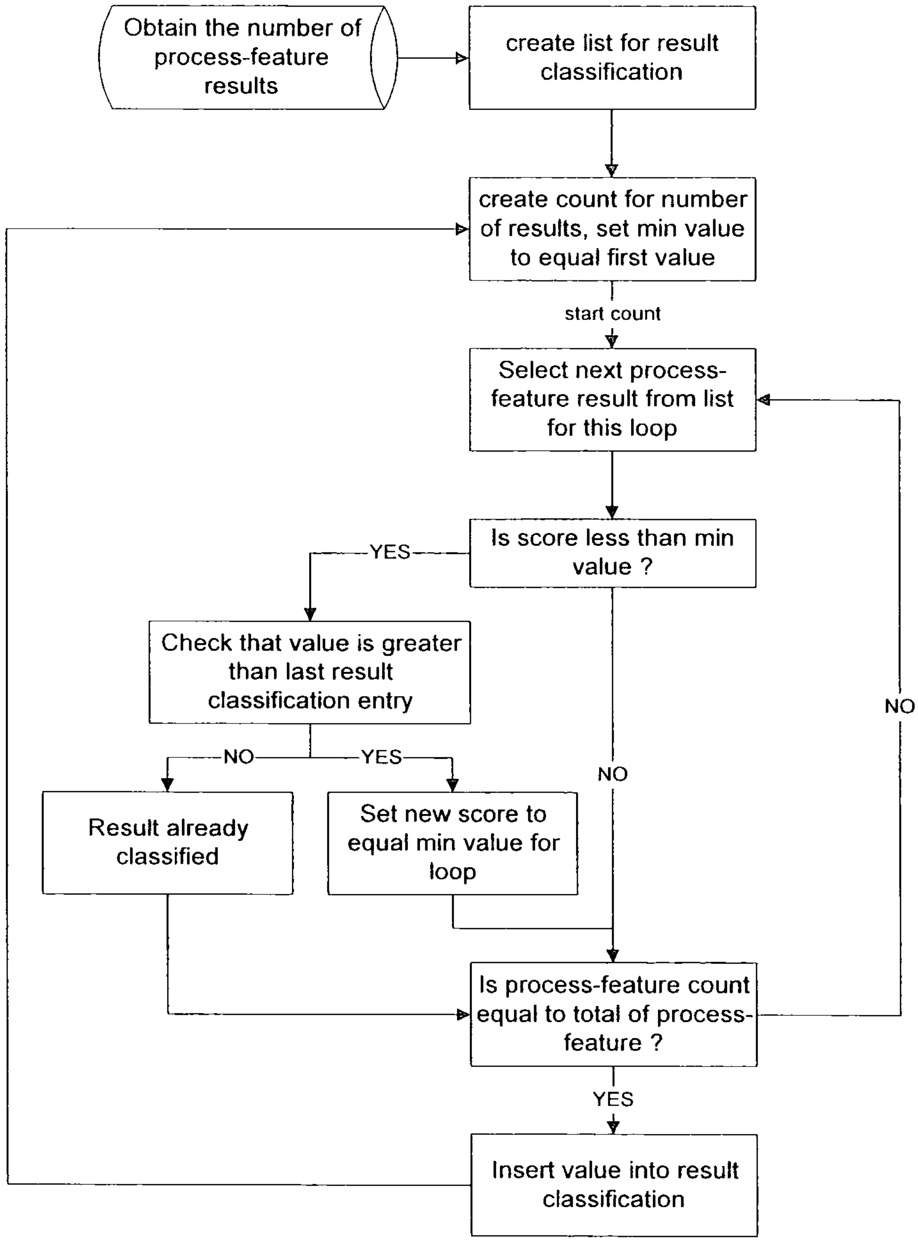

Figure 5.5: Order method functionality

5.5.5 Automatic machine selection functionality

From a system viewpoint, SCOPE has performed a series of tasks. The proposed manufacturing processes were identified, examined and evaluated. The identification has followed the principles laid out in chapter 4 (section 4.3). For each process the evaluation includes external transportation and factory costs considerations (see Equation 5.1). This is a reiteration of the process cost function presented in chapter 4 (section 4.7.1, equation 4.7), for an internal cost assessment. However external factory considerations have been included.

$$C_T = M_c + F_r + T_e \tag{5.1}$$

Where, C_T the calculated cost per part (£), M_c the total material cost per part (£), P_r the total process cost per part (£), T_p the total processing time for quantity (sec.), F_r the total factory cost per part (£), H_n the required batches per quantity, T_c the tooling cost per part (£), Q the required quantity and T_e the external transportation cost (£).

5.6 External considerations

The proposed process model has illustrated the need for internal costing analysis that is more detailed than the basic process cost. Due to the nature of the distributed PS problem, external factors are fundamentally important in any eventual cost analysis.

Different formats of external transportation have been discussed in chapter 2 (section 2.3). The many formats of external transportation, from cycle courier to the postal service to a ship container, impose varying cost and time values on the process selection. Due to time limitations of this work, it has not been practical to model all formats of transport for this thesis. It was therefore considered that six common formats of external transportation should be modelled, as shown in Table 5.2. The values given for each format are approximate values, and not entirely accurate. The inaccuracy occurs for example from variations in Transit Van capacity, between different makes.

Alternatively inaccuracies may occur from preferential rates from couriers or competitor rates. Real world models should therefore be based on actual courier rates supplied by the main factories couriers. The six presented formats have different capacities and speeds associated with the mode.

Table 5.2: Transportation formats

Mode	Volume (m)	Cost Rate (£/mile)
Transit van	1.5 x 2.0 x 1.5	0.34
Box truck	2.0 x 4.5 x 2.0	0.25
Articulated truck	3.0 x 7.0 x 2.5	0.30
Train	6.5 x 20.0 x 5.5	0.30
Air	2.5 x 10.0 x 2.5	0.30
Sea	3.5 x 20.0 x 3.5	0.30

As explained, the values given for transportation capacity are approximations based on average freight geometry. In reality the *weight* of a cargo play as important a role in the cost calculation of freight as the size, particularly for air transport. Alternatively *groupage* charges for road transport are an alternative way to send a delivery. For *groupage* the cost is based on both the size and weight of the delivery, and whatever else is dispatched on the same lorry. Next-day delivery couriers often base charges on *groupage*. It is not possible to account for this scenario, since other deliveries are unknown to the main factory and therefore the external cost assessment will not try to include *groupage*.

The calculations are however based on volume alone since it has not been possible to model exact transport forms, and to pick an arbitrary value for weight would be futile in the generic theme is this work. The method presented is thought sufficient to prove the concept of external transportation consideration. From the given table it is possible to assign a transport mode for the specified product quantity. The transportation cost associated with the external transportation is thus:

$$T_p = \frac{\frac{V_P \times Q}{V_M} \times CR \times D}{Q} \qquad (5.2)$$

Where, T_P is the cost per part associated with external transportation (£), V_P the volume of the part (m^3), Q is the order quantity, V_M the capacity of the transportation mode (m^3), CR the cost rate associated with the transportation mode (£/m) and D the distance between the supplier factory and the customer site (m).

5.7 Result classification

To permit the available results to be used for FS it is considered that a record of the PS results is retained. It was considered that a database be used to store the process results. Data from this database can be utilised in two formats. The stored results enable the same product model to be reassessed many times for different factories and processes. In addition, it enables the results to be made available for factory selection.

The information that is required should relate to the individual process, the factory to which it belongs, and the manufacturing attributes considered during production. These attributes may include any of the *Resource/Tool* values obtained from manufacturing process database (see Chapter 4, section 4.4.5). It is therefore necessary to consider all factors in the eventual model and to select those values that will be of significance during factory selection (see Table 5.3).

Table 5.3: Result attributes

Factor	Significance
Batch size	This is the optimal batch size suggested by the PS algorithm
Cost per part	For any PS calculation the calculated cost per part is presented
Material	The field contains the material associated with the PS calculation

Delivery date	Denotes the number of days until the required quantity is completed
Internal transportation mode	The time between the required processes and the cost rate is calculated
External transportation mode	The method of external transportation is presented
Factory holding cost	The cost associated with the operating costs of the factory
Process utilisation	The percentage utilisation obtained from the process
Quality rate	The possible quality rate, as associated with the process
Factory name	The general name of the factory facility, used as a reference point during factory assessment
Product name	The name given to the result set denotes the modelled product
Order number	Identifier for product name
Required features	The possible features as produced by the individual process
Volume	The material volume specified by the product model
Quantity	The order quantity as specified by the product model
Production rate	The individual production rate depending upon the required features and the volume
Typeclass	The family name given to each process to identify certain core attributes for process planning

5.8 Discussion

It has previously been shown (see Chapter 4, section 4.3) how process cost models has previously been adopted to assess either singular or few processes, but the PS approach illustrates the benefits of generic distributed process assessment.

The product model and manufacturing process data required for PS is identified and the subsequent manual and automatic process selection methods described. Thus far the work has been focused on the single site analysis. The rest of the thesis will encapsulate the supply chain.

Chapter Six

Factory Selection

6.1 Introduction

The Process Selection (PS) phase (see chapter 5) of this research has proved to be useful for identifying operations within a single site. However, it is not possible to visualise a comparison between results from different sites or suppliers using the PS level of assessment. The Factory Selection (FS) chapter describes the methods used to manipulate the PS results in order to identify the most suitable supplier manufacturing processes, based on the attributes provided by the PS result set. Figure 6.1 shows the position of FS in the overall architecture of SCOPE and FM99. The mathematical techniques adopted during FS are described within this chapter. These methods are accompanied by illustrated examples of the user interface. Further manipulation of the FS function within SCOPE can be found in the testing and results chapter.

As explained in chapter 3, FS is the second level of assessment, the first being PS, where PS results are required prior to FS. FS alters the preferences of the *Quality*, *Delivery* or *Cost* to suit a particular requirement. FS can be run at any given time using previously stored results from PS.

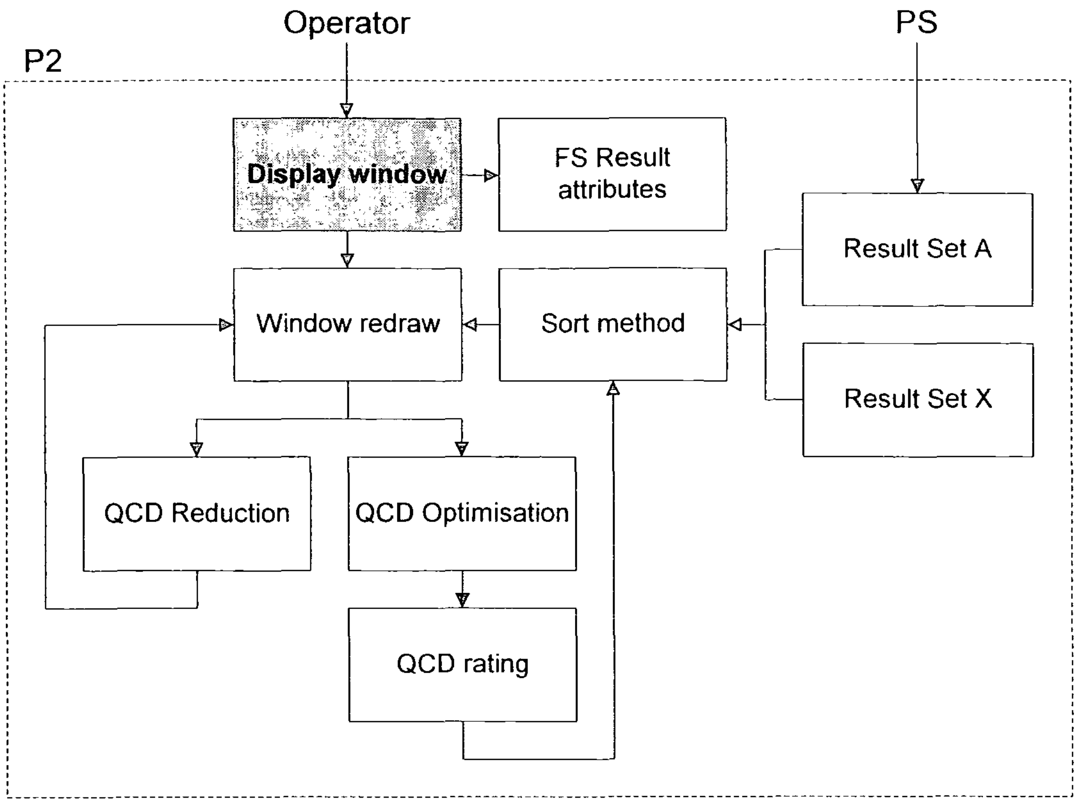

Figure 6.1: Dashed line indicates Factory Selection within SCOPE

The results provided by the PS algorithm are a prerequisite for FS. It is the order in which the results are viewed that identifies the preferred suppliers. It is considered important to note that a PS result set contains those results pertaining to a specific product model and not to a single company. It is therefore possible for a single result set to contain solutions from multiple sources. A sorting algorithm is required to sift through the result set and rank the results. Following this, the results can be displayed to the user for additional manipulation according to their preference.

6.2 Specification of factory selection

When saving the results within the PS algorithm it is necessary to store the maximum amount of data possible to facilitate later assessment. It is considered that all data relating to operation capabilities and utilisation should be retained. As fourteen data fields are described within the PS result set it is not feasible to utilise every attribute during further assessment of the FS manipulation, bearing in mind that the focus of this research is to present a rapid method for initial process selection. The available data would generate more data than is thought manageable. Rather, it is more important to identify those key variables of the PS result set that can be used to classify the results. Table 6.1 presents the PS result set identification.

Table 6.1: PS result set identification

Result field	Attribute
Factory name	Identifies the supplier associated with the specific PS result.
Process name	Recalls the model of the operation used in the PS assessment.
Type class	Refers to the manufacturers name of the process.
Delivery	Returns the days required for production of the order quantity.
Production rate	Identifies the production rate of the operation.
Quantity	Given as the required order, this differs according to manual input.
Total Cost	This is the total cost for a single part.
Quality	Recorded as the scrap rate of production.
Material	This element is required since different materials may be considered for separate locations and this needs to be recorded in the final analysis.
Features	The features considered for manufacture confirm that the analysis is correct.
Volume	The volume of raw material required.
Transport mode	Identifies the method of external transportation.
Factors	Returns the internal factory considerations, including transportation, operating costs and storage costs.
Utilisation	Records the optimisation of the operations, if processes are not fully optimised then a percentage utilisation is recorded.

6.2.1 Attribute selection

It is considered important to select those factors that are going to influence the users decision during FS. The questions that need to be answered are; how many factors need to be integrated into the FS manipulation? And, why include those factors in the FS manipulation?

It is critical to identify those essential factors required for factory rationalisation. The primary factor that should be included is *Total Cost*, based on the requirement that cost is critical for all rational manufacturing process assessments, i.e. when time is a priority. In particular circumstances it is appreciated that the cost is not the governing factor and therefore other factors are required that would influence the user decision. Factors relating to the *Order Quantity* and *Production Rate* may influence the assessment because they control the *Delivery* time. However, since all PS results do not have the same initial *Order Quantity*, it is recognised that the *Production Rate* is reflected in the eventual *Delivery* and therefore is deemed less influential than *Delivery*. *Quality* also contributes to the assessment by virtue of the required value specified by the product model. The *Quality* tolerance required for a product is considered critical to process assessment. It is possible for a process to have a rapid *Delivery* time and a competitive *Cost*, but if the *Quality* is poor, then further consideration is necessary. It is considered that the *Transportation Mode*, which highlights the external movement of parts, is not critical to FS results. This is based on the link between *Transportation Mode* and *Delivery* time, where the *Delivery* attribute includes the external transportation of parts. *Features*, which describe the make-up of the product prior to PS, are not relevant to FS, because this attribute must be acceptable to allow PS. Other attributes relating to the *Factory Name* and *Process Name* are not considered in further assessment, but act as identifiers for FS manipulation.

It has therefore been decided to base FS assessment on the following key attributes of the PS result set. *Quality* (parts per million for scrap rate), *Cost* (associated with production of a single part on a specific operation) and *Delivery* (days required to return required order quantity). By combining these factors, the assessment techniques will not only be able to model the cost of production but also be able to judge whether the cost of an operation is outweighed by speed of delivery or improved quality.

6.3 Factory selection functionality

The general purpose of FS is to optimise factory results. It is therefore the function of FS to present these results in a structured manner, such that they can be understood and disseminated. It was considered that the objective of FS was to present the PS results so that the user was able to compare multiple results from a single PS results file. Initial assessment should be carried out independently of user interference for an unbiased view.

A direct approach is required to formalise the FS results using the PS result set. The sort method should present the results based on the process attributes of *Cost*, *Quality* and *Delivery (QCD)*. A less formal strategy is then required to manipulate those results of significant importance to the user requirements. To follow this function several approaches are required to analyse the FS results, see Figure 6.2.

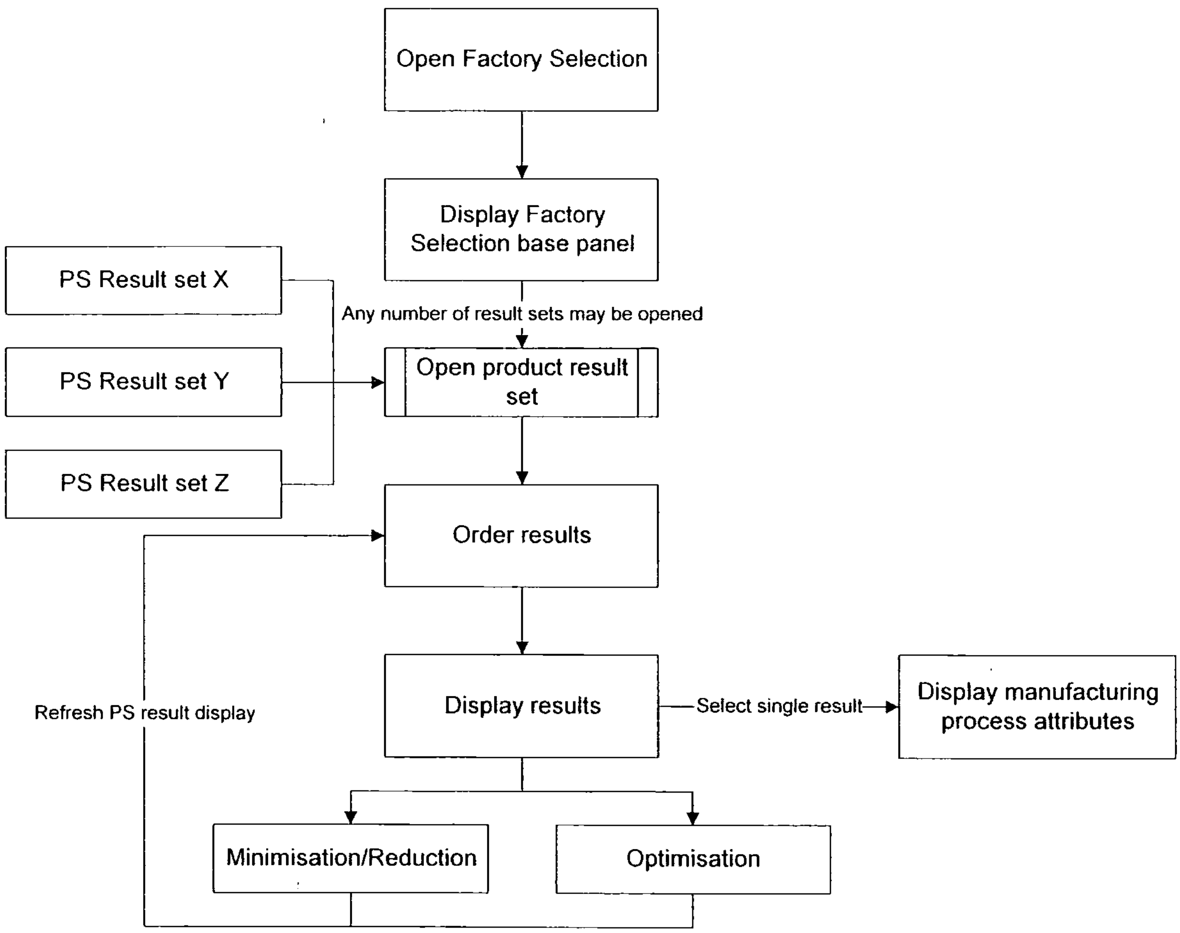

Figure 6.2: Factory selection functionality

It is now important to clarify how the user can assess the results presented by the Process Selection (PS) assessment. The results are initially shown in an optimal format by the order method, assuming that equal importance and merit is placed on the *Cost,* *Quality* and *Delivery* (QCD) factors. However this does not allow the user any interaction to prioritise these factors. Separate methods are required to allow the user to manipulate the data. For example, the user may be looking to optimise a single factor of the assessment, i.e. *Cost, Quality* or *Delivery.* This approach may be of benefit when attempting to minimise the cost of a product or improve the delivery of an item. Alternatively the user may wish to optimise the combined QCD assessment, looking at all the factors. This method would highlight the combined strength or weakness of the results. This differs from the initial order method, since the user is able to specify preference during assessment.

6.4 Results rationalisation

Using the functionality described, the first step is to rationalise the results according to the QCD values. The immediate problem faced during the assessment is to determine a way to combine and sort results that have different units of measurement. The units of measurement are, pounds for *Cost,* days for *Delivery* and parts per million scrap rate for *Quality.* The requirement is therefore to normalise this data and remove the units of measurement from consideration.

It is important to appreciate the variation in the PS results, how different manufacturing processes will perform, and how this will be reflected in the distribution. The varying manufacturing processes may return vastly different QCD results for a single product model, differing additionally in *quantity*, *material* and *external transportation distance* (the later three variables are not considered during QCD but illustrate factors that influence the results).

There are many statistical techniques for sorting data, but it was decided to adopt a normal distribution curve. Normal distribution is the most important continuous distribution in statistics, and the measured quantities of QCD follow a normal distribution (Crawshaw and Chambers, 1988). Approximately 95% of the normal distribution lies within ± 2 standard deviations of the mean, and approximately 99.7% of the standard distribution lies within ± 3 standard deviations of the mean (see Figure 6.3).

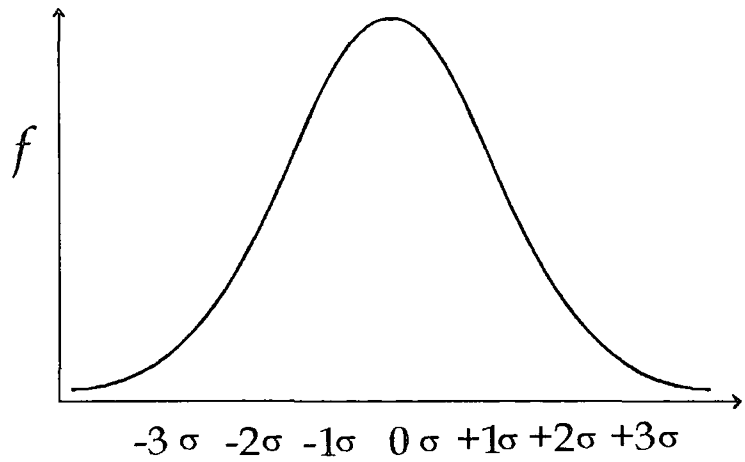

Figure 6.3: Normal distribution, showing 3 standard deviations

The standard deviation is given by,

$$S = \sqrt{\frac{\Sigma(O_i - E_i)^2}{n}} \tag{6.1}$$

The deviation values for QCD are combined to give the cumulative deviation value. Individual result elements can either conform to the mean of the deviation, or have a significant deviation value (see Figure 6.4). This significant value can be either positive or negative depending on the individual result (for the purpose of this work, positive results are significantly worse and negative results significantly better). By using this method to normalise the data, individual criterion are equally weighted, and a significant difference from the mean result will be reflected in the given combined total. For results that have significant difference in more than one attribute of the evaluation, the combined result could appear average since opposing results would have a cancellation effect.

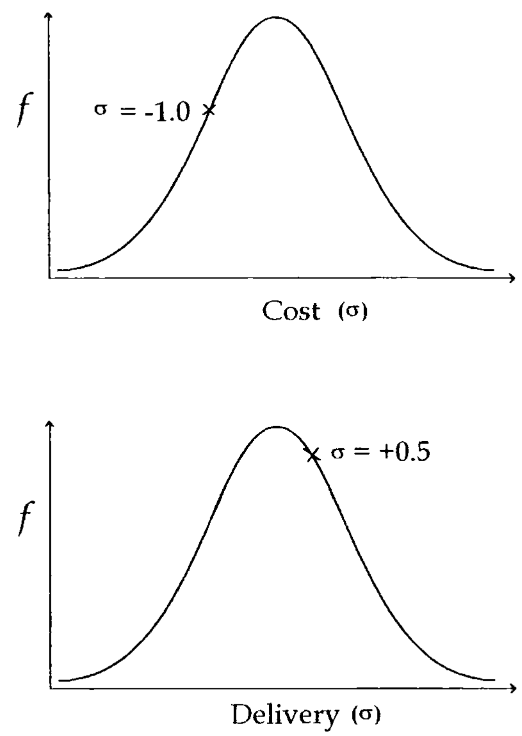

Figure 6.4: QCD Standard deviation values

The obtained results are ranked by the order method according to the minimum QCD value returned by deviation. The minimum value can have a negative value for results that have a combined negative deviation score. For the example shown in Figure 6.4, the combined result is:

$$-1.0+0.0+0.5 = -0.5 \quad (6.2)$$

It is then the role of the FS manipulation methods to tailor the PS results to the users specification.

6.4.1 Method justification

Normal distribution has been illustrated and described as being the chosen method for combining the QCD attributes of the PS results, and displaying the initial results. It is accepted that the data does not classically adhere to a distribution, since a distribution represents multiple results compiled from a single operation, and the variation thereof. The generated data reflects a group of results with a common attribute, the product model. Within that grouping there are many varying factors that will influence the final result. The following lists contain related factors that compile to generate firstly the cost, but also the quality and delivery of a product during assessment.

Cost

- Manufacturing method cost rate (£/hr)
- Manufacturing capacity (parts per hour)
- Capacity of transportation mode (m^3) [1]
- Internal transportation velocity (m/s)
- External transportation velocity (km/hr)
- Material cost (£/kg)
- Factory cost rate (£/hr)
- Tooling cost (£)
- Tooling interval quantity (number)
- Number of operations, (number)
- Order quantity (number)
- Number of loads (quantity/capacity) [2]
- Internal transportation distance (m)
- External transportation distance (km)
- Material volume (kg)
- Daily operating hours (hr)
- Changeover time (hr)

Quality

- Specified Quality by the product model (ppm)

Delivery

- External transportation distance (km)
- Capacity of transportation mode (m^3) [3]
- Manufacturing capacity (parts/hr)
- Factory operating hours (hr)
- External transportation velocity (km/hr)
- Number of loads (quantity/capacity) [4]
- Order quantity (number)

It is very difficult therefore to determine a meaningful method, to sort and display the initial results. The results comprise various manufacturing methods that have differing settings. For example, these can be *Order quantity*, *Material, External transportation distance* or *Factory operating hours.* Any PS result set may contain multiple iterations of results, generated though different factories, using different machines, operating at varying rates and producing different quantities.

[1] Relates to both Internal and external Transportation mode.
[2] Relates to both the Internal and external number of loads.
[3] See footnote 1.
[4] See footnote 2.

Solely considering QCD results as the foundation of FS assessment is feasible. It is argued that since the direction of the analysis will consistently tend the results in the correct direction, that the principle for initial assessment is justified.

To simplify this method, linear distribution could be achieved by dividing the results by the mean value of the result set. The mean value however can be distorted by significantly high or low individual results. To combine three dimensionless group mean values would only exaggerate the distortion of the mean value. Alternatively *Cost* could have been considered as the sole attribute for initial assessment. In doing so all results would be ranked in ascending order. Bearing in mind several of the attributes from the *cost* model i.e. Material, Quantity, External Transportation mode etc, this has no greater meaning or relevance than the given model.

Continued manipulation by the operator, using QCD optimisation and QCD reduction, can categorically clarify the PS results.

6.5 Result ordering

From the QCD rationalisation, the results are ranked according to their combined standard deviation value. The ordering method is a common function of both the optimisation and minimisation/reduction methods used to redraw the result set according to the new result information.

The order method was developed to manipulate a specific PS result set. The functionality does not specify which FS method is operating the algorithm. Rather it identifies the new order of the result set as specified by the optimisation method. A list is supplied to the method that contains the variance of all the FS results for a given PS result set, the ordering method then ranks the results to that list. The method deletes the existing result set from view and scrolls through the new result set list for the minimum value. The Simplex method (see Chapter 2, section 2.3) can be applied to this method for searching of the minimum value. If two results are given the same QCD standard deviation value, it is the result that is encountered first that is given priority in the result classification. This is not to say that the result is thought more significant.

6.5.1 Product model presentation

After initiating the FS order method, the results will be presented to the user. For the user to make best use of the available information it is thought that more information should be made available than the QCD ratings given. For example, it has been explained that a PS result set is specific to a product part, not an individual result generation (see Chapter 5, Section 5.8). Results are recorded for different suppliers, using different materials, quantities and processes. The information presented to the user should reflect this diversity of data. A decision was required to determine the correct data for rational and logical assessment. Each attribute of the PS result set was considered, but it was not thought relevant to include all elements. At a factory level internal factors that are not the users responsibility, such as internal transportation, are of less importance since they cannot be controlled, than controllable factors such as material or quantity. For each of the presented results the information includes:

- Combined - The combined display contains the factory name, the process type and the production cost. This is the general information page presented to the user on entry to the FS result identification.
- Material - The material cell includes the factory name and the specified material
- Cost - The factory name and the specified cost is combined
- Quality - For the quality cell the factory name and the quality are included
- Process - The process machine name and the factory are combined
- Delivery - The required days until delivery and the factory name are given
- Production Rate - The process production rate and the factory name are shown

It is possible to monitor the design attributes during FS manipulation.

6.6 QCD Optimisation

In conjunction with the deviation value returned in the initial analysis, the optimisation feature utilises the PS result set. From the given results the optimisation separates the *Quality, Cost* and *Delivery* deviation values. These individual values will be required by the method.

To facilitate the user, the optimisation function has been designed to graphically indicate the different levels of importance for the QCD functions (see, figure 6.5). A weighted result can be obtained to the preference of the user.

Figure 6.5: QCD Optimisation

By adjusting the scroll bars for the separate options it is possible to weight the preference of the result set. This can either take the form of selecting a single option, leaving the other two as zero, thereby setting the preferred criteria at 100%, or by adjusting more than one bar to give different results. From the illustrated example (figure 6.5), it can be seen that *Quality* has an importance score of 2, equating to 25% of the total importance score. *Cost* has an importance score of 5, equating to 62.5% of the total importance, and *Delivery* has a score of 1, which is 12.5%.

The result as expressed in equation 6.3, is then transferred to the PS result set for the chosen product model and then the results are altered according to the updated information.

$$R = \sum f(Q + C + D) \tag{6.3}$$

Where f is the percentage function of the optimisation.

6.6.1 QCD Optimisation functionality

The purpose of the QCD optimisation method is to rank the results according to importance. The functionality of the optimisation is to decide what values to assign to the deviation value. From the QCD optimisation window (figure 6.5) the importance score and the QCD percentage relating to the score are 25%, 62.5% and 12.5% respectively. The percentage score is derived from a proportion of the combined QCD score, given as 2,5 and 1. The individual QCD element is then related to the combined QCD total.

An individual QCD element can be described as:

$$E_T = \frac{100}{\left(E_Q + E_C + E_D\right)} \times E_{QCD} \qquad (6.4)$$

Where, E_{QCD} is the total value of quality, cost or delivery.

By rearranging the equation to equal E_Q, E_C or E_D the percentage value is generated.

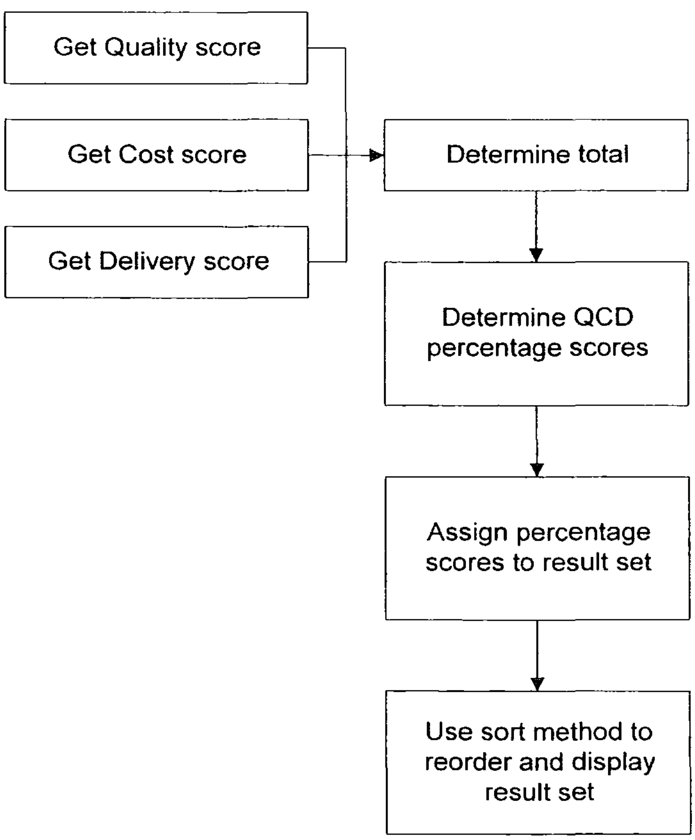

Figure 6.6: QCD Optimisation functionality

The optimisation process is shown in figure 6.6. The figure shows the use of the order method for ranking the result set. The QCD values are obtained from the optimisation window and then deviation techniques are applied to combine the values, determining the magnitude of the value in relations the re-evaluated results. Once the results have been passed back through the 'order' method they can be redisplayed.

6.7 Reduction of QCD

Unlike the previously mentioned technique for data manipulation, the reduction technique does not alter the combined deviation score of the results. Instead, the results are removed from consideration if they fall outside the specified threshold limits. The limits are set by the user to optimise the number of results considered. As illustrated in Figure 6.7, the maximum and minimum limit values for each criterion of a specific product model are obtained directly from the PS result set limits. The user then reduces the results to suit.

Figure 6.7: QCD Minimisation

An example would be that the delivery criteria might range from 3 to 134 days for a product, but the requirement is that the product must be produced within 21 days. Even though result information was obtained for other values, the user now has the ability to delete these results from view and consider those results that are left. These results are not removed from the result database, rather removed from the current analysis.

6.7.1 QCD reduction functionality

For the minimisation/reduction function (see Figure 6.8), the maximum and minimum values for QCD are determined from the PS result set. Unlike the *Cost* and *Delivery* scrolls, the *Quality* scroll can be seen to have an equal maximum and minimum value, which are 50. This is a result of all PS results having the same stored *Quality* value, for the given example.

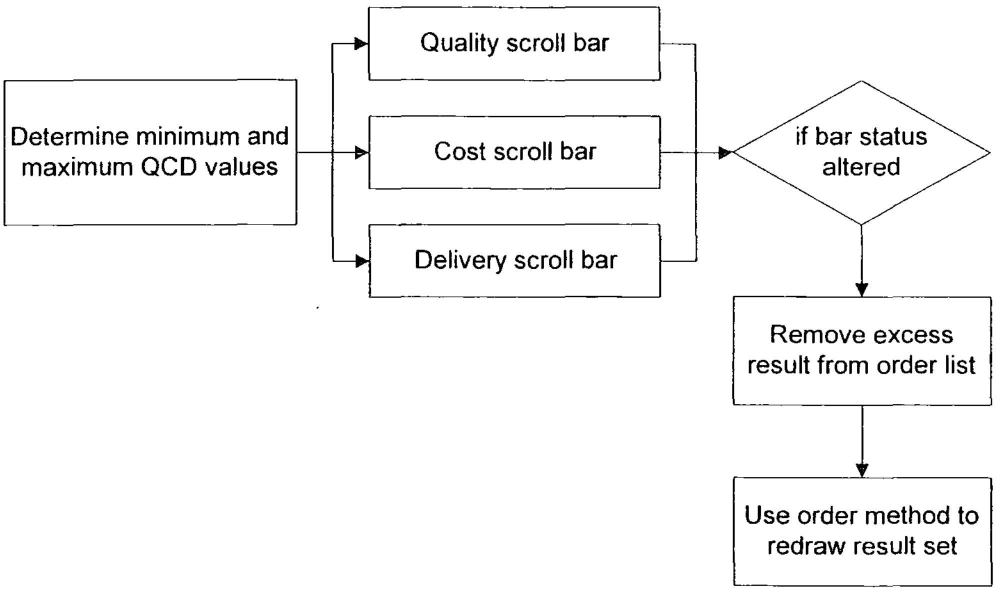

Figure 6.8: QCD Reduction functionality

For the other attributes of the given example the maximum and minimum values have been assigned, and the scroll mechanism increments, or decrements the value. For the *Cost* values, the adjustment is carried out in 0.1 increments to simulate ten pence changes, and for the *Delivery* it is increments of 1, which relates to extra days.

6.8 Summary

This chapter illustrates the manipulation of the PS results. Initially the attributes of the result set were exposed, and is followed with a discussion concerning those attributes of the results that are required for factory selection. The optimisation and minimisation methods for result rationalisation have been illustrated and explained.

Chapter Seven

Testing and Results

7.1 Introduction

It is the purpose of this chapter to present a framework for the testing and evaluation of the presented methods and software. In principle this should entail a full industrial test programme, whilst operating as a Java application across the Internet. It is however impractical and naïve to contemplate such a testing schedule, since any company would not be prepared to install a prototype software system, with limited testing and security onto their computer network. The creation of a secure network, adopting rigorous data protection, was not a practical or economic solution considering the time and funding given. In addition, it is feasible to consider a manufacturing network that specialises in particular manufacturing processes, thus limiting the testing capabilities. It was therefore proposed that an alternate testing programme be designed and implemented to evaluate the methods and software.

It was considered that the testing would be carried out within the local network of the University of Durham. An artificial network of factory databases was created using actual data obtained from collaborating companies, for the purpose of real product assessment. For the purpose of the testing programme, the SCOPE system was run independently from all satellite factories. This format is preferable for the purpose of testing and analysis since it is not restricted to a single company network or process capabilities.

7.2 Testing Aims and Requirements

To accurately monitor the functions of SCOPE a testing format is required that will allow each element to be illustrated clearly, thus allowing transparency of the analysis. Two methods were used for the testing of the SCOPE system models and functionality:

1. Compile the manufacturing process data and product model and test the functionality of the Process Selection (PS) and Factory Selection (FS) features.

2. Present case studies of industrial data to validate the PS and FS functions.

The generated manufacturing process data model was initially developed using manufacturing process information from Electrolux Outdoor Products, (Newton Aycliffe, UK). Additional testing was performed using process information from other facilities.

The evaluation of the PS function is achieved by manipulating the data provided by the generated manufacturing process model. It is necessary to demonstrate a number of aspects of PS:

(i) It can be applied for a range of product model configurations, sourced from a distributed network of suppliers,

(ii) It can produce alternative production options, identifying alternative production methods by either manual or automatic assessment,

(iii) The process selection is both technically feasible and realistic (i.e. no manufacturing constraint are violated),

(iv) Estimated times and quality levels are sufficiently accurate,

(v) Process selection results are produced in a sufficiently automated way, in an acceptable time scale (SCOPE is intended to evaluate all initial concepts for production).

Many of these criteria relate to the overall function of the SCOPE system. The FS phase of the system is evaluated by the manipulation of result sets generated by the PS phase of the SCOPE system. Again it is necessary to demonstrate a number of aspects of the factory selection process.

(i) It can be applied for a variety of manufacturing operations,

(ii) It can produce alternative manufacturing options from the same product design, identifying alternative supplier operations automatically,

(iii) The factory selection manipulation methods estimate with sufficient accuracy,

(iv) Results are produced in a sufficiently automated way, in an acceptable time scale (SCOPE factory selection is a rapid evaluation tool, so that it may be run many times as the design continually evolves).

The tests that have been carried out were designed to assess the criteria by running only the necessary functions of the system when possible, in order to reduce the time required for testing. The Process Selection evaluation can be divided into stages according to the main planning steps: process identification, process evaluation, process selection and final selection.

7.3 Generated information assessment

Initial assessment is carried out on components that form a Lawn Mower assembly, designed and manufactured by Electrolux Outdoor products. Further examples of the product model are then generated by using the system to model components requiring a variety of manufacturing operations.

To create an aggregate product model, the selection of the positive feature is critical. It is possible that there will be more than one positive feature that could represent the basic component shape. In these circumstances, the selection of the best feature should be made on the basis of preserving design intent. It should be recognised that the shape of the positive feature will influence the possible processing options.

7.3.1 Product Model Analysis

The data was manually inputted to build the feature based product model. An overview of the model can be seen in figure 7.1, (a full product model listing is given in Appendix F). It can be seen that five sub-assemblies were created. The selection of the sub-assemblies is based purely on the assembly viewpoint. It is perfectly legitimate to classify the sub-assemblies from a job perspective, i.e. moulding, castings and fabrication, or indeed to specify each component only as part of the general assembly.

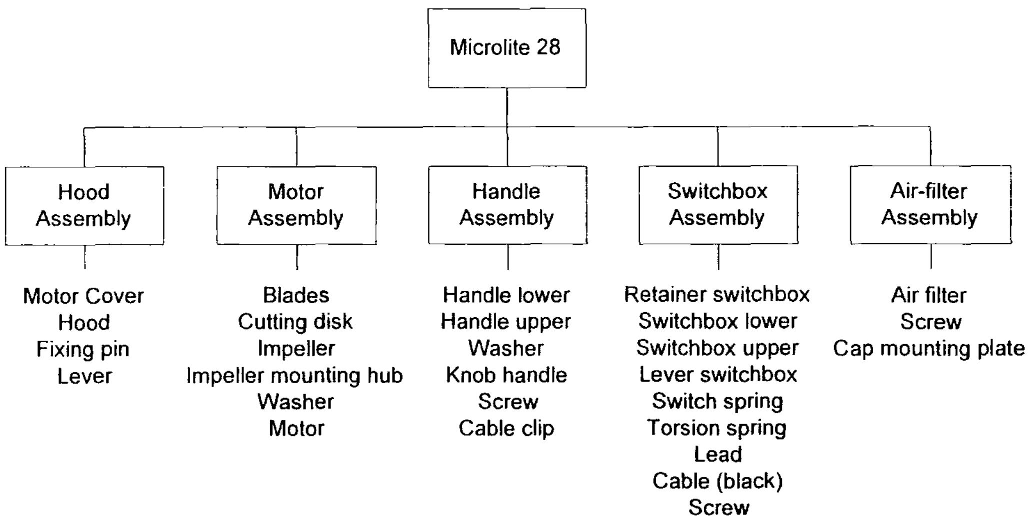

Figure 7.1: Microlite 28 product model

From the product overview it is possible to identify 28 different parts that constitute the general assembly. The overview does not indicate the quantity of each part required, but the full product description as found in Appendix F, describes, for example, that 8 impeller blades are supplied as part of the kit assembly. For a total cost assessment the quantities of the parts required must be taken into account.

A more detailed examination of the product model highlights the detail of information required for the SCOPE assessment. One of the simplest forms is the *Blade* (see Figure 7.2). The indicated method for assessment has been described as 'moulded', the volume of the raw material is therefore described in terms of a cylinder.

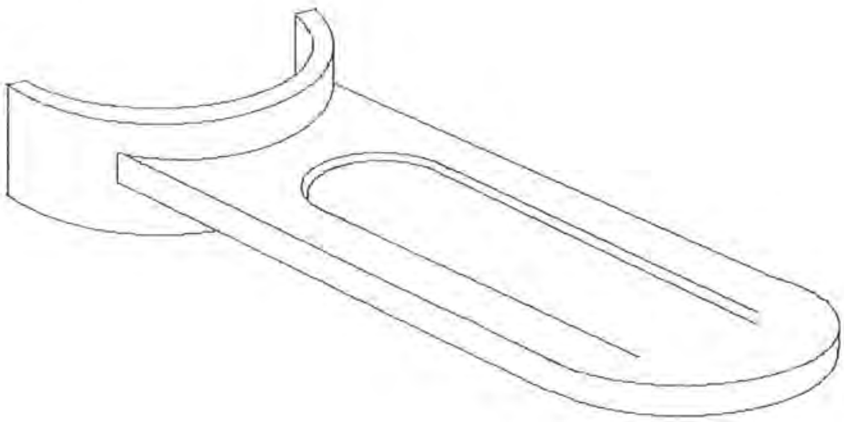

Figure 7.2: Blade configuration

An examination of the component features can be seen in figure 7.3. It has been stated that the positive feature is the most important element. For the given example, the required material is stated within the aggregate product model; also the designated form of the part is associated to the material. For a thermoplastic part as specified by the *Blade*, the positive feature is described as a moulded form (see Figure 7.3).

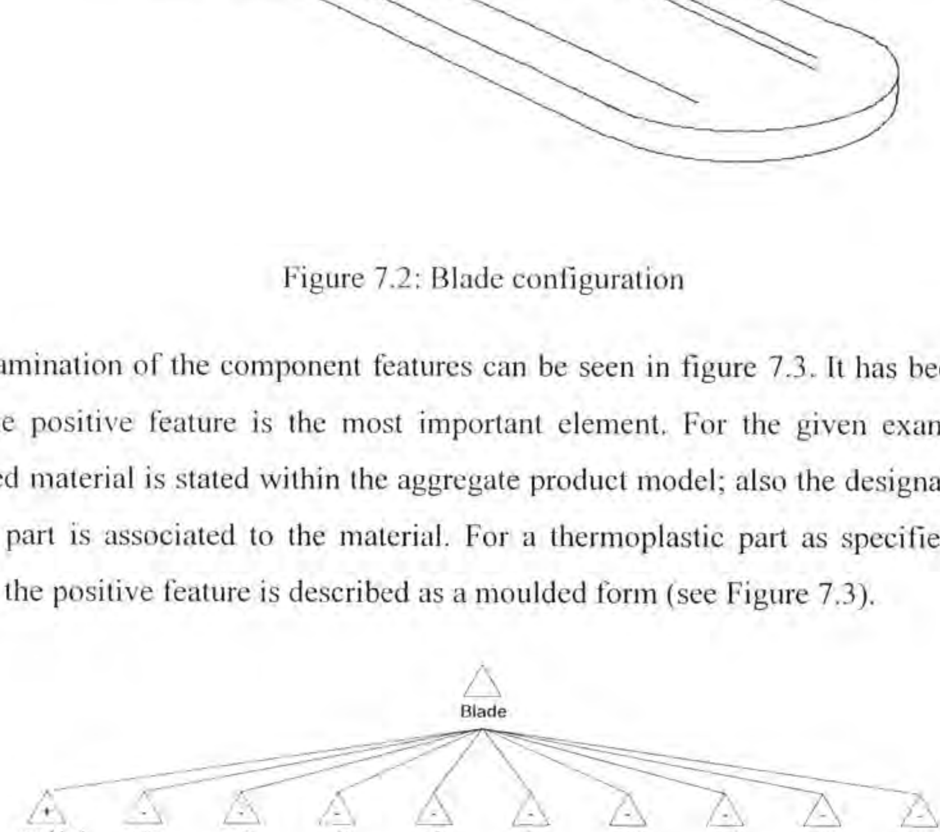

Figure 7.3: Feature relations

Also detailed within the aggregate product model, as described by Maropoulos *et al.*, (1998) are the features that constitute the part. The structure includes *sf2*, a 'prismatic curved surface with fixed profile' that relates to both the internal and external crescent form of the blade lug. The origin of the feature is set to a radius. The third *sf2* feature relates to the profile of the blade tip. The top and bottom face profile of the blade are given as *pfa*, 'prismatic face: any flat surface'. The indent on the face of the blade is described as a 'pocket', *ppk*. The position of the pocket within the blade is also given by the feature attributes. A complete machining feature classification can be found in Appendix D. In conjunction with these details the geometry of each feature is illustrated by figure 7.4. It is the geometry of the raw material, in this instance a 'moulded' form that denotes the raw material volume.

It should be noted that positive features describe the raw material blank for a product. Operations performed on this material are therefore termed negative features since they relate to the removal of material.

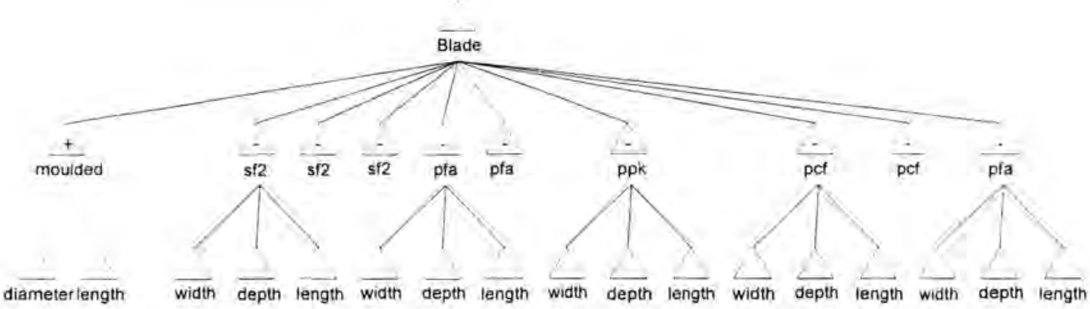

Figure 7.4: Feature descriptions.

The product model selection screenshot in figure 7.5 illustrates the details that are given to the user before the part is selected for assessment. It is possible to model each assembly-component separately and then to build a cost model of the results. This will be described later.

From a system viewpoint the initial step is to load the product model into the computer. The *Input file* field remains blank for the purpose of the assessments given in this thesis, since the required product models are already installed into the SCOPE system. Operating the Open button completes initiating the transfer sequence. This automatically transfers the data from the source file to a database that has the destination file name. The format of the destination file is the same as the input file.

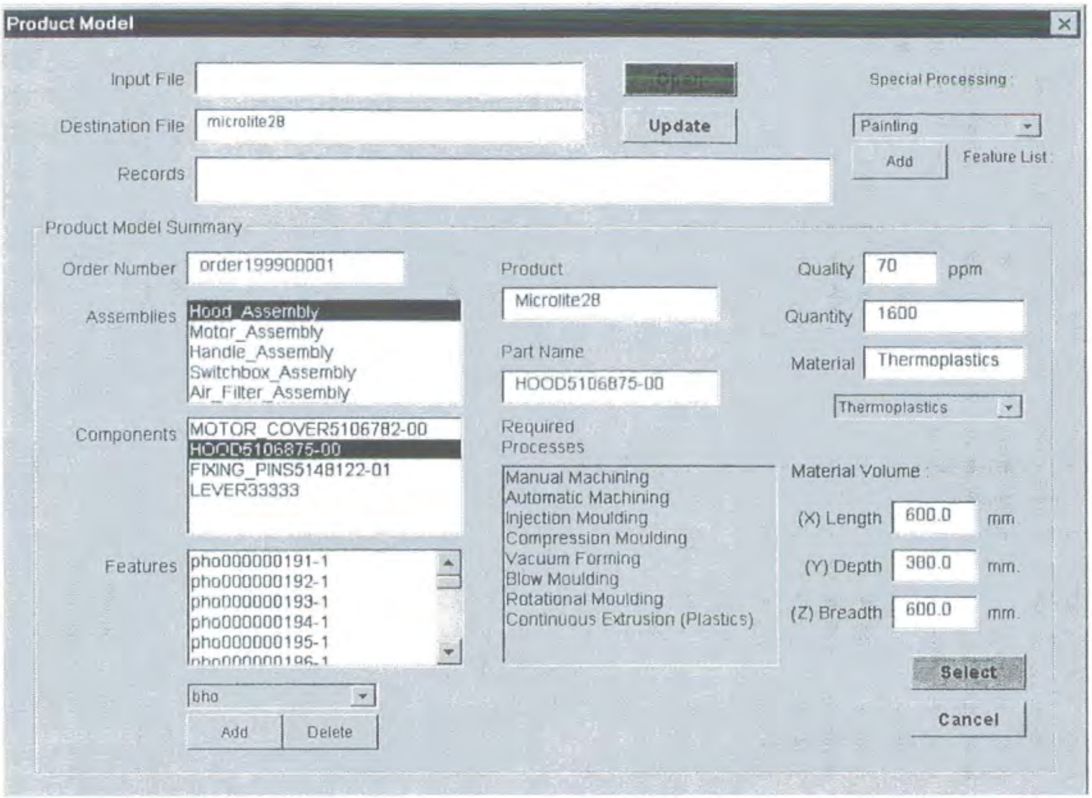

Figure 7.5; Product model selection for the *Hood Assembly*

When the *Destination file* has been opened, either the assemblies within the model are indicated, or if the model has no assemblies and only parts then the parts will be indicated. It is then the prerogative of the user to indicate the next function of the system. The example that has been used shows that the *Hood Assembly* of the Microlite 28 is required. There are now a number of components shown that belong to the *Hood Assembly*. For any given component there is a list of features relating to that component, these have individual signatures denoting that there can be multiple features of the same type in a single component.

A second example of the product model format can be seen in figure 7.6

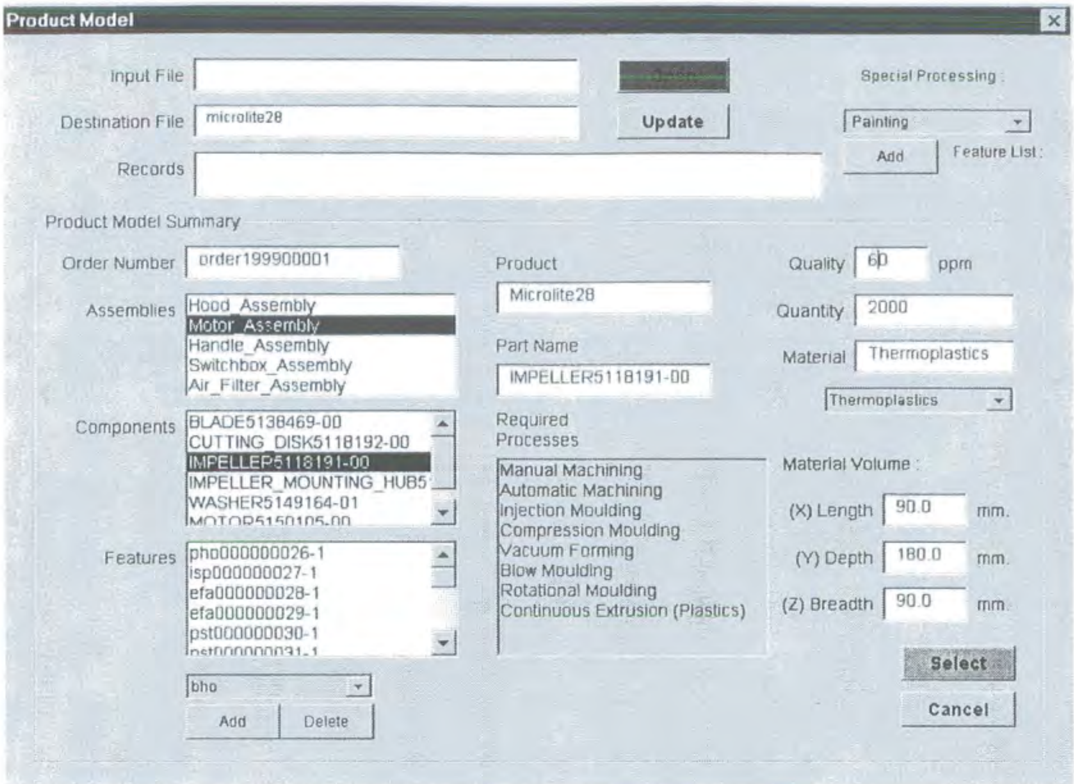

Figure 7.6; Product model selection for the *Motor Assembly*

At this point in the assessment there is no reference to the supply chain. The required material has been selected and the *Required Processes* are indicated, these are all the processes within SCOPE that are deemed feasible for the specified material. There has been no assessment thus far as to the suitability of the given processes to the *required features*.

7.3.2 Factory Model Analysis

For the purpose of verifying the manufacturing process data, an examination of the database is required to identify the validity of the processes illustrated by Factory Modeller 99 (FM99). A portion of the *Flymo* manufacturing processes can be seen in figure 7.7. Two buildings exist at the Flymo site, one for assembly and one for moulding. Proof of the facilities can be seen in the parent listing for the buildings, as highlighted in Table 7.1, a full listing of the facility being available in appendix D.

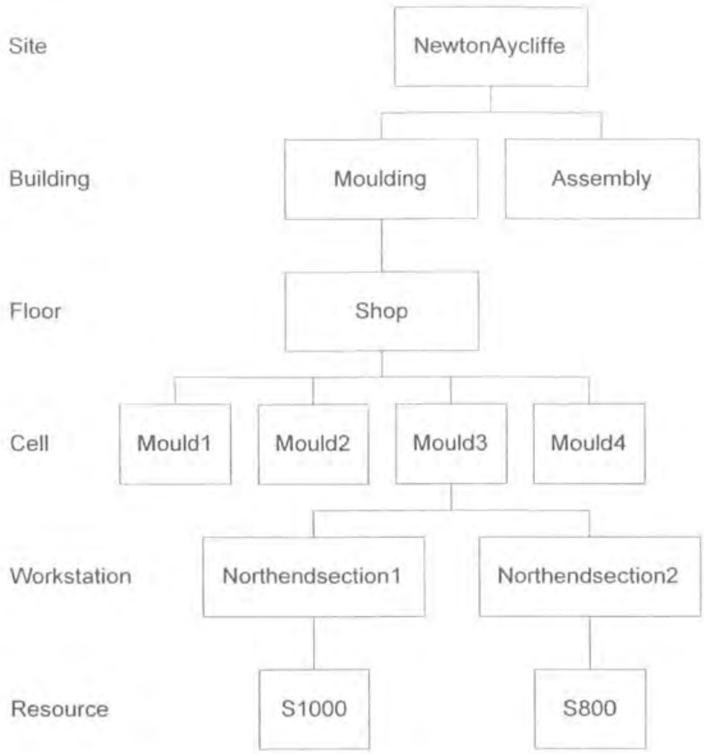

Figure 7.7: Flymo factory overview

Table 7.1: Factory model classification

NAME	PARENT	PROPLIST	VALUE
NewtonAycliffe	SITE,	site,	NewtonAycliffe,
	Flymo	buildings	2
Moulding	BUILDING,	xgeom,	201,
	NewtonAycliffe	ygeom,	142,
		xcoord,	120,
		ycoord,	0,
		avail,	True,
		floors	1
Assembly	BUILDING,	xgeom,	100,
	NewtonAycliffe	ygeom,	142,
		xcoord,	0,
		ycoord,	0,
		avail,	True,
		floors	1

From a system perspective, at this level in the assessment a connection has now been established between the user location and the supplier factory. Access to the available processes has been clarified (see Figure 7.8). For further assessment of the Process Selection functions it is now necessary to detail the results of the applied functions.

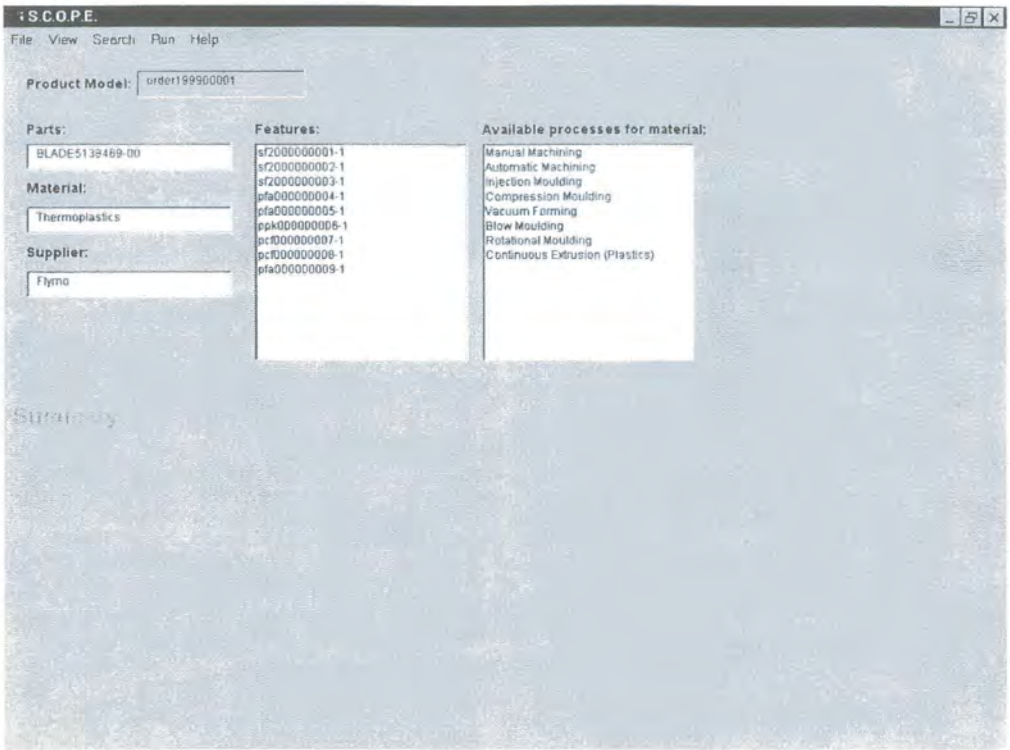

Figure 7.8: Summary of product model constraints.

7.4 Process Selection

The assessment of the Process Selection (PS) will be described herein. Simple examples will be used to demonstrate the functionality. For easy visualisation of the PS output, screen shots have been used during the assessment. Three PS stages have been performed; process identification, process examination and process evaluation. In the first stage the alternative process selection options for the given product model are identified. These options are checked to remove those operations that have violated the constraints of the product model. In the second stage the operation options are identified and separated into the appropriate primary, secondary and tertiary steps where required. The third stage is the calculation of processing and set-up times for each of these steps according to the relevant process model. Finally the system generates a number of alternative process selection results for the component using PS.

7.4.1 Product Data

Manufacturing operations within Flymo have formed the basis of the testing requirements. Actual production data has been used by the FM99 as discussed earlier and Flymo also supplied a product to be modelled against that data. The cost and time attributes of the generated manufacturing process data is specific to the Microlite 28 lawn mower. This is the smallest of the Flymo lawn mower range, with a cutting diameter of 28cm. An aggregate product model has been constructed for the complete product, linking the individual items by the parent structure.

Table 7.2: Microlite28 product data

Part Description	Operation Description	Operating cost (£/hr)	Base Minutes (deciminutes)	Base Cost (£/part)	Total Cost (£/part)
Impeller mounting hub	Moulding	11.66	0.834	0.162	
Impeller mounting hub	Labour	16.20	0.140	0.034	0.196
Impeller	Moulding	18.04	0.750	0.226	
Impeller	Labour	16.20	0.150	0.041	0.267
Cutting disc (28cm)	Moulding	11.66	0.750	0.146	
Cutting disc (28cm)	Labour	16.20	0.120	0.032	0.178
Blade	Moulding	11.66	0.250	0.049	
Blade	Labour	16.20	0.100	0.027	0.077
Cap filter mounting	Moulding	11.66	0.667	0.130	
Cap filter mounting	Labour	16.20	0.150	0.041	0.171
Motor cover	Moulding	23.61	0.750	0.295	
Motor cover	Labour	16.20	0.420	0.110	0.405
Hood Printed	Printing		0.800		
Hood printed	Print/Pack	16.20	0.804	0.216	0.216
Hood (basic hover) 2	Moulding	35.54	1.08	0.646	
Hood (basic hover) 2	Labour	16.20	0.280	0.076	0.716
Switchbox lower - UK	Moulding	18.04	0.325	0.098	
Switchbox lower - UK	Labour	16.20	0.080	0.022	0.120
Lever Switchbox	Moulding	23.61	0.284	0.112	
Lever Switchbox	Labour	16.20	0.160	0.043	0.155

Cord anchor bell mounting	Moulding	11.66	1.670	0.324	
Cord anchor bell mounting	Labour	16.20	0.360	0.098	0.422
Pivot pin	Moulding	11.66	1.064	0.208	
Pivot pin	Labour	16.20	0.480	0.130	0.338

The Microlite 28 lawn mower is described in terms of the actual processing time and the labour associated with that part (see Table 7.2). For the purpose of the later assessment an additional column is added to this table to highlight the total cost of the operation. For example, a 'blade' has been described in the information supplied by Flymo as having a moulding cost of £0.049 and a labour content of £0.027, therefore the compound cost has been described as being £0.077 or 7.7p each.

7.4.2 Factory Data

The presented example has been examined at a workstation level, such that costing assessment can be carried out at either a workstation/cellular level, or at a factory/site level. The information contained within each level identifies the process with relation to the factory position for transportation purposes. Additional information pertaining to the availability of a given level of assessment is also given. The benefit of this is to minimise time wasting during assessment. A section of the Flymo factory can be seen in figure 7.7, showing the operations that are available for later assessment.

The analysis presented thus far has focused upon the prerequisite requirements of the PS assessment. Therefore since all the data is now in place the selected component can be modelled against the required features.

An optimal assessment for the *Hood* is given in Figure 7.9.

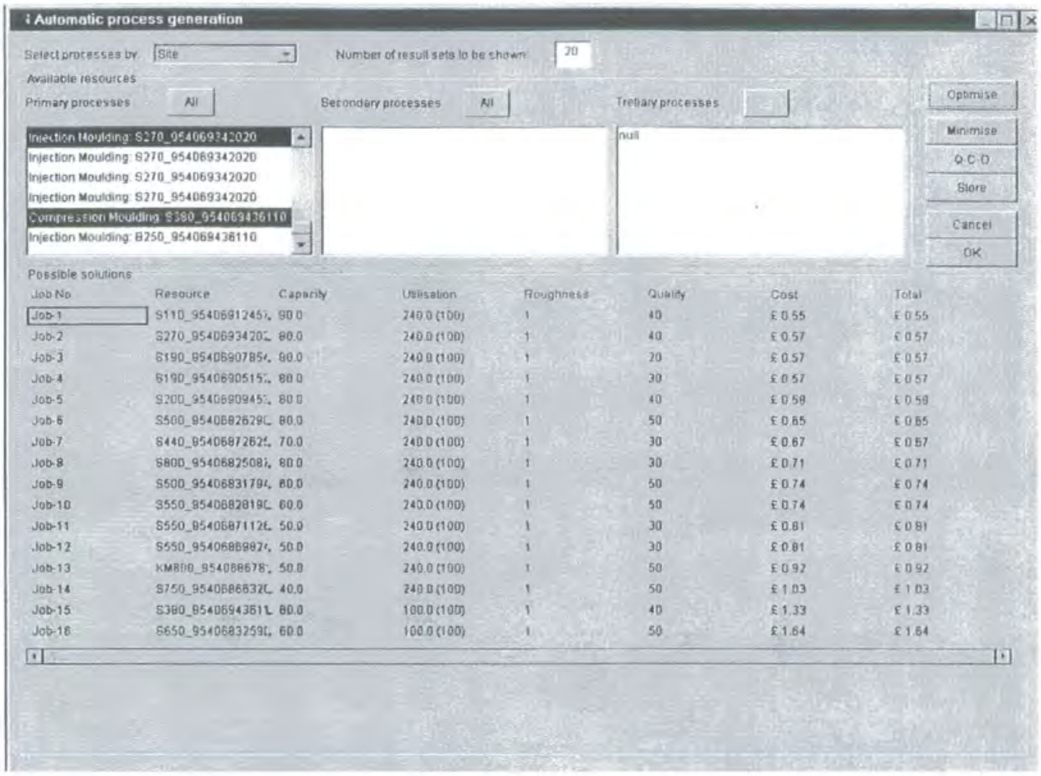

Figure 7.9: *Hood* optimal assessment

For the specified component *Hood*, the Flymo data indicates that a value in the region of £0.71 per component is calculated. The results that are generated have a range of £0.55 to £1.64. This includes internal and external transportation. For the purpose of the SCOPE analysis it is not possible to say that the cheaper options are the preferred routes, since variables such as the production rate may make certain options untenable. The FS models this function.

A direct comparison between actual costing against calculated results for the same process indicates that an actual value of £0.71 compares favourably with a calculated value of £0.74. Compiling the material cost, production cost and the transportation cost, generates this value.

The build-up of the cost model initially determines the number of required features and the volume of material, where the units of measurement for volume are cubic millimetres. The volume of the *Hood* is 600mm x 380mm x 600mm, based on the initial billet size. The material mass can then be calculated from the volume and the density of the chosen material. For the *Mower Hood* application, the density of thermoplastic is given as 0.957g/cm^3. Therefore the material mass in kilograms for this part is calculated, (equation 4.1). No exception is considered for hollow parts during material calculation:

$$(0.06m \times 0.038m \times 0.06m) \times 0.957g/cm^3 = 0.131\ Kg \qquad (7.1)$$

From the mass the cost is generated, see equation 4.1:

$$(0.131kg) \times (2.01£/kg) = £0.263 \qquad (7.2)$$

To generate the manufacturing cost there are further attributes of the product model and manufacturing process data required. The product order quantity for this assessment has been 1600. A value has been created to specify the number of hours operated by Flymo per day. This is set at 14, with an hourly operating expense of £16.20 per hour. This value covers factory overheads, lighting, heating and maintenance.

The number of operations required to create the *Hood* design is, of course, process specific. For example a manual machining operation would require multiple set-ups to generate the product design, but the injection moulding facilities of the Flymo site are capable of single operation cycles. To determine the suitability of the design each design is verified against the feature table held within the process classes. If any conflicts occur with a single feature, such as an internal feature request for an operation without that capability then the operation is rejected. Similarly for multiple operations where conflicts may occur, such as tolerance limits, then the operations are rejected. For automatic machining selection, as denoted in this example, a secondary machining operation would have been utilised if all features could not be fulfilled.

Following process verification, process costing is required. To use the 'like-for-like' process in this example, S550_95406831794 identifies the process as an S550 injection moulding operation. The following 12 digit number denotes the time and date that the process was created. It is therefore possible to add similar S550 processes because they will be identified with a different time signature. With reference to the manufacturing process data, the process has the following attributes:

X Geometry (m)	2
Y Geometry (m)	11
X Co-ordinate (m)	2
Y Co-ordinate (m)	1
Availability (Boolean)	TRUE
Power (kW)	550
Quality (parts per million)	50
Utilisation (percentage)	50
Cost rate (£/hr)	18.52
Typeclass (family name)	Injection Moulding
Company (manufacturer)	UNKNOWN
Production rate (parts per hour)	80
Roughness (microns, surface finish)	1
Flexibility (adaptability)	30

The next step is to calculate the machining cost, based on the factory operating hour's machine capabilities. This is given by equation 4.7

$$0.263 + \frac{((18.52 \times 25) + (25 \times 16.20) + (1 \times 200))}{2000} = £0.74 \quad (7.3)$$

The final element of the costing assessment is the transportation requirement. For 2000 parts delivered in a box lorry with an internal capacity $18m^2$, over a distance of 15km at a cost rate of £0.25 per kilometre the resultant value per part is given by equation 4.5

$$\left(\frac{0.131 \times 2000}{18}\right) \times \left(\frac{15 \times 0.25}{2000}\right) = £0.0273 \quad (7.4)$$

In real terms this value is negligible in this instance.

A second example illustrating an alternate component is given in figure 7.10. The *Motor Cover* results indicate a calculated value range of £0.37 to £1.39. The actual value for the motor cover is given as £0.41. As with the previous result, if a direct comparison is drawn between the actual value to the calculated value for the same operation then the calculated value is given as £0.40.

Variables that are not obvious that will alter the process costing include the internal and external transportation. During assessment the user is asked to specify both values. At an internal level there are two forms of assessment, the cellular level and the factory level. It was considered important to specify both levels to accommodate product driven factory design which may have a conveyor format for cellular transportation against a process driven layout that may favour an Automatic Guided Vehicle for increased flexibility. At the cellular level there is the ability to specify the mode (which governs the unit capacity of the format), the cost rate and the velocity. This format is echoed by the factory transportation format. At an external level the cost consideration are the same, but it is the transportation mode that alters, this accommodates for rail, air and sea use.

Any results stored during the PS assessment will retain information on whether internal, external or factory costs have been included in the assessment.

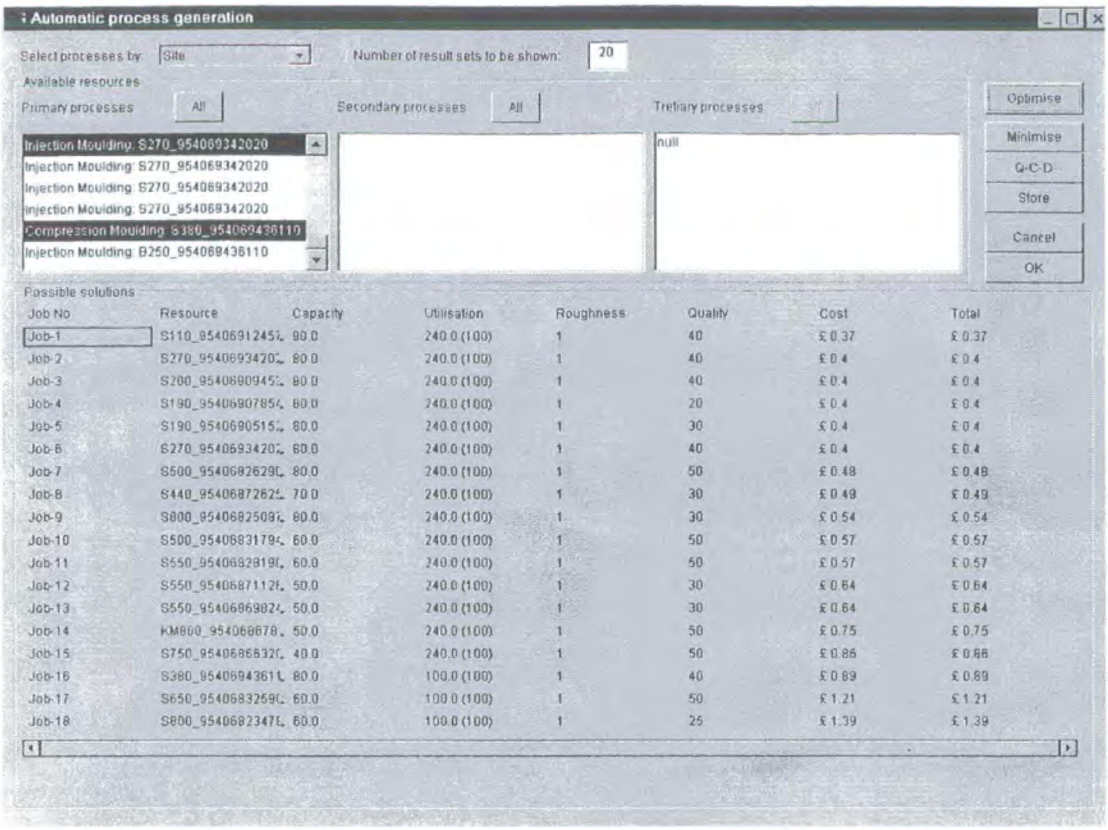

Figure 7.10: *Motor Cover* PS assessment

The combined results indicate that, "like-for-like" the PS function calculates the process results with reasonable accuracy. What is therefore required is an analysis of the alternate operations against different factory operations.

An analysis of these results is required to demonstrate the general validity of the costing model against the actual values obtained. An overview of a selection of processes tested from the Microlite 28 product against Flymo factory data values can be seen in figure 7.11. The analysis of the results show that for the examples given, part 1 the *Hood* (Basic cover) 2, 2 is the Cutting disc, 3 the Motor cover, 4 the *Impeller mounting hub*, 5 the Cord anchor bell and 6 the *Hood* (Basic cover) 1. Additionally a comparison to the actual manufacturing processes can be found in Figure 7.12.

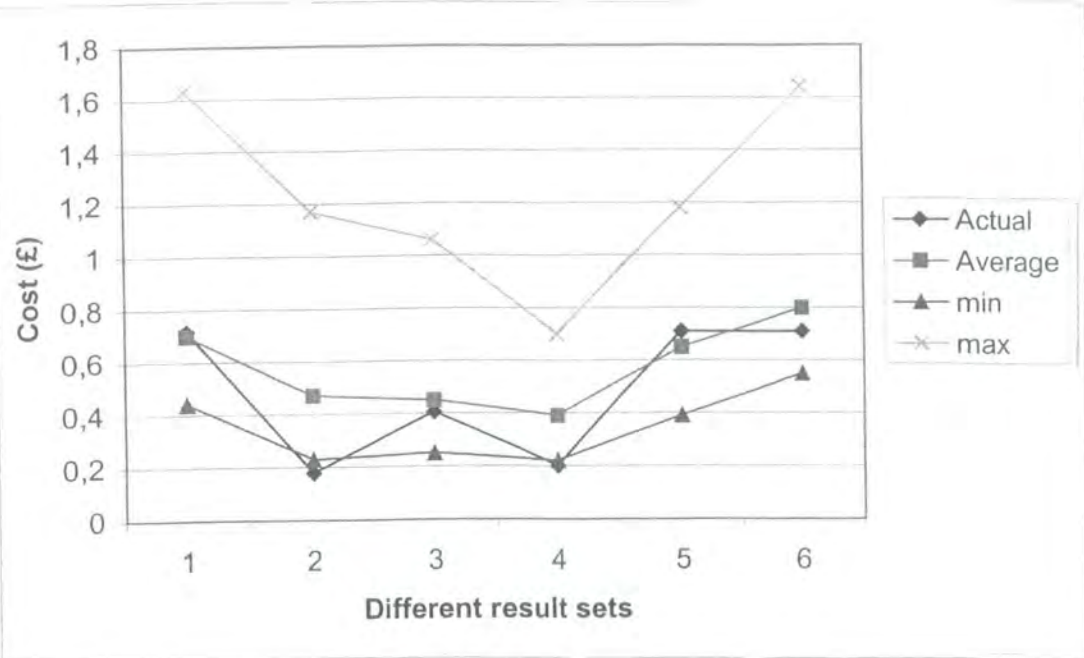

Figure 7.11: Process result comparison

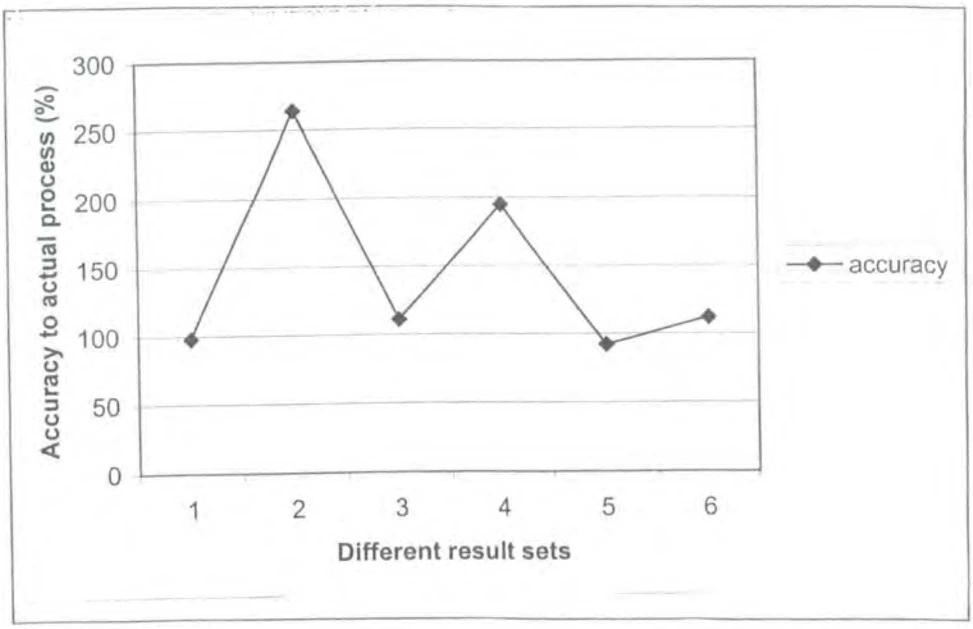

Figure 7.12 Process accuracy comparison

The actual 'like-for-like' machine comparisons have been given earlier along with complete analyses of the PS assessment calculations. These examples are accompanied with screen shots of the process results. The median value for the accuracy is given as 118%. However for four of the examples the value is as close as 108% of the actual value. Discrepancies within examples 2 and 4 are considered as shortfalls in the moulding operation of the part. The SCOPE system does not accommodate multiple parts into the same mould. Therefore for examples 2 and 4 which are specified as pair moulds the manufacturing cost would be halved.

A more detailed look at the 'Motor cover' identifies that for the given test, the quantity required was given as 10,000 parts. The assessment was carried out on a factory level whereby no restrictions on machine use were imposed. A graph of the given results can be seen in figure 7.13.

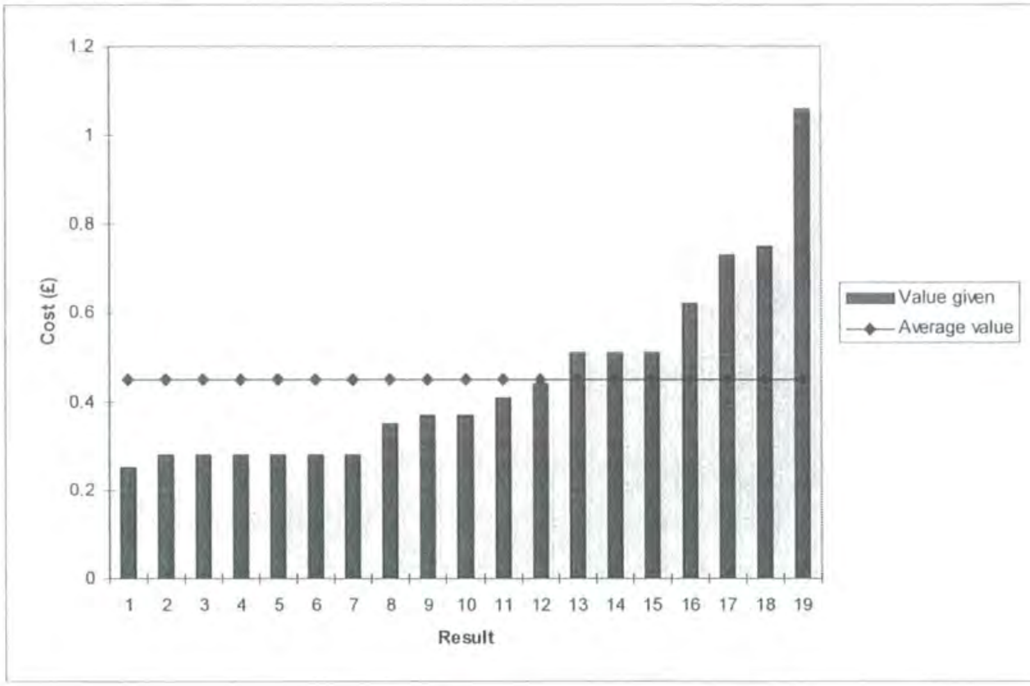

Figure 7.13: Motor cover results set.

For this result, the average is given as £0.45, where the actual value is stated as £0.40, the projected value being 12% from the actual value. By the examples given, it has been shown that this variability is feasible for the assessed products. For figures 7.9 and 7.10, the factory selection result sets are created. Those results identified as being if significant interest can therefore be stored.

7.5 Factory Selection

The objective of this assessment is to rationalise the result sets as produced by PS. It is important to understand that at this level of manipulation there are many operations that may prove ultimately ineffective but are included for initial assessment and comparison. Initially the product components can be illustrated simultaneously, as seen in figure 7.14. This facility aids the selection process, since it is now possible to witness the selected process from each supplier.

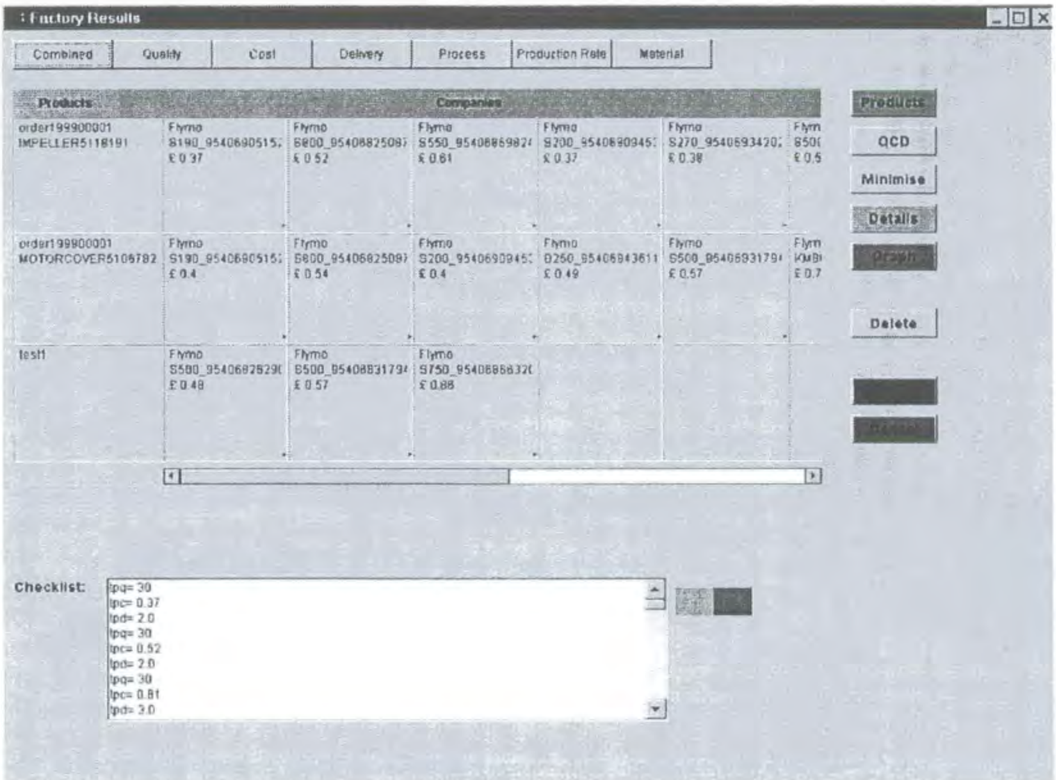

Figure 7.14: Multiple factory selection

The attributes listed enable the comparison of different attributes of the product components. It may be essential to know the lead-time for a given machine, therefore the *Delivery* function will indicate the lead-time required for the specified quantity. It is important to also have a *Quantity* attribute listed, since additional process selection results can be gained at any time. Thus, the specified quantity may differ.

There are other factors that will alter the presented result sets, as indicated above the delivery quantity issue is just one factor that is specific to a process selection result.

Additionally, there is the *Process* and *Quantity* relationship, where a specified process can be utilised more efficiently for a different component.

From the basic process result set view it is possible to manipulate the order of the results to suit the required criteria (cost, quality, delivery, material or process). Figure 7.15 illustrates the minimisation facility that removes those result set entries that are greater than the desired threshold.

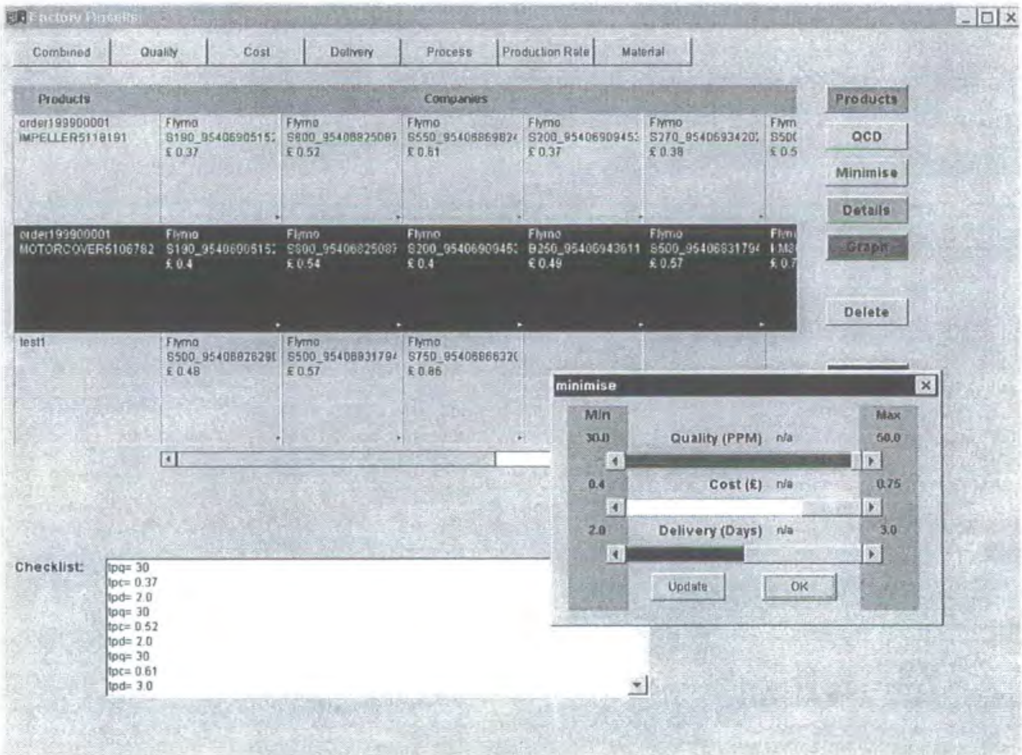

Figure 7.15: Highlighting of the minimisation function

For the given result set it can be seen that the "combined" view is used. The limit of the assessment presently allows all entries to be viewable. A simple slide bar operation is used to alter the results. This assessment does not alter the order of the result set, other than removing entries.

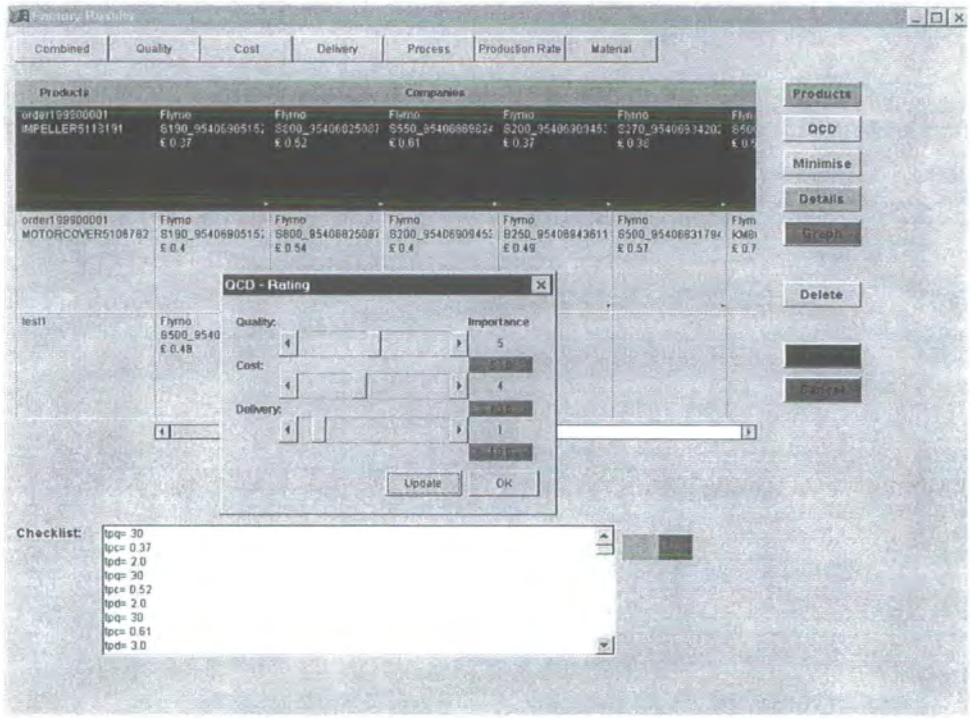

Figure 7.16: Optimisation rating functionality

Further assessment that alters the order of the presented result set is given in Figure 7.16. For this part of the assessment the designated results set has altered to give priority to the ‘Cost’, ‘Quality’ and ‘Delivery’ factors.

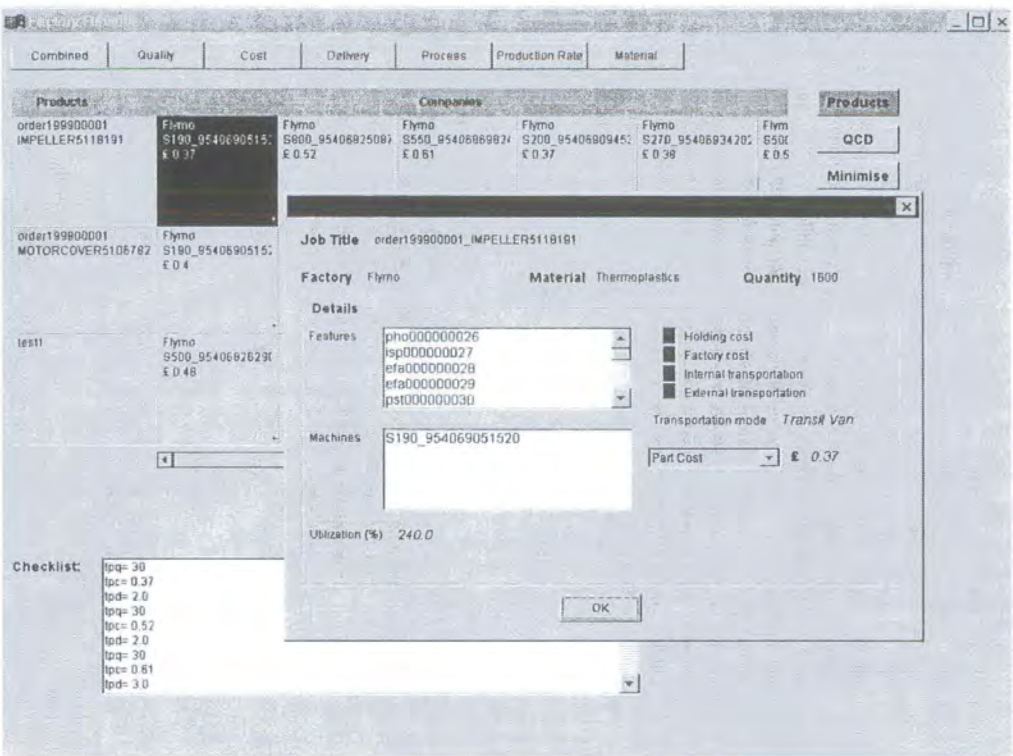

Figure 7.17: Individual process details

Finally the details that are compiled to give the process results can be illustrated, see Figure 7.17. For the given example it can be seen that both internal and external transportation has been considered. Also this facility enables the user to identify exactly the required features of the product component and the specified processes. Additionally, a secondary feature is the ability to predict a batch cost. This cost is based on the required quantity and for the given example, where the component cost is £0.37, then the production cost for 1600 components is approximately £592.

To aid the overall result assessment a separate feature of the SCOPE system enables the user to build up a Bill of Materials for a given product. Each assembly is indicated and the relating components can be completed. The aim of such a facility is to approximate the cost and delivery requirements for a given product model.

It is more difficult to quantify the validity of results presented by the Factory Selection phase of SCOPE. The individual process costings for 4 of the 6 products tested returned an accuracy to within approximately 12%. The Factory

Selection results are therefore not in question, rather the order in which the results are given.

7.6 *Case Study Material*

Due to recent changes in both fuel prices and government funding, the public transport sector is in a phase of growth. Information for the case studies has been obtained from Volante PTIS, a public transport interiors company based in County Durham. The general business comprises of decorative high-pressure laminates used for rail and bus interiors. Laminates are bought from a number of international suppliers, namely Formica and Perstorp, in sheet form of various thicknesses from 0.7mm to 20mm. There are standard sizes for material supply, 2800mmx1290mm and 4120mmx1540mm being two examples. Volante are then able to fabricate and assemble parts using CNC controlled woodworking routers and presses to form ceiling panels, window surrounds and dado panels.

Unlike Flymo, internal process costing at Volante is based on a flat factory cost rate for processes and not process specific. This therefore creates problems during assessment, since actual quotes are not based on real time data.

7.6.1 Case Study 1: PS for Coving panel construction

The traditional method for panel construction of bus interiors is bonding aluminium to high-pressure laminate. Volante are interested in changing this construction to suit their expertise, and various analyses have been performed to quote for this work. The demand for this work from a single bus manufacturer who produces 10 buses per week would be 60 panels per week. This supply doubles if the buses are double-deckers. For Coving panel construction it is proposed to change the construction from a veneered aluminium / laminate sheet to a composite laminate form. In real terms, the options available to Volante are vacuum forming of a laminated structure or pressing of a compact laminate. In either scenario this amounts to about 40 hours of work for two people per week.

From a general assembly drawing of the part it has been possible to construct the required product model. The material has been described as a Fibre Reinforced composite having a volume of 2000mm x 230mm x 3mm, see Figure 7.19. The material composition requires a multiple layer construction. For this product it would be a 3-layer lay-up and therefore the cost reflects this composition. Additionally, the adhesive used between the layers should be included in the required cost rate.

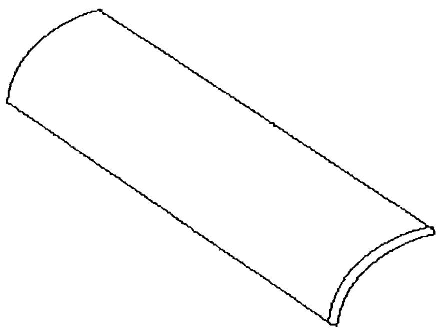

Figure 7.18: Coving panel construction

The Process Selection assessment of the Coving panel is disclosed hereafter, it considers all operations capable of fulfilling the product requirements.

Table 7.3 Coving panel assessment

Job	**Resource**	**Capacity** (parts per hour)	**Utilisation**	**Cost (£)**
Job-1	Amaspress	1.5	90%	21.65
Job-2	LTpress	1.4	90%	22.53
Job-3	Coldjig	0.25	95%	73.75

The results given indicate that there are two manufacturing options, either a heated vacuum press (Amaspress and LTpress) or a manual jig (Coldjig) developed for the operation and is based on the cure rate of the adhesive used in the operation.

The material cost associated with the operation is based on a 3-layer construction consisting of 2 face laminate materials and a backing board. A material sheet size of 2800mm x 1290mm, which would allow 5 panels per sheet, at a cost of approximately

£15.00 per sheet for the face laminate and £8.00 for the backing board is considered. The material cost is

$$\frac{15.00}{3}\times 2 = £6.00 \text{ plus, } \frac{8.00}{5} = 1.60 \text{ equals, } £7.60. \tag{7.5}$$

Additionally an adhesive cost of £1.00 per panel is allowed.

The processing cost based on the production rate of the operation in relation to the possible utilisation and a flat factory rate of £12.00 per hour, is given in table 7.4.

Table 7.4: Production cost results for Coving panel

Operation	**Production cost**
Amaspress	£8.72
LTpress	£9.43
Coldjig	£50.40

An alternative solution would require a different material composition and therefore would be considered as an alternate assessment.

7.6.2 Case Study 2: PS for Ceiling panel construction

A requirement for perforated ceiling panels were placed on Volante, see figure 7.19. The figure is an approximation of the design, but has a reduced detail level. The actual panel had 50 rows of holes, each containing 20 holes. Therefore the number of features totalled 1004, because there are the four sides of the panel to also consider. The material requirement is 1020mm x 740mm x 3mm. For a sheet size of 3120mm x 1540mm the material utilisation is 94.25%. This assessment is required to determine the most appropriate sheet size. At a cost of approximately £30.00 for a 3mm sheet of this size, the material cost per panel can be given as £5.00. More accurately the material cost is calculated as (equation4.1):

$$1400 \times 0.002264 \times (1.05 \times 1.49) = £4.96 \tag{7.6}$$

Where 1400 is the density of laminate (kg/m^3), 0.002265 is the volume of the part (m^3), the waste coefficient is given as 1.05 for CNC operations and £1.49 is the kilogram cost of laminate.

This machine detail would take considerable time for a manual operation and therefore CNC controlled operations are required.

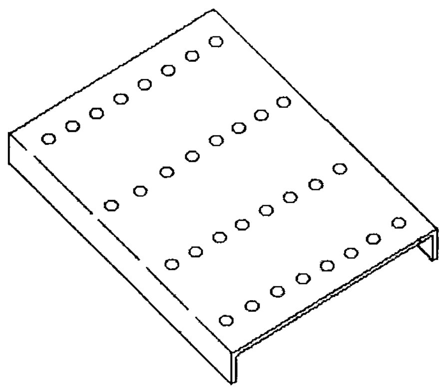

Figure 7.19: Ceiling panel construction (approximation).

For the required contract the number of panels required is 1960. For the ceiling panel construction there are many operations to consider, these are the routing operations for the channels where the panel is bent and the perforation of the panel. The *hot size* for batches of panels through a CNC router is 10, that is to say that after every 10 panels the machine requires retooling, see equation 4.2. Therefore the required batches as given by the *hot size* is given as:

$$\frac{1960}{10}+1=197 \text{ batches} \qquad (7.7)$$

To follow the procedure for the costing of a single machine, the realistic production time, as given by P_a (see equation 4.3), for a CNC router is given by (equation 7.8):

$$\frac{1850}{1004}=1.84 \text{ parts per hour} \qquad (7.8)$$

Where the specified operations her hour is given as 1850, and the operations required for this part is noted as 1004, where this total features of the panel. Therefore it is possible to produce 1.84 panels per hour.

The actual processing time requires the tooling and batch considerations to be added to the realistic production time, thus (see, equation 4.4):

$$\frac{1}{1.84}+\left(\frac{197\times 0.0055}{1960}\right)=0.544\,\text{hrs} \tag{7.9}$$

Where the number of batches, multiplied by the time taken to change the tooling (hours), and divided by the production quantity gives the actual processing time per part.

The internal transportation consideration of the process details the distance between the manufacturing process and the depot or stores (see, equation 4.5). The distance is noted as 30m and the Forklift used at Volante has a capacity of $3m^3$, and the velocity is 2.5m/s.

$$\frac{(1.02\times 0.74\times 0.003)}{3}\times\frac{30}{2.5}=0.0091\,\text{hrs} \tag{7.10}$$

The factory cost is therefore the combined process and transportation times, multiplied by the factory operating cost rate (see, equation 4.6). At Volante the factory cost rate is £12.00 per hour.

$$(0.544+0.0091)\times 12=6.64 \tag{7.11}$$

The cost per part, for CNC operations is given as (see, equation 4.7):

$$4.96+6.64=11.60 \tag{7.12}$$

The full listing of results presented in table 7.4 reflect that both the CNC operations and other manufacturing processes. Additionally it can be seen that operations can be split between processes.

Table 7.5: Ceiling panel assessment

Job	Resource	Capacity	Utilisation	Cost (£)
Job-1	UXrouter	2	90%	11.60
Job-2	Thermwood	2	90%	11.60
Job-3	Wadkinrouter	2	90%	11.60
Job-4	Staticrouter	1	80%	20.00
Job-5	Pedestal	0.8	100%	15.00
Job-5	Staticrouter	20	12%	99.60
Job-6	Pedestal	0.8	100%	15.00
Job-6	UXrouter	20	10%	120.00

From the results given in table 8.5, it can be seen that jobs 5 and 6 are double operations and therefore require compiling, job-5 costing £115.60 and job-6 costing £139.00. These results reflect the time required to manually machine the detail into the panel. More importantly, the utilisation of the secondary operation can be seen to be 10-12%, denoting that the routing operation spends almost 90% of the production time for this job unused.

Production costs associated with the methods can be seen to vary drastically between manual and automated operations, and a similar difference can be seen with the delivery date. The results obtained were based on a required batch size of 30.

Table 7.6: Ceiling panel result components

Job	Delivery (Hours = days)	Production cost
1	15 = 2	£6.60
2	15 = 2	£6.60
3	15 = 2	£6.60
4	30 = 3	£15.00
5	38 = 3	£15.20
6	38 = 3	£15.20

It can be seen that the material cost is approximately 20% of the eventual retail value.

7.6.3 External Considerations

The external cost consideration relating to these results is based on the transportation cradle required. There are a number of different standard box sizes possible for external transportation from Volante, each having a standard base size (1200mm x 2000mm) and a variable height, these include 300mm, 600mm and 1200mm. For the Coving panels, a 300mm high box is typically used. This box would not reflect the most efficient size for volume to cost ratio, but it is common for the supplier to specify the required quantity and date for delivery. Therefore the required container is not necessarily the optimal container. At Volante the external cost is based in a rate of 34p per mile. Considering the fact that the panels are required at Wigan (approximately 120 miles (or 180km)) from the factory, the cost per crate is 120 x 0.34 = £40.80. The *correction* factor added to the material volume reduces the components per crate from 200 per box to 80 per box however the required batch quantity is 60. The transportation cost per panel is £0.68, to be added to the processed cost.

7.6.4 Factory Selection at Volante

For the purpose of eventual factory selection, the modelling of Volante as an independent factory is necessary, based on the presumption that the values given reflect those quoted to customer companies. The factory selection function is therefore feasible for any given customer to model new or existing parts supplied by Volante, independently, against the processes at Volante. The case studies presented are therefore legitimate for assessment.

Viewing the compounded results (Table 7.7) highlights the differences between the processes used for the different operations. It is considered that from a customer perspective the results given allow for the evaluation of a material or process prior to design confirmation.

Table 7.7: Combined result classification

Product	Process			
Coving panel	Volante Amaspress £21.65	Volante LTpress £22.53	Volante Coldjig £73.75	
Ceiling panel	Volante UXrouter £11.60	Volante Thermwood £11.60	Volante Wadkinrouter £11.60	Volante Staticrouter £20.00

The delivery results shown (Table 7.8) indicate that the Coldjig method would take approximately 3 working weeks to produce. This value is rejected from any further assessment due to delivery requirements.

Table 7.8: Delivery result classification

Product	Process			
Coving panel	Volante Amaspress 3 days	Volante LTpress 4 days	Volante Coldjig 17 days	
Ceiling panel	Volante UXrouter 2 days	Volante Thermwood 2 days	Volante Wadkinrouter 2 days	Volante Staticrouter 3 days

The case study and function material presented has illustrated the diversity of the SCOPE system for moulding, forming CNC automatically controlled machining and manual machining operations. It is considered that this is a suitable range of processes to test the methods properly. The main family of operations not presented herein is casting, the factors considered during the assessment are similar to those adopted during a moulding operation. Therefore it is assumed that casting operations would behave in a similar fashion to moulding operations.

7.7 Summary

To conclude, the testing and evaluation of the proposed methods have been undertaken through the development of SCOPE. It has been demonstrated that SCOPE is capable of generating process plans from the given resources model data and that these plans are feasible. The PS function of the SCOPE system has illustrated the ability to calculate to a reasonable confidence level, process results that are comparable with values observed in industry. Additionally, the FS phase of the assessment has proved a useful aid in identifying suitable supplier processes, based on control factors such as cost, quality and delivery.

It was unfortunately not possible to test the system in a working design environment where real-time design changes could be rapidly assessed and therefore no firm conclusions can be drawn as to the feasibility of such a system as part of an integrated concurrent engineering system.

Chapter Eight

Discussion and Conclusions

8.1 Introduction

It has been the intention of this work to illustrate the value of supplier capabilities during the evaluation of an initial design. The framework for the assessment of manufacturing operations of the extended enterprise during early product design is illustrated through the implementation of the computer software system, SCOPE.

The objectives of this research, as stated in Chapter 1, section 1.6, were as follows:

1. To assess previous methods used for the generic process selection problem and outline process selection requirements for the extended enterprise.

2. To develop a manufacturing process data model to accommodate generic manufacturing process information. The manufacturing process families of casting, moulding, machining and fabrication should be represented within the system.

3. To develop methods for Process Selection of the supply chain using the defined manufacturing process data model and to expand the Factory Selection method.

4. To implement the methods for Process Selection. It is proposed that this should include a factory model generation package for developing new factory manufacturing process data models.

5. To evaluate the implemented Process Selection and Factory Selection methods using data gathered from industrial collaboration.

8.2 Discussion

8.2.1 Existing work

A comprehensive review of published literature has been presented, discussing the main topics of investigation. Supply Chain Management was identified as a key element of this work, the most relevant topics being supplier integration, physical distribution, capacity and flexibility. In particular, it was proposed that the identification of manufacturing processes during early process selection would add a new paradigm of flexibility to product development. It has been stated that much of the work relating to supply chain management was strategic, and models were presented to demonstrate structured supply chain configurations. Additionally, supplier integration was said to go beyond the purchasing and supply management of a relationship to also include inventory, logistics infrastructure and materials management, illustrating how best to work with, and not dictate to suppliers. It was noted that no previous work discussed the role of suppliers during product development, addressing which manufacturing process information is required to assist product development.

Supply chain literature has been very useful during the conception of this research, to identify management techniques currently adopted for supply chain integration (Ellram, 1990 and Harland, 1995). The information has also been required to understand which manufacturing factors (i.e. cost, delivery, quality) are thought important for supplier assessment. It was found that cost is the predominant factor for supplier assessment, although it was established that cost is not sufficient for a strategic partnership (Spekman, 1988). Instead a diverse range of factors, including logistics and materials would produce more accurate results.

The adoption of Concurrent Engineering has lead to the restructuring of all design and manufacturing disciplines. In particular, computer based tools for product development. Computer-aided engineering illustrates that computer technology influences the manufacturing process, from design through to manufacture. The discipline of product development, including process selection and factory selection was required to identify existing methods for process selection. It is also noted that operational constraints during process selection improve manufacturing reliability. It is therefore considered that the inclusion of supply chain manufacturing processes during process selection will enable greater choice.

Existing methods for process selection were found to fall into two categories, either *shape complexity* or *feature generation*. Work relating to generic process costing relied upon the manual assessment of shape complexity from a three dimensional form, thus failing to utilise any automation of this procedure. The aggregate product model adopted to rationalise the part geometry in terms of features has allowed processes to be selected on the basis of definite feature capability, instead of probable part geometry. The attributes of design and manufacture need to be integrated at an earlier stage than at present, to enable suppliers to be considered earlier in the manufacturing cycle. Work relating to flexibility was found to be deficient regarding the innovation of products and manufacturing solutions, consequently avoiding early product development. However, the work on flexibility did present useful ideas for innovative operational principles and supporting information (Eloranta *et al.,* 1995). It was considered that the early identification of manufacturing processes during product development would result in additional flexibility. Moreover, the adoption of Java as a programming language is considered essential to the ability of the process selection software to operate between companies, across the Internet.

8.2.2 Data collection and storage

Primarily there are two sections to data collection and storage, firstly the adopted *data format,* for both the product and process model, and secondly, the *collection format,* for manufacturing process information. The topic of process planning combines product identification, process classification and process selection. The format of data for the product model was stated as *feature recognition*. It has been possible for the developed software system (SCOPE), to utilise the product model developed by the Design and Manufacture Research Group. This is the full extent of commonality between group members. The information was presented in the form of an aggregate product model, describing the product model as a combination of features.

Process modelling, which has been illustrated as an important issue for data modelling has been formalised through the presented generic manufacturing process data model. This thesis has highlighted the ability of the manufacturing process data model, illustrating both the capabilities of individual processes and combined assets of the factory. It has not been the intention of this research to present a detailed process planning function for the extended enterprise. The data required for such a system would require detailed information on many manufacturing operations, which was beyond the remit of this work. Incidentally, detailed work already exists for the embodiment phase of design, developed by the University of Durham, Design and Manufacture Research Group on machining, welding and assembly.

The development of the Factory Modeller 99 software, installed at supplier factories, will generate a standard *collection format* for the manufacturing process data collection. It was not initially thought that Factory Modeller 99 required a detailed explanation, since the software is a basic database entry tool, compiled for easy assembly of factory manufacturing databases. However, the format of the factory model is a novel feature of this work, presenting the factory as a multi-tiered organisation. The thought process employed in the development was paralleled from the aggregate product model development by the Design and Manufacture Research group. For each tier of the factory there is a list of properties, and a corresponding list of attributes. Information retrieval is made easy at each stage by a pointer to the next level of required data.

8.2.3 Implementation

The implementation of the process selection and factory selection methods has been possible through the development of the software, SCOPE. Whereas the development of this system has not been the focus of this research, the development required careful attention and consideration to facilitate operation. The system was designed for easy operation, by users without an in-depth knowledge of computer software. In principle the system was designed to mimic a Microsoft application, using different windows to input data. For example, during process selection, criteria are required to complete the information needed for assessment. Therefore, information windows are presented to the user to complete the data, similar to the Control Panel window in the Windows operating system. Error handling during development was carefully considered, and time was taken to eliminate user mistakes from SCOPE.

Internet access required to link supplier databases to the SCOPE system was achieved through research into computer software development. Once again, the software has not been the focal theme of this research, but different software was considered during the development of this research. Discussions were held with other members of the research group, who had more programming experience, and contact was made with other research groups at conferences to discuss Internet programming development. It was discovered that larger research groups were using the Visual C programming language, and a Common Gateway Interface to link database technology. The benefit of such a system allowed different database technology to be read by the application. Many people were developing these systems to create the interface technology. The Java technology used during the development of this research was adopted because it avoided many of the interface problems encountered by the Visual C programming. The system was restricted to the Java database, required at the supplier location. The research was initiated in October 1996, and programming was completed by May 1999. During this period the Java software evolved from edition 1.01 to 1.2, with several fixes and edition reviews between. Presently (January, 2001) Java is at edition 3.0. The choice for the system was an application or a web applet (web embedded program). It would be perceived more appropriate to have a web applet, since Internet connectivity is the essence of the research. However, at the time of writing the application Java would not allow data transfer between databases situated on different servers. Therefore an application was developed.

Implementation of this research was carried out in three distinct phases; process selection, factory selection and product data collection. During the development of process selection various methods were written to facilitate information transfer. Primarily the product model data, used as the input for the assessment. The Process Selection methodology implemented during the development of this research has proved a suitable strategy for modelling process selection during early product development. It is considered that the analysis of existing process selection methods has clarified the position of SCOPE within the design cycle. Factory selection considered realistic factors within the design process, including process characteristics, production constraints and delivery. Product data collection was achieved through the development of Factory Modeller 99, see Chapter 8, section 8.2.2.

8.2.4 System Evaluation

The testing and evaluation of the implemented methods have been undertaken through the development of the software, SCOPE. It has been demonstrated in Chapter 7 that the Process Selection function has the ability to calculate to an acceptable confidence level, process results based on partial product model data, that are comparable with values observed in industry, using generated manufacturing process data. In addition, the presented process selection results have been compared to actual process data. The results have proven that the data is sufficiently accurate, i.e. within 10% of identical machine data for real data, to substantiate the method as a viable process selection tool.

Manufacturing process data storage methods described throughout this work have proved successful for rapid assessment of manufacturing processes. Typically an assessment would take approximately 30 seconds to evaluate 50 manufacturing processes, with many different primary and secondary combinations, to produce about 150 results. These results are then ordered in accordance to cost. Additionally, the factory selection phase of the assessment has proved a useful aid in identifying suitable supplier processes, based on control factors such as cost, quality and delivery.

It was unfortunately not possible to test the system in a working design environment where real-time design changes could be rapidly assessed. Therefore no firm conclusions can be drawn at this time as to the feasibility of such a system as part of an integrated concurrent engineering system.

It is not feasible to suggest that Factory Selection or Process Selection should be used ultimately for supplier selection. Since, preliminary selection is based on partial product data and cost assessment is not sufficiently accurate. The cost model used for Factory Selection has been found to have a flaw, regarding information distribution. Normal distribution has been applied to the attributes of Cost, Delivery and Quality, assuming that the results would tend towards a normal distribution curve. However, this does not appear to be the case for all assessments. Assessment concerning multiple variables is complex. For Cost, Quality and Delivery, all attributes need to be minimised for optimal calculation. The results given by the Factory Selection are not wrong, but it is considered that it would not be appropriate for detailed selection.

8.3 Conclusions

The research described in this thesis has addressed the following issues:

- It is recognised that there is a need to optimise the design for a given problem, and this can be best achieved by presenting all possible manufacturing solutions. To facilitate this it is proposed that supplier manufacturing processes should be included to add a new paradigm to process selection.

- Concurrent Engineering requires that the process selection function be initiated as early as feasibly possible. This means commencing the design cycle, when only partial design information is available. It is unsuitable to implement a conventional computer aided process planning systems at this stage without detailed design information.

- It is necessary to compare and contrast between alternative process selection options at an early stage, if designs are to be optimised for a particular manufacturing process. It is considered that suppliers' manufacturing processes should be compared to evaluate different manufacturing methods.

- It is identified that design engineers are not able to identify all possible manufacturing process and material combinations for a given design, leading to a decision based on intuition instead of assessment. Support software is required to aid the designer in the process and factory selection process.

In order to address these problems:

- A manufacturing process data model has been proposed that allows the representation, and storage, of factory data at varying levels, and in a hierarchical way, to accommodate internal and external cost considerations of a supplier factory.

- A methodology for process selection has been developed that incorporates an automated process selection system, for the conceptual stage of design. The assessment of production costs and times using generic process models operate on reduced product data.

- A generic factory selection framework has been developed that includes a sort algorithm for initial identification and ordering of results. In addition, manipulation techniques have been developed that enable the design engineer to prioritise process attributes.

- The above system has been implemented using the platform independent programming language, Java. The Java language enables the system to be operable on any computer platform (i.e. windows, UNIX, etc.) Testing of the system has yielded positive results, regarding identical process comparison.

The research in this thesis demonstrates novelty in the following ways:

- Alternative costing models for process selection have been based primarily on shape complexity and require human intervention to complete an assessment. The proposed method utilises the form of the design by the features generated, and takes into account individual process capabilities based on the required features. Therefore processes are selected based on their feature capability.

- The inclusion of the extended enterprise within process selection enables multiple considerations to be given to any product. In addition, the research identifies internal and external transportation considerations within any cost assessment.

- As the system generates multiple results for any given product, factory selection can be used to compare process capabilities. This facility provides the user with the ability to screen suppliers.

8.4 Recommendations for further work

The development of this research has identified many new channels of investigation. Recommendations fall into two categories; those directly related to the continued development of this research, and those observed during the development of this research. Those directly related to the continued development include an improved factory selection assessment model, considering more factory attributes, and not distorted by the variation of manufacturing process results. Also, an improved costing model, to allow parallel consideration of manufacturing process operations. Factors observed during the development of this work include multiple loading of manufacturing processes, such as casting or moulding processes. Similarly, process optimisation, such as casting, moulding, or CNC routing for raw material optimisation.

Concerning the further developments of SCOPE, the presented methods for process selection and factory selection assume a normal distribution to the data when ordering after assessment. This may not be the case for all assessments, and it is therefore considered that further investigation is required to ascertain an alternate grouping for the population assessment of manufacturing processes. Various forms of normalisation have been identified throughout this research, including standard deviation and mean value, but no singular method has been identified that would provide more accurate results than the method given. By developing a more accurate sort method, the data may be considered for detailed process selection or possibly supplier vendoring.

At present the limitations of the software include the inability to model multiple processes concurrently, thus loading only single processes. Effectively this would equate to splitting the demand across several manufacturing processes or even factories. To achieve this, the user would need to specify a delivery date, and then SCOPE would need to spread the demand across the supplier network to achieve the required delivery date. The importance of supplier relationships would be amplified by such a procedure, requiring co-operation between suppliers. It is not anticipated that this function would be useful for conceptual design, but the function would be appropriate for process selection during embodiment or detailed design.

An additional feature to the system, similar to the loading problem described above, is the capacity loading of a single machine. Considering moulding or casting operations, where multiple parts may be created by one mould. The system presently assumes one part per cycle. Where the capacity of the machine enables multiple parts per cycle the SCOPE system should reflect this option. The result would allow more accurate costing for moulding, casting, routing, and forming operations, plus a reduction in delivery time.

A further issue raised during the course of this research is real-time data capture. That is, the data provided by statistical process control, process cost and timing information. It is suggested that such data could be linked to the manufacturing process database to updated process costing, utilisation and availability. The information generated would therefore be utilised by the SCOPE system to maximise the accuracy of any further assessment.

The integration of assembly functions, such as gluing, fastening and bolting into the SCOPE system would enable a subassembly operation to be evaluated as part of the initial design. This operation has limited impact since the idea of assembly modelling to generate the most efficient method of manufacture is based on a detailed time and motion study of the workplace. The information generated at the initial phase could be only based in existing operation workstations capabilities. However, the fact remains that information could be generated to evaluate a rough cost, quality and delivery assessment for a subassembly.

Regarding observed manufacturing problems, it has become apparent during data collection that for moulding, casting and CNC routing operations, parts are nested together into moulds or sheets to minimise the production time and to improve the material utilisation. It is therefore suggested that a further area of research would be to explore these operations to optimise this characteristic. This function is valid since parts are presently manually nested to maximise material utilisation and this may take several hours depending upon the number of components to consider, it is also open to human error. More specifically for CNC routing operations, material utilisation is dependant upon sheet size and component size. The laminate or wood material is only available in specific sizes (4120mm x 1540mm, 3050mm x 1540mm, 3050mm x 1290mm and 2800mm x 1290mm) and therefore the problem is one of optimising the utilisation of any part geometry, of which there may be several for any particular job to a variety of material sizes. It is possible to nest different products instead of single components.

A function that has not been explored is the packaging of items. From a system viewpoint, this is the time and cost associated with the packaging of items, including the costs of manufacturing crates or pallets. The implication being that if these factors are not properly assessed prior to manufacture then the correct profit margin would not be considered. The idea that parts are simply placed into a container for internal or external transportation is not realistic. There is a market segment devoted to the assessment and design of packaging. Ultimately this information is required within the sales and administration of any factory to generate the packing list and to inform the freight carrier of quantities, weight and size of the shipment. The problem therefore is to generate a method for the optimisation of packaging. This may take the form of acknowledging that there are standard forms of packaging (i.e. vertical, horizontal, end-to-end, top-to-tail) and that for any given format there are standard box sizes (2000mm x 1000mm x 300mm/600mm/900mm/1200mm). Therefore an assessment could be generated efficiently to assess the validity of any given box size, the content of that box and the format of packaging. The result would be an automatically generated parts list for any box as required by sales and administration and the box size and weight.

8.4.1 Summary

The channels of investigation discussed add both new functions to the presented software system, and maintain the automated nature of the process and factory assessment. Revised manufacturing process costing assessment will enable the system to be operated for conceptual and detailed process selection. An appreciation of the process loading problem will enable more realistic process and material utilisation. Additionally further work relating to process packaging would exploit external transportation considerations.

Process and factory selection will be enhanced by the further optimisation and knowledge of supplier capabilities.

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APPENDIX A

Appendix A: Process classification

Automatic Machining

(Process diagram)

General Description

The removal of material by chip processes using sequenced or simultaneous machining operations on cut to length bar or coiled bar stock. The material is automatically fed into the machine.

Typical Applications

Attributes

Materials: Irons, carbon steel, alloy steel, stainless steel, copper & alloys, aluminium & alloys, magnesium & alloys, zinc & alloys, lead & alloys, nickel & alloys, titanium & alloys

Mechanical properties

Minimum tolerance: (mm) 0.55

Minimum weight: (kg) 0.5

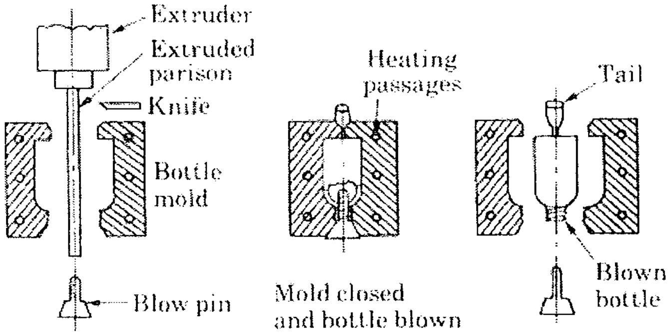
Maximum weight: (kg) 50

Tooling and die costing: (£) 300

Tooling time: (min) 20

Optimal batch size: 1000

Blow Moulding



General Description

Blow moulding is a modified extrusion and injection moulding process. In extrusion blow moulding, a tube is extruded (usually turned so that it is vertical), clamped into the mould with a cavity much larger than the tube diameter, and then blown outward to fill the cavity. Blowing is usually done with an air blast, at a pressure of 350-700kPa.

Typical Applications

Most polymer containers up to 5 gallons, toys and auto-heater ducting

Attributes

Materials: Thermoplastics

Mechanical properties

Minimum tolerance: (mm) 0.55

Minimum weight: (kg) 0.5

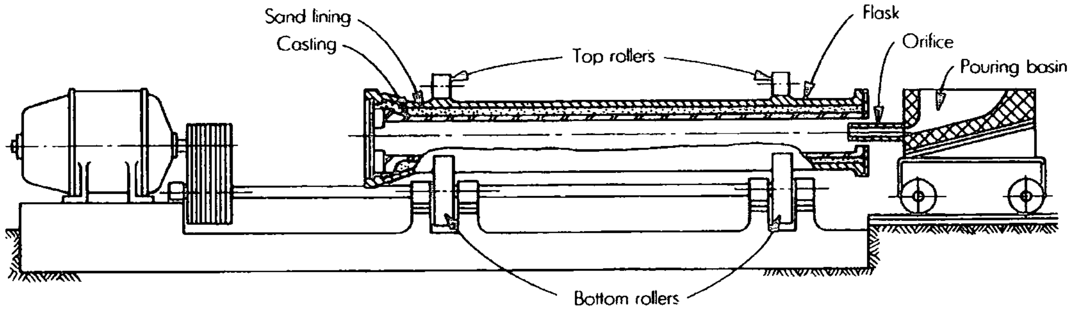
Maximum weight: (kg) 50

Tooling and die costing: (£) 2000

Tooling time: (min) 180

Optimal batch size: 1000

Centrifugal Casting



General Description

As its name implies, the centrifugal-casting process utilises the inertial forces caused by rotation to distribute the molten metal into the mould cavities. The three types of centrifugal casting are true centrifugal casting, semi centrifugal casting, and centrifuging.

Typical Applications

Gun barrels, lampposts, and wheels with spokes

Attributes

Materials: Irons, carbon steel, copper & alloys, aluminium & alloys, nickel & alloys

Mechanical properties

Minimum tolerance: (mm) 0.55

Minimum weight: (kg) 0.5

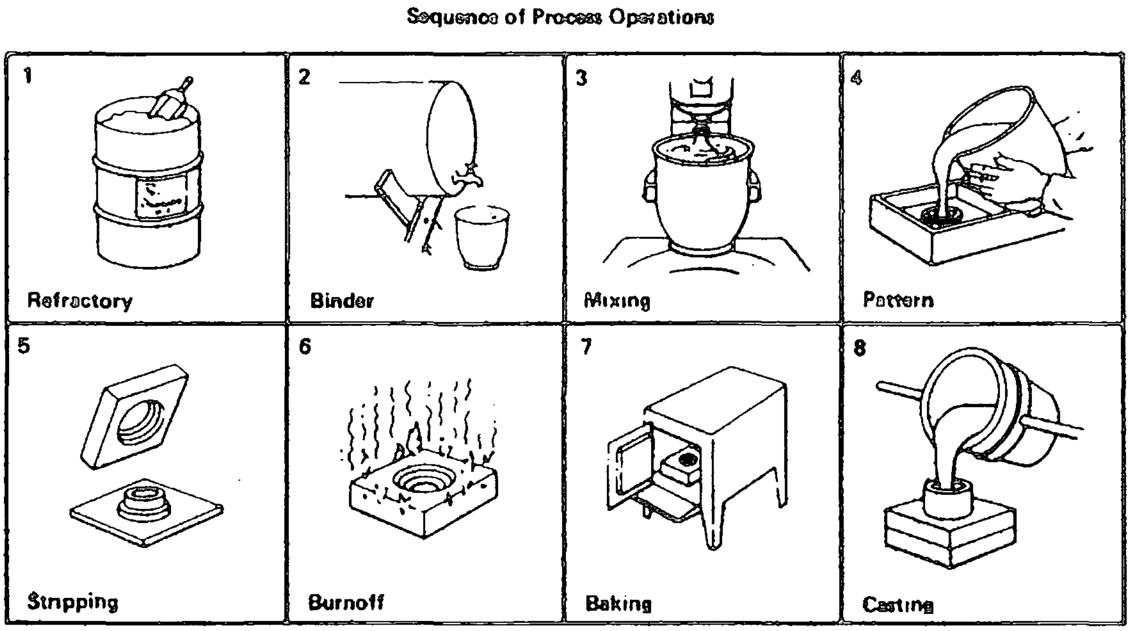
Maximum weight: (kg) 50

Tooling and die costing: (£) 1000

Tooling time: (min) 240

Optimal batch size: 1000

Ceramic Mould Casting



General Description

The ceramic moulding process uses refractory mould material for high-temperature applications. The method is called cope-and-drag investment casting. The slurry is poured over the pattern (usually made from wood or metal) and allowed to set. After setting the mould is removed from the pattern and baked to remove moisture.

Typical Applications

Attributes

Materials: Irons, carbon steel, alloy steel, stainless steel, copper & alloys, aluminium & alloys, magnesium & alloys, zinc & alloys, tin & alloys, nickel & alloys

Mechanical properties

Minimum tolerance: (mm) 0.38

Minimum weight: (kg) 0.2

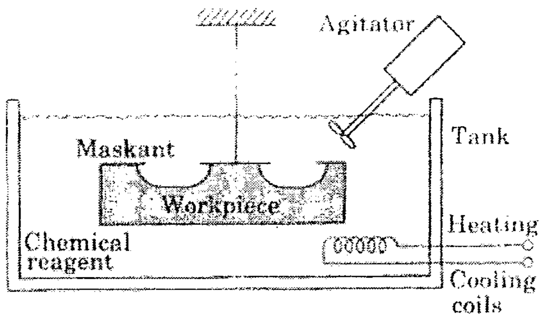
Maximum weight: (kg) 5

Tooling and die costing: (£) 1500

Tooling time: (min) 300

Optimal batch size: 50

Chemical Machining



General Description

It is known that certain chemicals attack metals and etch them, thereby removing small amounts of material from the surface. Thus chemical machining operates by removing material from the surface by dissolution, using chemical reagents, such as acids and alkaline solutions.

Typical Applications

Engraving metals and hard stones, printed circuit boards and microprocessor chips.

Attributes

Materials: Carbon steel, alloys steel, copper & alloys, aluminium & alloys, magnesium & alloys, zinc & alloys, tin & alloys, lead & alloys, nickel & alloys, titanium & alloys, ceramics, precious metals

Mechanical properties

Minimum tolerance: (mm) 0.55

Minimum weight: (kg) 0.5

Maximum weight: (kg) 50

Tooling and die costing: (£) 1000

Tooling time: (min) 300

Optimal batch size: 1000

Closed Die Forging

(Process diagram)

General Description

The block to be forged is prepared by such means as cutting or cropping from an extruded or drawn bar stock. The blank is then placed in the lower die and as the upper die begins to descend, the blanks shape gradually changes. In true closed die forging, flash does not form, and the work piece completely fills the die cavity.

Typical Applications

Crankshafts, airframe components, Tools, Nuclear components and agricultural equipment.

Attributes

Materials: Carbon steel, alloy steel, stainless steel, aluminium & alloys, copper & alloys, magnesium & alloys, titanium and nickel and & alloys

Mechanical properties

Minimum tolerance: (mm) 0.5

Minimum weight: (kg) 0.01

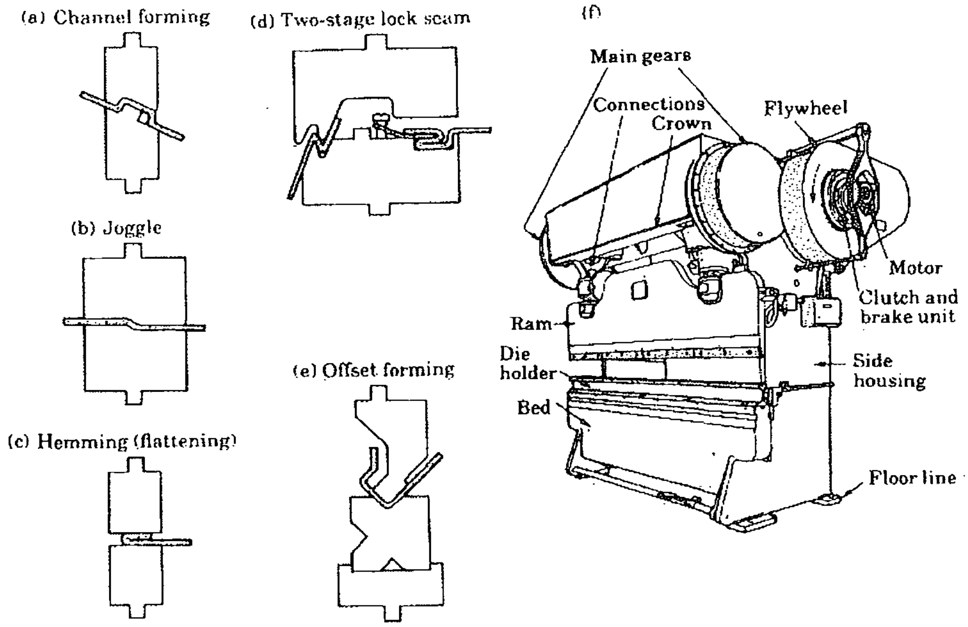
Maximum weight: (kg) 100

Tooling and die costing: (£) 5000

Tooling time: (min) 400

Optimal batch size: 5000

Cold Forming



General Description

Cold forming uses coils of wire stock and three to four cavities in the dies. A cut-off machine is included in the machine. Machines are ordered to handle the limited range of diameters. The gripping dies are at the front of the machine and the operator places the stock in the one cavity and then another. Forming is done principally by the heading tool but can also be done by the clamping die.

Typical Applications

Small fasteners

Attributes

Materials: Carbon steel, alloy steel, stainless steel, copper & alloys, aluminium & alloys, magnesium & alloys, zinc & alloys, tin & alloys, lead & alloys, nickel & alloys

Mechanical properties

Minimum tolerance: (mm) 0.06

Minimum weight: (kg) 0.001

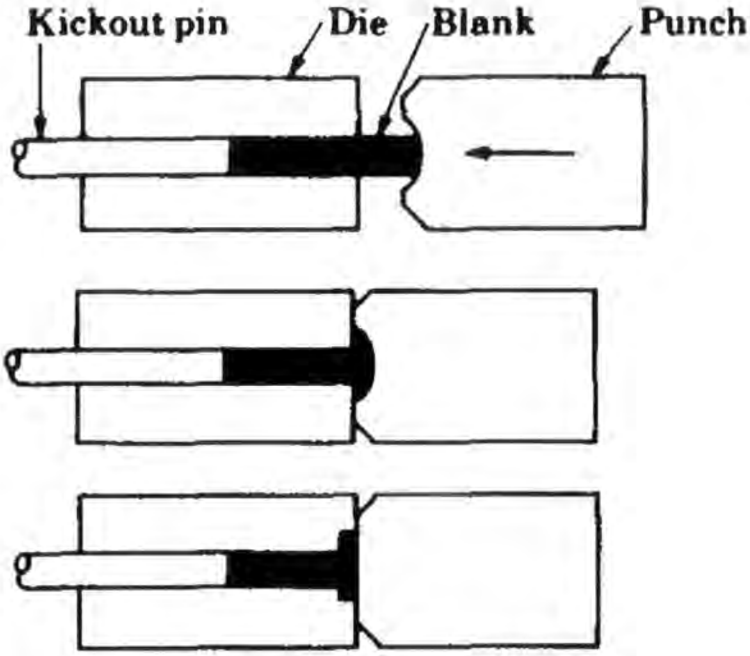
Maximum weight: (kg) 50

Tooling and die costing: (£) 1000

Tooling time: (min) 120

Optimal batch size: 5000

Cold Heading



General Description

Stock material is gripped in a die with usually one end protruding. The material is then formed by successive blows into the desired shape by a punch or a number of progressive punches. Shaping of the shank can be achieved simultaneously.

Typical Applications

Nails, Fasteners, spark plug pot, ball joint, shafts

Attributes

Materials: Carbon steel, steel alloys, stainless steel, aluminium & alloys, copper & alloys, nickel & alloys, precious metals

Mechanical properties

Minimum tolerance: (mm) 0.55

Minimum weight: (kg) 0.5

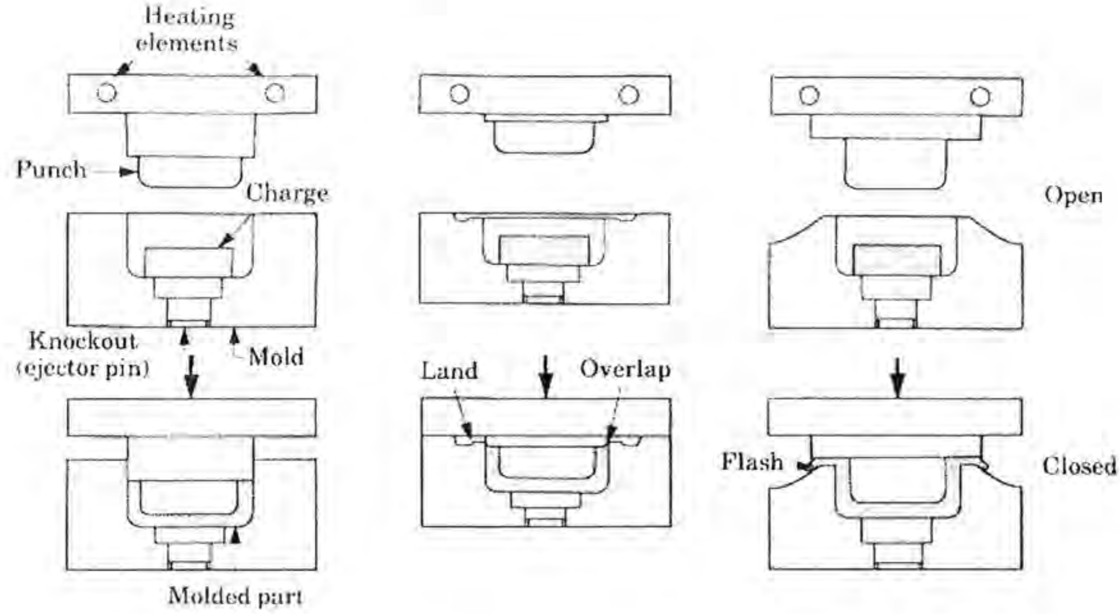
Maximum weight: (kg) 50

Tooling and die costing: (£) 1200

Tooling time: (min) 100

Optimal batch size: 1000

Compression Moulding



General Description

In compression moulding, the plastics compound is placed in a heated mould. The compound softens and becomes plastic as the upper part of the die moves, compressing the material to the required shape and density. Continued head and pressure produce the chemical reaction that hardens the thermosetting material.

Typical Applications

Attributes

Materials: Thermoplastics, thermosets, FR composites

Mechanical properties

Minimum tolerance: (mm) 0.18

Minimum weight: (kg) 0.004

Maximum weight: (kg) 20

Tooling and die costing: (£) 800

Tooling time: (min) 100

Optimal batch size: 100

Contact Moulding

(Process diagram)

General Description

Contact moulding processes use a single male or female mould made of materials such as reinforced plastics, wood or plaster. Contact moulding is used for making products with high surface area-to-thickness ratio. This is a "wet" method, in which the reinforcement is impregnated with the resin at the time of moulding. The material is placed and formed in the mould and the squeezing action repels any trapped air and compacts the part.

Typical Applications

Bathtubs, boat hulls and shower units

Attributes

Materials: FR composites

Mechanical properties

Minimum tolerance: (mm) 0.55

Minimum weight: (kg) 0.5

Maximum weight: (kg) 50

Tooling and die costing: (£) 400

Tooling time: (min) 150

Optimal batch size: 1000

Continuous Extrusion (Metal)

(Process diagram)

General Description

Powders can be compacted by extrusion; the powder is encased in a metal container and extruded. After sintering, performed powder metallurgy parts may be reheated and forged in a closed die to their final shape

Typical Applications

Attributes

Materials: Carbon steel, alloy steel, stainless steel, copper & alloys, aluminium & alloys, magnesium & alloys, zinc & alloys, tin & alloys, lead & alloys, nickel & alloys, titanium & alloys

Mechanical properties

Minimum tolerance: (mm) 0.55

Minimum weight: (kg) 0.5

Maximum weight: (kg) 50

Tooling and die costing: (£) 1000

Tooling time: (min) 180

Optimal batch size: 1000

Continuous Extrusion (Plastics)

(Process diagram)

General Description

The raw materials in the form of thermoplastic pellets, granules, or powder are placed in a hopper and fed into the extruder barrel. The barrel is equipped with a screw that blends and conveys the pellets down the barrel. The internal friction from the mechanical action of the screw, along with the heaters around extruder's barrel, heats the pellets and liquefies them. The molten plastic is forced through a die. The extruded product is then cooled.

Typical Applications

Solid rods, channels, window frames and architectural components

Attributes

Materials: Thermoplastics, thermosets

Mechanical properties

Minimum tolerance: (mm) 0.25

Minimum weight: (kg) 0.001

Maximum weight: (kg) 50

Tooling and die costing: (£) 900

Tooling time: (min) 120

Optimal batch size: 1000

Electrical Discharge Machining

(Process diagram)

General Description

Electrical discharge machining is a method of removing metal by a series of rapidly recurring electrical discharges between an electrode and the work piece in the presence of a dielectric fluid. Minute particles of metal or chips, are removed by melting and vaporisation, and are washed from the gap by the dielectric fluid that is continuously washed between the tool and the work piece.

Typical Applications

Attributes

Materials: Carbon steel, alloy steel, stainless steel, copper & alloys, aluminium & alloys, magnesium & alloys, nickel & alloys, titanium & alloys

Mechanical properties

Minimum tolerance: (mm) 0.55

Minimum weight: (kg) 0.5

Maximum weight: (kg) 50

Tooling and die costing: (£) 1500

Tooling time: (min) 50

Optimal batch size: 1000

Electrochemical Machining

(Process diagram)

General Description

Electric energy is combined with a chemical to form a reaction of reverse plating. Direct current is continuously passed between the anodic work piece and cathodic tool through a conductive electrolyte. At the anode surface, electrons are removed by the current flow, and the metallic bonds are broken. Dissolved material is removed from the gap between the work and the tool by the flow of electrolyte, which also aids in carrying away the heat.

Typical Applications

Attributes

Materials: Irons, carbon steel, alloy steel, stainless steel, copper & alloys, nickel & alloys, titanium & alloys, ceramics

Mechanical properties

Minimum tolerance: (mm) 0.55

Minimum weight: (kg) 0.5

Maximum weight: (kg) 50

Tooling and die costing: (£) 3500

Tooling time: (min) 90

Optimal batch size: 1000

Electron Beam Machining

(Process diagram)

General Description

A pulsating stream of high-speed electrons produced by a generator is focused by electrostatic and electromagnetic fields to concentrate energy on a very small area of work. As the electron impinge on the work, their kinetic energy is transformed into thermal energy and evaporates the material locally.

Typical Applications

Rocket fuel injectors or injection nozzles on diesel engines

Attributes

Materials: Irons, carbon steel, alloy steel, stainless steel, copper & alloys, aluminium & alloys, nickel & alloys, titanium & alloys

Mechanical properties

Minimum tolerance: (mm) 0.55

Minimum weight: (kg) 0.5

Maximum weight: (kg) 50

Tooling and die costing: (£) 2000

Tooling time: (min) 60

Optimal batch size: 1000

Gravity Die Casting

(Process diagram)

General Description

The mouton metal is poured under gravity into the permanent mould and allowed to solidify. This is similar to low pressure die-casting where the pressure is maintained until the metal has completely solidified in the mould. The part is then ejected from the mould.

Typical Applications

Attributes

Materials: Irons, carbon steel, copper & alloys, aluminium & alloys, magnesium & alloys, zinc & alloys, tin & alloys, lead & alloys, nickel & alloys

Mechanical properties

Minimum tolerance: (mm) 0.15

Minimum weight: (kg) 0.05

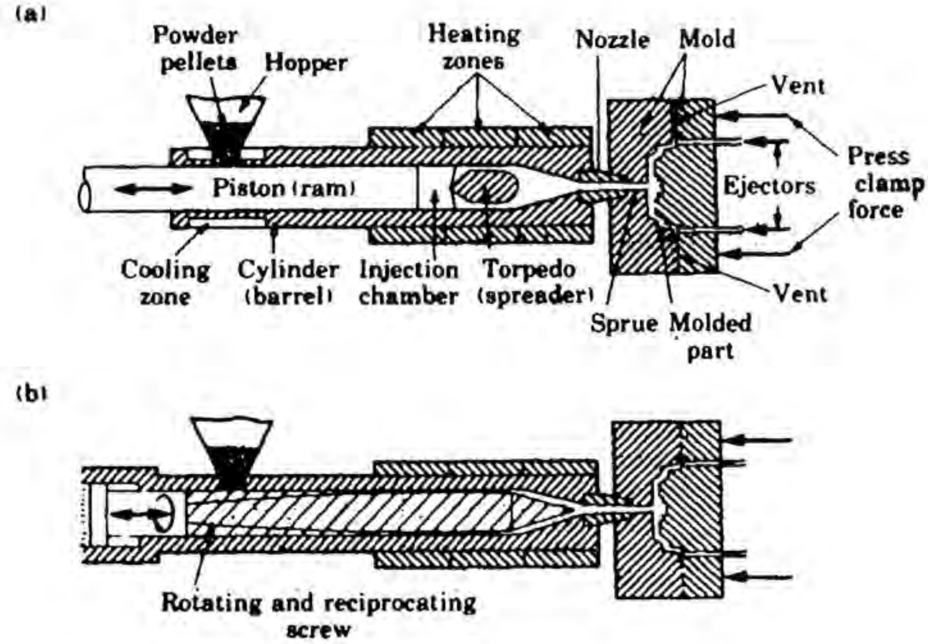
Maximum weight: (kg) 10

Tooling and die costing: (£) 5000

Tooling time: (min) 180

Optimal batch size: 5000

Injection Moulding



General Description

The pellets or granules are fed into a heated cylinder, where they are melted. The melt is then forced into a split-die chamber, either by a hydraulic plunger or by the rotating screw system of an extruder. As the pressure builds up at the mould entrance, the rotating screw begins to move backwards under pressure, thus controlling the volume of material injected. The screw is then pushed forward forcing the molten plastic into the mould cavity.

Typical Applications

Attributes

Materials: Thermoplastics, thermosets

Mechanical properties

Minimum tolerance: (mm) 0.55

Minimum weight: (kg) 0.5

Maximum weight: (kg) 50

Tooling and die costing: (£) 2500

Tooling time: (min) 240

Optimal batch size: 1000

Investment Casting

(Process diagram)

General Description

Investment casting involves the formation of an expendable pattern in a die or mould and the use of the pattern to form a mould in an investment material. When the mould of investment material has set, the pattern is melted, burned, or dissolved out and the past is cast. This method is sometimes known as the lost-wax process because of the loss of the pattern during mould formation.

Typical Applications

Turbine blades, burner nozzles, armament components, lock components, Industrial hand tools bodies

Attributes

Materials: Carbon steel, steel alloys, stainless steel, aluminium & alloys, copper & alloys, magnesium & alloys, nickel & alloys, reactive metals, precious metals

Mechanical properties

Minimum tolerance: (mm) 1.0

Minimum weight: (kg) 0.005

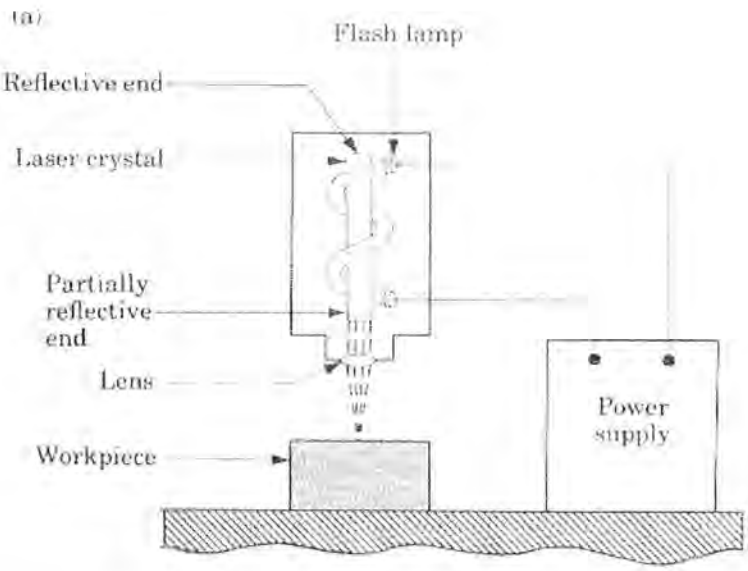
Maximum weight: (kg) 100

Tooling and die costing: (£) 4000

Tooling time: (min) 360

Optimal batch size: 1000

Laser Beam Machining



General Description

The source of energy is a laser, which focuses optical energy on the surface of the work piece. The highly focused, high-density energy melts and evaporates portions of the work piece in a controlled manner.

Typical Applications

Attributes

Materials: Irons, carbon steel, alloy steel, stainless steel, copper & alloys, aluminium & alloys, nickel & alloys, titanium & alloys

Mechanical properties

Minimum tolerance: (mm) 0.55

Minimum weight: (kg) 0.5

Maximum weight: (kg) 50

Tooling and die costing: (£) 800

Tooling time: (min) 30

Optimal batch size: 1000

Manual Machining

(Process diagram)

General Description

The removal of material by chip processes using sequenced or simultaneous machining operations on cut to length bar or coiled bar stock. The material is manually fed into the machine

Typical Applications

Attributes

Materials: Irons, carbon steel, alloy steel, stainless steel, copper & alloys, aluminium & alloys, magnesium & alloys, zinc & alloys, tin & alloys, lead & alloys, nickel & alloys, titanium & alloys

Mechanical properties

Minimum tolerance: (mm) 0.55

Minimum weight: (kg) 0.5

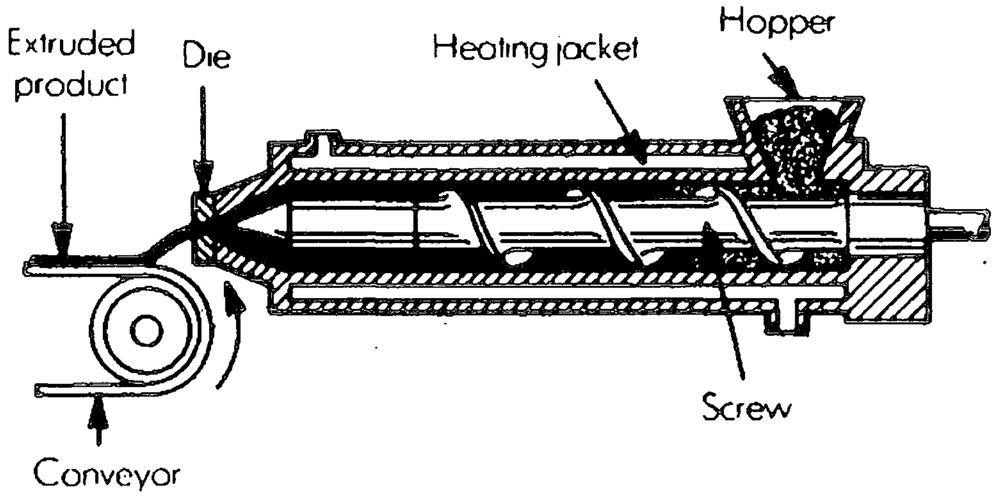
Maximum weight: (kg) 50

Tooling and die costing: (£) 50

Tooling time: (min) 1

Optimal batch size: 200

Plaster Mould Casting



General Description

A permanent pattern is surrounded by plaster slurry that sets to a solid, self-supporting mould rigid enough to be handled. The mould parts are then stripped from the pattern and baked to remove moisture. Undercut areas and internal surfaces are formed by separate pieces and cores.

Typical Applications

Attributes

Materials: Copper & alloys, aluminium & alloys, zinc & alloys, tin & alloys, lead & alloys

Mechanical properties

Minimum tolerance: (mm) 0.25

Minimum weight: (kg) 0.05

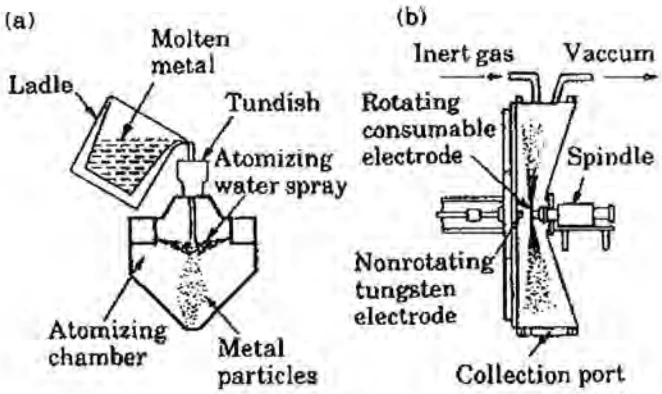
Maximum weight: (kg) 10

Tooling and die costing: (£) 400

Tooling time: (min) 120

Optimal batch size: 50

Powder Metallurgy



General Description

Powder metallurgy is a metalworking process used to consolidate particle matter, both metallic and/or non-metallic. There are three basic steps in conventional powder metallurgy. These steps are mixing together of the metal powders together with lubricants, compacting an exact measured amount into the die cavity and sintering.

Typical Applications

Gears, cams, bushings, cutting tools porous products such as filters

Attributes

Materials: Irons, carbon steel, alloy steel, stainless steel, copper & alloys, aluminium & alloys, nickel & alloys, titanium & alloys, ceramics

Mechanical properties

Minimum tolerance: (mm) 0.55

Minimum weight: (kg) 0.5

Maximum weight: (kg) 50

Tooling and die costing: (£) 1500

Tooling time: (min) 240

Optimal batch size: 1000

Pressure Die Casting

(Process diagram)

General Description

The molten metal is forced upwards by gas pressure into a graphite or metal mould. The pressure is maintained until the metal has completely solidified in the mould. The molten metal may also be forced upwards by a vacuum, which also removes dissolved gases and gives he casting lower porosity.

Typical Applications

Carburettors, motors, business-machines, appliance components, hand tools and toys.

Attributes

Materials: Copper & alloys, aluminium & alloys, magnesium & alloys, zinc & alloys, tin & alloys, lead & alloys

Mechanical properties

Minimum tolerance: (mm) 0.55

Minimum weight: (kg) 0.5

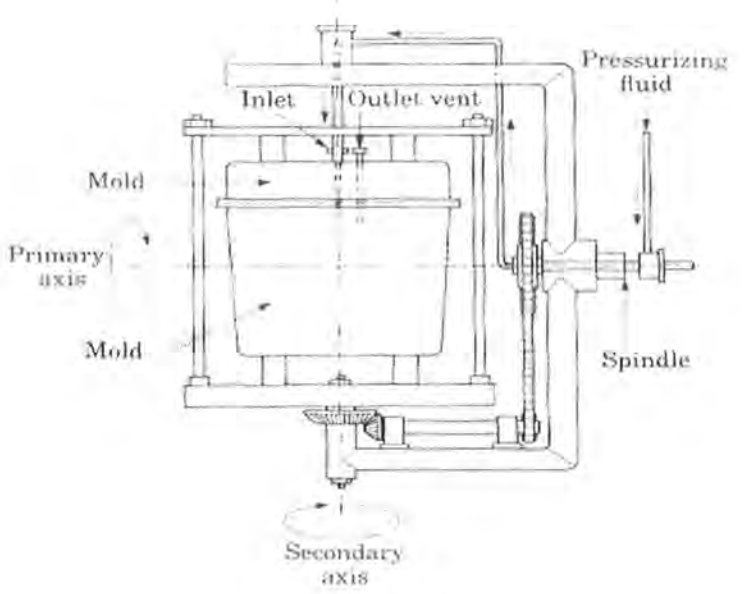
Maximum weight: (kg) 50

Tooling and die costing: (£) 8000

Tooling time: (min) 300

Optimal batch size: 1000

Rotational Moulding



General Description

The thin-walled metal mould is made of two pieces (split female mould) and is designed to be rotated about two perpendicular axes. A pre-measured quantity of powdered plastic material is placed inside the warm mould. The mould is heated, using a large oven, while it is rotated about the two axes. The action tumbles the powder against the mould where heating fuses the powder without melting it.

Typical Applications

Tanks of various sizes, boat hulls, buckets, housings, toys carrying cases and footballs

Attributes

Materials: Thermoplastics, thermosets, FR composites

Mechanical properties

Minimum tolerance: (mm) 0.55

Minimum weight: (kg) 0.5

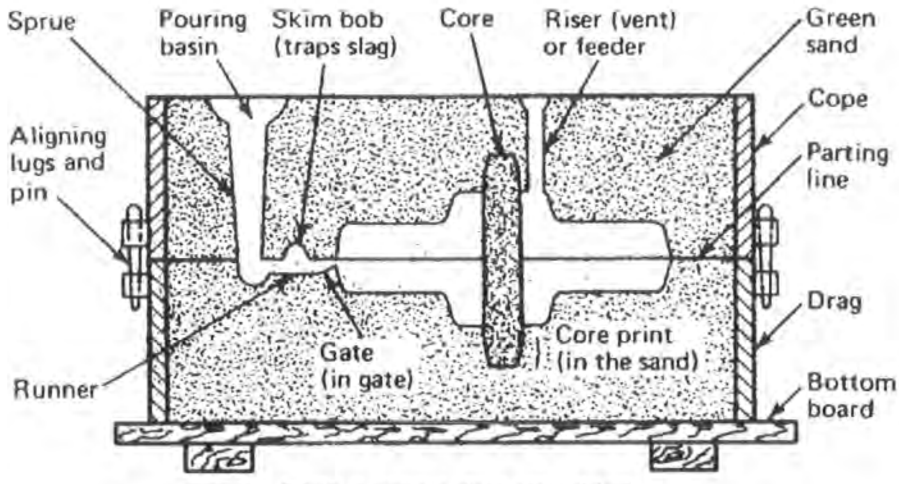
Maximum weight: (kg) 50

Tooling and die costing: (£) 500

Tooling time: (min) 240

Optimal batch size: 1000

Sand Casting



Flask = cope + drag assembled

General Description

Simply stated, sand casting consists of placing a pattern (having the shape of the desired cast) in sand to make an imprint, incorporating a gate system, filling the resulting cavity with mouton metal, allowing the metal to cool until it solidifies, breaking away the sand mould, and removing the casting. It is still the most widely used form of casting.

Typical Applications

Engine blocks, Engine manifolds, machine bases, gears, pulleys

Attributes

Materials: Cast iron, carbon steel, steel alloys, stainless steel, aluminium & alloys, copper & alloys, zinc & alloys, magnesium & alloys and nickel & alloys

Mechanical properties

Minimum tolerance: (mm) 1.2

Minimum weight: (kg) 0.1

Maximum weight: (kg) 100

Tooling and die costing: (£) 200

Tooling time: (min) 300

Optimal batch size: 200

Sheet Metal Forming

(Process diagram)

General Description

Forming is a method of producing shapes by stressing metal beyond its yield strength, but not past its ultimate tensile strength. The forces applied during forming are in opposite directions, just as in shearing. Bending forces, however, is spread further apart, resulting in plastic distortion of metal without failure.

Typical application

File cabinets, car bodies, aircraft fuselages and beverage cans

Attributes

Materials: Carbon steel, stainless steel, copper & alloys, aluminium & alloys, zinc & alloys, nickel & alloys, titanium & alloys

Mechanical properties

Minimum tolerance: (mm) 0.05

Minimum weight: (kg) 0.0001

Maximum weight: (kg) 500

Tooling and die costing: (£) 1500

Tooling time: (min) 360

Optimal batch size: 1000

Sheet Metal Shearing

(Process diagram)

General Description

Sheet metal is cut by subjecting it to shear stresses typically between a punch and a die. The major processing parameters in shearing are the shape and material for the punch and die, the spread of the punching, lubrication, and the clearance between the punch and the die. The clearance is the major factor in determining the shape and quality of the sheared edge.

Typical Applications

Attributes

Materials: Carbon steel, stainless steel, copper & alloys, aluminium & alloys, zinc & alloys, nickel & alloys, titanium & alloys

Mechanical properties

Minimum tolerance: (mm) 0.05

Minimum weight: (kg) 0.0001

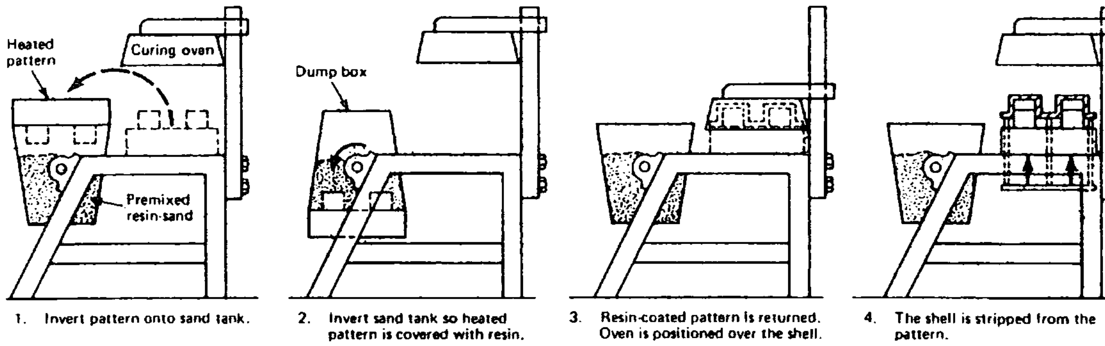
Maximum weight: (kg) 500

Tooling and die costing: (£) 2000

Tooling time: (min) 420

Optimal batch size: 1000

Shell Moulding



General Description

In this process, a mounted pattern made of a ferrous metal is heated, coated with a parting agent, and clamped in a chamber containing fine sand containing thermosetting resin. The chamber is rotated allowing it to coat the pattern. The assembly is then placed in an oven for a short period to complete the curing of the resin. The shell is removed from the pattern using built-in ejector pins.

Typical Applications

Attributes

Materials: Irons, carbon steel, alloy steel, stainless steel, copper & alloys, aluminium & alloys, nickel & alloys

Mechanical properties

Minimum tolerance: (mm) 0.5

Minimum weight: (kg) 0.1

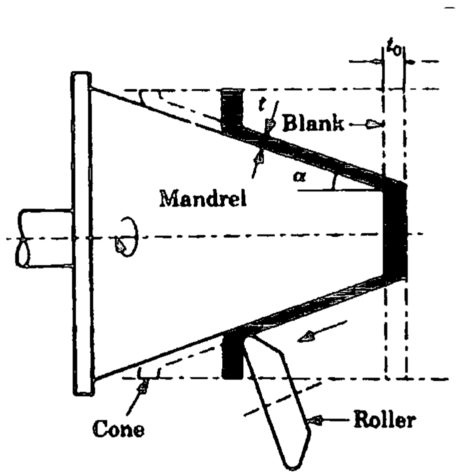
Maximum weight: (kg) 10

Tooling and die costing: (£) 400

Tooling time: (min) 240

Optimal batch size: 600

Spinning



General Description

Spinning is a chipless production method of forming axially symmetrical metal shapes. It is a point deformation process by which a metal disc, cylindrical work piece, or preform is plastically deformed into contact with a rotating chuck by axial or axial-radial motions of the tool or rollers.

Typical Applications

Cones, hemispheres, tubes and cylinders

Attributes

Materials: Carbon steel, alloy steel, stainless steel, copper & alloys, aluminium & alloys, magnesium & alloys, zinc & alloys, tin & alloys, lead & alloys, nickel & alloys

Mechanical properties

Minimum tolerance: (mm) 0.55

Minimum weight: (kg) 0.5

Maximum weight: (kg) 50

Tooling and die costing: (£) 1000

Tooling time: (min) 120

Optimal batch size: 600

Ultrasonic Machining

(Process diagram)

General Description

Ultrasonic machining is a process by which work piece material is removed and an exact shape is imparted on the work piece surface via the cutting action of abrasive slurry that is driven by a tool vibrating at high frequency in line with its longitudinal axis.

Typical Applications

Used to produce blind and through holes, slots and irregular shapes

Attributes

Materials: Carbon steel, alloy steel, stainless steel, nickel & alloys, titanium & alloys, ceramics

Mechanical properties

Minimum tolerance: (mm) 0.55

Minimum weight: (kg) 0.5

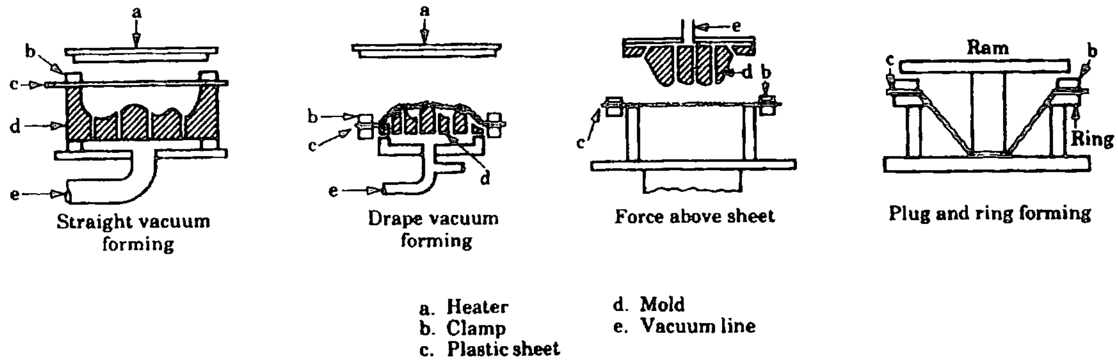
Maximum weight: (kg) 50

Tooling and die costing: (£) 2000

Tooling time: (min) 180

Optimal batch size: 400

Vacuum Forming



General Description

In this process, a thermoplastic sheet is heated in an oven to the sag point. The sheet is then removed from the oven, placed over a mould, and pulled against the mould through the application of a vacuum. Since the mould is usually at room temperature, the shape of the plastic is set upon contacting the mould.

Typical Applications

Attributes

Materials: Thermoplastics

Mechanical properties

Minimum tolerance: (mm) 0.55

Minimum weight: (kg) 0.5

Maximum weight: (kg) 50

Tooling and die costing: (£) 200

Tooling time: (min) 30

Optimal batch size: 500

APPENDIX B

Materials Database

Material	Density (g/cm^3)	Average cost (£/kg)	Bar cost (£/kg)	Sheet cost (£/kg)	Rod cost (£/kg)
Irons	7.9	0.33	0.33	0.33	0.33
Steel (carbon)	7.8	0.49	0.49	0.49	0.49
Steel (Alloy)	7.81	0.7	0.7	0.7	0.7
Stainless steel	7.85	4.07	4.07	4.07	4.07
Copper & alloys	8.96	3.3199	3.3199	3.3199	3.3199
Aluminium & alloys	2.7	2.96	2.96	2.96	2.96
Magnesium & alloys	1.81	2.96	2.96	2.96	2.96
Zinc & alloys	7.1	1.07	1.07	1.07	1.07
Tin & alloys	7.3	6.51	6.51	6.51	6.51
Lead & alloys	11.3	6.51	6.51	6.51	6.51
Nickel & alloys	8.45	10.41	10.41	10.41	10.41
Titanium & alloys	4.96	15.07	15.07	15.07	15.07
Thermoplastics	0.957	2.01	2.01	2.01	2.01
Thermosets	0.945	3.03	3.03	3.03	3.03
FR composites	2.5	2.77	2.77	2.77	2.77
Ceramics	2.76	2.279	2.279	2.279	2.279

APPENDIX C

FLYMO MICROLITE 28: PRODUCT MODEL

Name	PARENTS	PROPLIST	VALUES
order917556713|	order917556713|	customer,product|	Flymo,Cordless_Srimmer, |
Cordless_Srimmer|	products, order917556713|	amount, base_part, breadth, hand_diff, length, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb, width|	1, Unknown , Unknown , Unknown , Unknown , Unknown , Unknown ,order917556713, Cordless_Srimmer, products, Unknown , Unknown , Unknown , Unknown , Unknown ,|
Strimmer|	assemblies, Cordless_Srimmer|	amount, base_part, breadth, hand_diff, length, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb, width|	1, Unknown , Unknown , Unknown , Unknown , Unknown , Unknown, Cordless_Srimmer, Strimmer, assemblies, 360, 360, 0.012077, 109.459039, Unknown ,|
plain_bolt917560101|	standard_parts, components, Strimmer|	afrtype, amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, rs_stock_no, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	threaded, 11, 0, mild steel, 0, Unknown , Unknown, Strimmer, 525-802, plain_bolt917560101, components, 360, 0, 2.92000e-07, 0.002283,|

cylinder917560101|	cylinder, plain_bolt917560101|	diameter, length, parent, selfname, typeclass, volume, weight_mb|	6.0, 20.0, plain_bolt917560101, cylinder917560101, features, 4.93000e-07, Unknown ,|
etd917560101|	etd, plain_bolt917560101|	component, desc, number, parent, rank, selfname, setup, typeclass, prefix, it, roughness|	Unknown , Unknown , 1, plain_bolt917560101, Unknown , etd917560101, Unknown , features, etd, Unknown , Unknown ,|
length_etd917560101|	length, etd917560101|	name, upper, lower, nominal, typeclass|	Unknown , Unknown , Unknown , 16.0, geometry,|
diameter_etd91756010 1|	diameter, etd917560101|	name, upper, lower, nominal, typeclass|	Unknown , Unknown , Unknown , 4.0, geometry,|
pitch_etd917560101|	pitch, etd917560101|	name, upper, lower, nominal, typeclass|	Unknown , Unknown , Unknown , 1.0, geometry,|
Battery_Cover|	components, Strimmer|	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	1, 0, mild steel, 0, Unknown , Unknown , Strimmer, Battery_Cover, components, 360, 360, 0.00018, 0.005616,|
moulded917560022|	moulded, Battery_Cover|	breadth, length, parent, selfname, typeclass, volume, weight_mb, width|	20.0, 100.0, Battery_Cover, moulded917560022, features, Unknown , Unknown , 90.0,|

Handle_Top|	components, Strimmer|	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	1, 0, mild steel, 0, Unknown , Unknown , Strimmer, Handle_Top, components, 360, 360, 0.00195, 0.06084,|
moulded917559986|	moulded, Handle_Top|	breadth, length, parent, selfname, typeclass, volume, weight_mb, width|	50.0, 260.0, Handle_Top, moulded917559986, features, Unknown , Unknown , 150.0,|
Base_Top|	components, Strimmer|	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	1, 0, mild steel, 0, Unknown , Unknown , Strimmer, Base_Top, components, 360, 360, 0.00162, 0.050544,|
moulded917559950|	moulded, Base_Top|	breadth, length, parent, selfname, typeclass, volume, weight_mb, width|	50.0, 180.0, Base_Top, moulded917559950, features, Unknown , Unknown , 180.0,|
Top_Assembly|	assemblies, Strimmer|	amount, base_part, breadth, hand_diff, length, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb, width|	1, Unknown , Unknown , Unknown , Unknown , Unknown , Unknown , Strimmer, Top_Assembly, assemblies, 360, 360, 0.002645, 60.045410, Unknown ,|

Power_Ass|	assemblies, Top_Assembly|	amount,base_part, breadth, hand_diff, length, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb, width|	1,Unknown ,Unknown ,0 ,Unknown ,0 ,Unknown ,Unknown ,Top_Assembly,Power_Ass,assemblies,360,360,0.000667,59.965391,Unknown ,|
Light_Wire_Ass|	assemblies, Power_Ass|	amount,base_part, breadth, hand_diff, length, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb, width|	1,Unknown ,Unknown ,0 ,Unknown ,0 ,Unknown ,Unknown ,Power_Ass,Light_Wire_Ass,assemblies,360,360,1.18855e-06,0.009271,Unknown ,|
Black_Wire|	components, Light_Wire_Ass|	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	1,0,mild steel,0,Unknown ,Unknown ,Light_Wire_Ass,Black_Wire,components,180,0,9.42750e-08,0.000735,|
wir917559696|	wir, Black_Wire|	diameter, length, parent, selfname, typeclass, volume, weight_mb|	2.0,30.0,Black_Wire,wir917559696,features,Unknown ,Unknown ,|
Red_Wire|	components, Light_Wire_Ass|	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	1,0,mild steel,0,Unknown ,Unknown ,Light_Wire_Ass,Red_Wire,components,180,0,9.42750e-08,0.000735,|
wir917559672|	wir, Red_Wire|	diameter, length, parent, selfname, typeclass, volume, weight_mb|	2.0,30.0,Red_Wire,wir917559672,features,Unknown ,Unknown ,|
Board_Light|	components, Light_Wire_Ass|	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	1,care,mild steel,0,Unknown ,Unknown ,Light_Wire_Ass,Board_Light,components,360,360, 1.00000e-06,0.00780,|
sheet917559614|	sheet, Board_Light|	breadth, length, parent, selfname, typeclass, volume, weight_mb, width|	5.0,20.0,Board_Light,sheet917559614,features,Unknown ,Unknown ,10.0,|
Battery|	components, Power_Ass|	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	1,care,mild steel,0,Unknown ,Unknown ,Power_Ass,Battery,components,360,360,0.00063,1.90000,|
prism917559506|	prism, Battery|	breadth, length, parent, selfname, typeclass, volume, weight_mb, width|	90.0,100.0,Battery,prism917559506,features,Unknown ,Unknown ,70.0,|

Resistor|	components, Power_Ass|	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	1,0,mild steel,0,Unknown ,Unknown ,Power_Ass,Resistor,components,360,360,5.40000e-06,0.04212,|
prism917559418|	prism, Resistor|	breadth, length, parent, selfname, typeclass, volume, weight_mb, width|	6.0,45.0,Resistor,prism917559418,features,Unknown ,Unknown ,20.0,|
micro_switch917559277|	assemblies, Power_Ass|	amount, base_part, breadth, hand_diff, length, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb, width|	1,Unknown ,Unknown ,Unknown ,Unknown ,Unknown ,Unknown ,Unknown ,micro_switch917559277, assemblies,360,360,3.00800e-05,55.00000,Unknown ,|
connecting_tag|	weight_flag, components, micro_switch917559277|	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	2,0,mild steel,0,Unknown ,Unknown ,micro_switch917559277, connecting_tag,components,360,180,4.00000e-08,0.002000,|
sheet917559277|	sheet, connecting_tag|	breadth, length, parent, selfname, typeclass, volume, weight_mb, width|	5.0,8.0,connecting_tag,sheet917559277,features,Unknown ,Unknown ,1.0,|
body|	weight_flag, components, micro_switch917559277|	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	1,care,mild steel,0,Unknown ,Unknown ,micro_switch917559277, body,components,360,360,3.00000e-05,0.015000,|
prism|	prism, body|	breadth, length, parent, selfname, typeclass, volume, weight_mb, width|	10.0,28.0,body,prism,features,Unknown ,Unknown ,15.0,|
Switch_Spring|	components, Top_Assembly|	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	1,0,mild steel,1,Unknown ,Unknown ,Top_Assembly,Switch_Spring,components,180,0,2.356875e-06,0.018384,|
cylinder917559200|	cylinder, Switch_Spring|	diameter, length, parent, selfname, typeclass, volume, weight_mb|	10.0,30.0,Switch_Spring,cylinder917559200,features,Unknown ,Unknown ,|
Safety_Button|	components, Top_Assembly|	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	1,0,mild steel,0,Unknown ,Unknown ,Top_Assembly,Safety_Button,components,360,360,1.12500e-05,0.000351,|

moulded917559137|	moulded, Safety_Button|	breadth, length, parent, selfname, typeclass, volume, weight_mb, width|	15.0,30.0,Safety_Button, moulded917559137,features,Unknown ,Unknown ,25.0,|
Switch|	components, Top_Assembly|	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	1,0,mild steel,0,Unknown ,Unknown ,Top_Assembly,Switch,components,360,360,1.42500e-05,0.000445,|
moulded917559038|	moulded, Switch|	breadth, length, parent, selfname, typeclass, volume, weight_mb, width|	15.0,95.0,Switch,moulded917559038,features,Unknown ,Unknown ,10.0,|
Handle_Bottom|	components, Top_Assembly|	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	1,0,mild steel,0,Unknown ,Unknown ,Top_Assembly,Handle_Bottom,components,360,360,0.00195,0.06084,|
bho917560745|	bho, Handle_Bottom|	component,desc,number,parent,rank,selfname,setup,typeclass,prefix,it,roughness|	Handle_Bottom,Unknown ,1,Handle_Bottom,Unknown ,bho917560745,1,features,bho,10,10.0,|
length_bho917560745|	length, bho917560745|	name, upper, lower, nominal, typeclass|	Unknown ,Unknown ,Unknown ,20.0,geometry,|
diameter_bho917560745|	diameter, bho917560745|	name, upper, lower, nominal, typeclass|	Unknown ,Unknown ,Unknown ,15.0,geometry,|
itd917560657|	itd, Handle_Bottom|	component,desc,number,parent,rank,selfname,setup,typeclass,prefix,it,roughness|	Handle_Bottom,Unknown ,1,Handle_Bottom,Unknown ,itd917560657,1,features,itd,10,10.0,|
pitch_itd917560657|	pitch, itd917560657|	name, upper, lower, nominal, typeclass|	Unknown ,Unknown ,Unknown ,1.0,geometry,|
diameter_itd917560657|	diameter, itd917560657|	name, upper, lower, nominal, typeclass|	Unknown ,Unknown ,Unknown ,4.0,geometry,|
length_itd917560657|	length, itd917560657|	name, upper, lower, nominal, typeclass|	Unknown ,Unknown ,Unknown ,10.0,geometry,|
moulded917558640|	moulded, Handle_Bottom|	breadth, length, parent, selfname, typeclass, volume, weight_mb, width|	50.0,260.0,Handle_Bottom,moulded917558640,features,Unknown ,Unknown ,150.0,|
Middle_Ass|	assemblies, Strimmer|	amount,base_part, breadth, hand_diff, length, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb, width|	1,Unknown ,Unknown ,0 ,Unknown ,0 ,Unknown ,Unknown ,Strimmer,Middle_Ass,assemblies,360,360,0.000708,0.195190,Unknown ,|

Sheath_Bottom|	components, Middle_Ass|	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	1,0,mild steel,0,Unknown ,Unknown ,Middle_Ass,Sheath_Bottom,components,360,360, 0.000343,0.010702,|
itd917560502|	itd, Sheath_Bottom|	component,desc,number,parent,rank,selfname, setup,typeclass,prefix,it, roughness|	Sheath_Bottom,Unknown ,1,Sheath_Bottom,Unknown ,itd917560502,1,features,itd,10,10.0,|
pitch_itd917560502|	pitch, itd917560502|	name, upper, lower, nominal, typeclass|	Unknown ,Unknown ,Unknown ,1.0,geometry,|
diameter_itd917560502 |	diameter, itd917560502|	name, upper, lower, nominal, typeclass|	Unknown ,Unknown ,Unknown ,4.0,geometry,|
length_itd917560502|	length, itd917560502|	name, upper, lower, nominal, typeclass|	Unknown ,Unknown ,Unknown ,10.0,geometry,|
moulded917557948|	moulded, Sheath_Bottom|	breadth, length, parent, selfname, typeclass, volume, weight_mb, width|	35.0,140.0,Sheath_Bottom,moulded917557948,features,Unknown ,Unknown ,70.0,|
Sheath_Top|	components, Middle_Ass|	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	1,0,mild steel,0,Unknown ,Unknown ,Middle_Ass,Sheath_Top, components,360,360,0.000343,0.010702,|
moulded917557869|	moulded, Sheath_Top|	breadth, length, parent, selfname, typeclass, volume, weight_mb, width|	35.0,140.0,Sheath_Top,moulded917557869,features,Unknown ,Unknown ,70.0,|
Tube_Wire_Ass|	assemblies, Middle_Ass|	amount,base_part, breadth, hand_diff, length, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb, width|	1,Unknown ,Unknown ,0 ,Unknown ,0 ,Unknown ,Unknown ,Middle_Ass,Tube_Wire_Ass,assemblies,360,360, 2.231133e-05,0.173787,Unknown ,|
Wire_Ass|	assemblies, Tube_Wire_Ass|	amount,base_part, breadth, hand_diff, length, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb, width|	1,Unknown ,Unknown ,0 ,Unknown ,0 , Unknown ,Unknown ,Tube_Wire_Ass,Wire_Ass,assemblies,360,360,3.13825e-07,0.002206,Unknown ,|
flymo_capacitor917558547|	standard_parts, components, Wire_Ass|	afrtype,amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, rs_stock_no, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	wiring,1,0,mild steel,0,Unknown ,Unknown ,Wire_Ass,Unknown ,flymo_capacitor917558547,components,360,360,3.10000e-08,2.50000e-07,|
prism917558547|	prism, flymo_capacitor917558547|	breadth, length, parent, selfname, typeclass, volume, weight_mb, width|	17.0,38.0,flymo_capacitor917558547,prism917558547,features,2.70000e-06,Unknown ,0.02,|

Long_Red_Black_Wire|	components, Wire_Ass|	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	1,0,mild steel,0,Unknown ,Unknown ,Wire_Ass,Long_Red_Black_Wire,components,360,0,2.82825e-07,0.002206,|
wir917558250|	wir, Long_Red_Black_Wire|	diameter, length, parent, selfname, typeclass, volume, weight_mb|	2.0,90.0,Long_Red_Black_Wire,wir917558250,features,Unknown ,Unknown ,|
Middle_Tube|	components, Tube_Wire_Ass|	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	1,0,mild steel,0,Unknown ,Unknown ,Tube_Wire_Ass,Middle_Tube,components,180,0,2.19975e-05,0.171581,|
pho917560575|	pho, Middle_Tube|	component,desc,number,parent,rank,selfname, setup,typeclass,prefix,it, roughness|	Middle_Tube,Unknown ,1,Middle_Tube,Unknown ,pho917560575,1,features,pho,10,10.0,|
length_pho917560575|	length, pho917560575|	name, upper, lower, nominal, typeclass|	Unknown ,Unknown ,Unknown ,70.0,geometry,|
diameter_pho917560575|	diameter, pho917560575|	name, upper, lower, nominal, typeclass|	Unknown ,Unknown ,Unknown ,18.0,geometry,|
cylinder917558093|	cylinder, Middle_Tube|	diameter, length, parent, selfname, typeclass, volume, weight_mb|	20.0,70.0,Middle_Tube,cylinder917558093,features, Unknown ,Unknown ,|
Bottom_Ass|	assemblies, Strimmer|	amount, base_part, breadth, hand_diff, length, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb, width|	1,Unknown ,Unknown ,Unknown ,Unknown ,Unknown ,Unknown ,Strimmer,Bottom_Ass,assemblies,360,360,0.004971,49.076325,Unknown ,|
Motor_Ass|	assemblies, Bottom_Ass|	amount, base_part, breadth, hand_diff, length, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb, width|	1,Unknown ,Unknown ,Unknown ,Unknown ,Unknown ,Unknown ,Bottom_Ass,Motor_Ass,assemblies,360,360,0.003309,49.024471,Unknown ,|
Motor_Rotor_Ass|	assemblies, Motor_Ass|	amount, base_part, breadth, hand_diff, length, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb, width|	1,Unknown ,Unknown ,Unknown ,Unknown ,Unknown ,Unknown ,Motor_Ass,Motor_Rotor_Ass,assemblies,360,360,0.002684,47.006126,Unknown ,|

Rotor_Ass|	assemblies, Motor_Rotor_Ass|	amount,base_part, breadth, hand_diff, length, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb, width|	1,Unknown ,Unknown ,0 ,Unknown ,0 ,Unknown ,Unknown ,Motor_Rotor_Ass,Rotor_Ass,assemblies,360,360, 0.000200,1.556126,Unknown ,|
Spring|	components, Rotor_Ass|	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	1,0,mild steel,1,Unknown ,Unknown ,Rotor_Ass,Spring,components,180,0,1.964063e-07,0.001532,|
cylinder917557642|	cylinder, Spring|	diameter, length, parent, selfname, typeclass, volume, weight_mb|	5.0,10.0,Spring,cylinder917557642,features,Unknown ,Unknown ,|
Locking_Button|	components, Rotor_Ass|	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	1,0,mild steel,0,Unknown ,Unknown ,Rotor_Ass,Locking_Button,components,360,360,8.40000e-06,0.06552,|
prism917557577|	prism, Locking_Button|	breadth, length, parent, selfname, typeclass, volume, weight_mb, width|	6.0,70.0,Locking_Button,prism917557577,features, Unknown ,Unknown ,20.0,|
Rotor|	components, Rotor_Ass|	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	1,0,mild steel,0,Unknown ,Unknown ,Rotor_Ass,Rotor,components,360,0,0.000191,0.289074,|
bho917560261|	bho, Rotor|	component,desc,number,parent,rank,selfname, setup,typeclass,prefix,it, roughness|	Rotor,Unknown ,1,Rotor,Unknown ,bho917560261,1,features,bho,10,10.0,|
length_bho917560261|	length, bho917560261|	name, upper, lower, nominal, typeclass|	Unknown ,Unknown ,Unknown ,20.0,geometry,|
diameter_bho917560261|	diameter, bho917560261|	name, upper, lower, nominal, typeclass|	Unknown ,Unknown ,Unknown ,5.0,geometry,|
cylinder917557501|	cylinder, Rotor|	diameter, length, parent, selfname, typeclass, volume, weight_mb|	90.0,30.0,Rotor,cylinder917557501,features,Unknown ,Unknown ,|
flymo_motor917557433 |	standard_parts, assemblies, Motor_Rotor_Ass|	afrtype,amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, rs_stock_no, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	Unknown ,1,Unknown ,Unknown ,Unknown ,Unknown ,Unknown ,Motor_Rotor_Ass,Unknown ,flymo_motor917557433,assemblies,360,180,0.002484,0.450000,|

body917557433|	weight_flag, components, flymo_motor917557433 |	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	1,care,mild steel,0,Unknown ,Unknown ,flymo_motor917557433,body917557433,components,360,180,0.002484,0.40000,|
prism917557433|	prism, body917557433|	breadth, length, parent, selfname, typeclass, volume, weight_mb, width|	45.0,920.0,body917557433,prism917557433,features,Unknown ,Unknown ,60.0,|
connecting_tag917557433|	weight_flag, components, flymo_motor917557433 |	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	2,0,mild steel,0,Unknown ,Unknown ,flymo_motor917557433,connecting_tag917557433, components,360,180,4.00000e-08,0.020000,|
sheet917557433|	sheet, connecting_tag917557433|	breadth, length, parent, selfname, typeclass, volume, weight_mb, width|	5.0,8.0,connecting_tag917557433,sheet917557433 ,features,Unknown ,Unknown ,1.0,|
axle917557433|	weight_flag, components, flymo_motor917557433 |	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	1,0,mild steel,0,Unknown ,Unknown ,flymo_motor917557433,axle917557433,components,360,0,3.928125e-07,0.05000,|
cylinder917557433|	cylinder, axle917557433|	diameter, length, parent, selfname, typeclass, volume, weight_mb|	5.0,20.0,axle917557433,cylinder917557433,features,Unknown ,Unknown ,|
Rotor_Cover|	components, Motor_Ass|	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	1,0,mild steel,0,Unknown ,Unknown ,Motor_Ass,Rotor_Cover, components,360,180,0.000191,0.289074,|
cylinder917557279|	cylinder, Rotor_Cover|	diameter, length, parent, selfname, typeclass, volume, weight_mb|	90.0,30.0,Rotor_Cover,cylinder917557279,features, Unknown ,Unknown ,|
Reel_Holder|	components, Motor_Ass|	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	1,0,mild steel,0,Unknown ,Unknown ,Motor_Ass,Reel_Holder,components,360,0,6.638531e-05,0.217805,|
cylinder917557167|	cylinder, Reel_Holder|	diameter, length, parent, selfname, typeclass, volume, weight_mb|	65.0,20.0,Reel_Holder,cylinder917557167,features, Unknown ,Unknown ,|
Motor_Case_Bottom|	components, Motor_Ass|	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	1,0,mild steel,0,Unknown ,Unknown ,Motor_Ass,Motor_Case_Bottom,components,360, 360,0.000184,0.005733,|

moulded917557121|	moulded, Motor_Case_Bottom|	breadth, length, parent, selfname, typeclass, volume, weight_mb, width|	35.0,70.0,Motor_Case_Bottom,moulded917557121,features,Unknown ,Unknown ,75.0,|
Motor_Case_Top|	components, Motor_Ass|	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	1,0,mild steel,0,Unknown ,Unknown ,Motor_Ass,Motor_Case_Top,components,360,360,0.000184,0.005733,|
moulded917557039|	moulded, Motor_Case_Top|	breadth, length, parent, selfname, typeclass, volume, weight_mb, width|	35.0,70.0,Motor_Case_Top,moulded917557039,features,Unknown ,Unknown ,75.0,|
Button|	components, Bottom_Ass|	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	1,0,mild steel,0,Unknown ,Unknown ,Bottom_Ass,Button,components,360,360,4.20000e-05,0.001310,|
moulded917556911|	moulded, Button|	breadth, length, parent, selfname, typeclass, volume, weight_mb, width|	15.0,70.0,Button,moulded917556911,features,Unknown ,Unknown ,40.0,|
Base_Bottom|	components, Bottom_Ass|	amount, hand_diff, material, nest_tangle, no_comps, numafcs, parent, selfname, typeclass, value_alpha, value_beta, volume, weight_mb|	1,0,mild steel,0,Unknown ,Unknown ,Bottom_Ass,Base_Bottom,components,360,360,0.00162,0.050544,|
itd917560404|	itd, Base_Bottom|	component,desc,number,parent,rank,selfname,setup,typeclass,prefix,it,roughness|	Base_Bottom,Unknown ,1,Base_Bottom,Unknown ,itd917560404,1,features,itd,10,10.0,|
pitch_itd917560404|	pitch, itd917560404|	name, upper, lower, nominal, typeclass|	Unknown ,Unknown ,Unknown ,1.0,geometry,|
diameter_itd917560404 |	diameter, itd917560404|	name, upper, lower, nominal, typeclass|	Unknown ,Unknown ,Unknown ,4.0,geometry,|
length_itd917560404|	length, itd917560404|	name, upper, lower, nominal, typeclass|	Unknown ,Unknown ,Unknown ,10.0,geometry,|
moulded917556773|	moulded, Base_Bottom|	breadth, length, parent, selfname, typeclass, volume, weight_mb, width|	50.0,180.0,Base_Bottom,moulded917556773,features,Unknown ,Unknown ,180.0,|

APPENDIX D

FEATURE CLASSIFICATION LISTING

Features/ Processes	Automatic Machining	Blow Moulding	Centrifugal Casting	Ceramic Mould Casting	Chemical Machining	Closed Die Forging	Cold Forming	Cold Heading	Compression Moulding	Contact Moulding	Continuous Extrusion (Plastics)
bho	1	1	1	1	1	0	0	0	0	1	0
cst	1	1	1	1	1	1	1	1	1	1	0
ecy	1	1	1	1	1	1	1	1	1	1	1
efa	1	1	1	1	1	1	1	1	1	1	1
egv	1	1	1	1	1	1	1	1	1	1	1
epf	1	1	1	1	1	1	1	1	1	1	1
erg	1	1	1	1	1	1	1	1	1	1	0
esp	1	1	1	1	1	1	1	1	1	1	0
etd	1	1	1	1	1	1	1	1	1	0	1
etp	1	1	1	1	1	1	1	1	1	1	0
htd	1	0	0	1	1	1	1	1	1	0	1
icy	1	0	1	1	1	1	1	1	1	1	1
igv	1	0	1	1	1	0	0	0	1	0	0
ipf	1	0	0	1	1	0	0	0	1	0	0
isp	1	0	1	1	1	1	1	0	1	0	0
itd	1	0	0	1	1	0	0	0	0	0	0
itp	1	0	0	1	1	1	1	0	1	0	1
pcb	1	0	1	1	1	1	1	1	1	1	1
pcf	1	1	1	1	1	1	1	1	1	1	1
pcs	1	0	1	1	1	1	1	1	1	1	1
pfa	1	1	1	1	1	1	1	1	1	1	1
pgv	1	0	0	1	1	0	0	1	0	1	1
pho	1	1	1	1	1	1	1	1	1	1	1
ppk	1	1	1	1	1	1	1	1	1	1	1
psd	1	1	1	1	1	1	1	1	1	1	1
pst	1	1	1	1	1	1	1	1	1	1	1
ptd	1	1	0	1	1	0	0	1	1	0	0
sf2	1	1	1	1	1	1	1	1	1	1	0
sf3	1	1	1	1	1	1	1	1	1	1	0
pky	1	1	1	1	1	1	1	1	1	1	0
vst	1	1	1	1	1	1	1	1	1	1	1

Features/ Processes	Continuous Extrusion (Metals)	Electrical Discharge Machining	Electrochemical Machining	Electron Beam Machining	Gravity Die Casting	Injection Moulding	Investment Casting	Laser Beam Machining	Manual Machining	Plaster Mould Casting	Pressure Die Casting
bho	0	1	1	1	1	1	1	1	1	0	1
cst	0	1	1	1	1	1	1	1	1	1	1
ecy	1	1	1	1	1	1	1	1	1	1	1
efa	1	1	1	1	1	1	1	1	1	1	1
egv	1	1	1	1	1	1	1	1	1	1	1
epf	1	1	1	1	1	1	1	1	1	0	1
erg	0	1	1	1	1	1	1	1	1	1	1
esp	1	1	1	1	1	1	1	1	1	1	1
etd	1	1	1	1	1	1	1	1	1	1	1
etp	0	1	1	1	1	1	1	1	1	0	1
htd	1	1	1	1	0	1	1	1	1	0	1
icy	1	1	1	1	1	1	1	1	1	1	1
igv	0	1	1	1	1	1	1	1	1	1	1
ipf	1	1	1	1	1	1	1	1	1	0	1
isp	1	1	1	1	1	1	1	1	1	1	1
itd	0	1	1	1	0	1	1	1	1	0	1
itp	1	1	1	1	1	1	1	1	1	0	1
pcb	1	1	1	1	1	1	1	1	1	0	1
pcf	1	1	1	1	1	1	1	1	1	1	1
pcs	1	1	1	1	1	1	1	1	1	0	1
pfa	1	1	1	1	1	1	1	1	1	1	1
pgv	1	1	1	1	0	1	1	1	1	0	1
pho	1	1	1	1	1	1	1	1	1	0	1
ppk	1	1	1	1	1	1	1	1	1	0	1
psd	1	1	1	1	1	1	1	1	1	1	1
pst	1	1	1	1	1	1	1	1	1	1	1
ptd	0	1	1	1	0	1	1	1	1	0	1
sf2	1	1	1	1	1	1	1	1	1	0	1
sf3	0	1	1	1	1	1	1	1	1	0	1
pky	0	1	1	1	1	1	1	1	1	0	1
vst	1	1	1	1	1	1	1	1	1	0	1

Features/ Processes	Rotational Moulding	Sand Casting	Sheet Metal Forming	Sheet Metal Shearing	Shell Casting	Spinning	Ultrasonic Machining	Vacuum Forming
bho	1	1	1	0	1	0	1	1
cst	1	1	1	0	1	0	1	1
ecy	1	1	1	1	1	1	1	1
efa	1	1	1	1	1	1	1	1
egv	1	1	1	1	1	0	1	0
epf	1	1	1	0	1	1	1	0
erg	1	1	1	1	1	0	1	1
esp	1	1	0	1	1	1	1	1
etd	1	1	1	0	1	0	1	1
etp	1	1	1	1	1	1	1	1
htd	0	1	0	0	1	0	1	0
icy	1	1	1	0	1	1	1	1
igv	0	1	1	0	1	0	1	1
ipf	0	1	0	0	1	1	1	1
isp	0	1	0	0	1	1	1	1
itd	0	1	0	0	1	0	1	0
itp	0	1	1	1	1	0	1	1
pcb	1	1	1	1	1	1	1	1
pcf	1	1	1	1	1	1	1	1
pcs	1	1	1	1	1	1	1	1
pfa	1	1	1	1	1	0	1	1
pgv	0	1	1	0	1	0	1	0
pho	1	1	1	1	1	0	1	0
ppk	0	1	1	1	1	0	1	0
psd	1	1	1	1	1	0	1	1
pst	1	1	1	1	1	0	1	1
ptd	0	1	0	0	1	0	1	0
sf2	1	1	1	0	1	0	1	1
sf3	1	1	0	0	1	0	1	1
pky	0	1	1	0	1	0	1	0
vst	1	1	1	1	1	0	1	1

APPENDIX E

FLYMO RESOURCES MODEL

Interactive SQL - Ford (dba) on DBServer

File Edit Command Window Help

Data

NAME
S1000_954068234780
S800_954068234780
S800_954068234780
S800_954068250870
S800_954068250870
S500_954068262900
S500_954068262900
S550_954068281900
S270_954069342020
S500_954068317940
S500_954068317940
S650_954068325900
S650_954068325900
S750_954068663200
S750_954068663200
KM800_954068678190
KM800_954068678190
S550_954068678190
S550_954068698240
S550_954068698240
S550_954068711260
S550_954068711260
S440_954068726250
S820_954068726250
S190_954069051520
S190_954069051520
S190_954069051520
S190_954069078540
S190_954069078540
S200_954069094530
S200_954069094530
S110_954069124570
S110_954069124570
S110_954069124570
S270_954069342020
S270_954069342020
S270_954069342020
S270_954069342020
S380_954069436110
B250_954069436110

Interactive SQL - Ford (dba) on DBServer

File Edit Command Window Help

Data

PARENTS
SITE,Flymo
BUILDING,NewtonAycliffe
BUILDING,NewtonAycliffe
FLOOR,Moulding
CELL,Shop_954067157190
CELL,Shop_954067157190
CELL,Shop_954067157190
CELL,Shop_954067157190
CELL,Shop_954067157190
CELL,Shop_954067157190
Northendsection1,mould3_954067879190
Northendsection2,mould3_954067879190
Northendsection3,mould3_954067879190
Northendsection4,mould3_954067879190
Northendsection5,mould3_954067879190
Northendsection6,mould3_954067879190
Northendsection7,mould3_954067879190
Northendsection1,mould4_954067938240
Northendsection2,mould4_954067938240
Northendsection3,mould4_954067938240
Northendsection4,mould4_954067938240
Northendsection5,mould4_954067938240
Northendsection6,mould4_954067938240
Midendsection1,mould5_954068004310
Midendsection2,mould5_954068004310
Midendsection3,mould5_954068004310
Midendsection4,mould5_954068004310
Midendsection1,mould6_954068064340
Midendsection2,mould6_954068064340
Midendsection2,mould6_954068064340
Midendsection2,mould6_954068064340
Midendsection4,mould6_954068064340
Midendsection3,mould6_954068064340
RESOURCE,Northendsection1_954068234780
RESOURCE,Northendsection1_954068234780
RESOURCE,Northendsection1_954068234780
RESOURCE,Northendsection1_954068234780
RESOURCE,Northendsection2_954068250870
RESOURCE,Northendsection2_954068250870
RESOURCE,Northendsection3_954068262900

Interactive SQL - Ford (dba) on DBServer

File Edit Command Window Help

Data

```
PARENTS
RESOURCE.Northendsection1_954068234780
RESOURCE.Northendsection1_954068234780
RESOURCE.Northendsection1_954068234780
RESOURCE.Northendsection2_954068250870
RESOURCE.Northendsection2_954068250870
RESOURCE.Northendsection3_954068262900
RESOURCE.Northendsection3_954068262900
RESOURCE.Northendsection4_954068281900
RESOURCE.Midendsection1_954069342020
RESOURCE.Northendsection6_954068317940
RESOURCE.Northendsection6_954068317940
RESOURCE.Northendsection7_954068325900
RESOURCE.Northendsection7_954068325900
RESOURCE.Northendsection1_954068663200
RESOURCE.Northendsection1_954068663200
RESOURCE.Northendsection2_954068678190
RESOURCE.Northendsection2_954068678190
RESOURCE.Northendsection2_954068678190
RESOURCE.Northendsection3_954068698240
RESOURCE.Northendsection3_954068698240
RESOURCE.Northendsection4_954068711260
RESOURCE.Northendsection4_954068711260
RESOURCE.Northendsection5_954068726250
RESOURCE.Northendsection5_954068726250
RESOURCE.Midendsection1_954069051520
RESOURCE.Midendsection1_954069051520
RESOURCE.Midendsection1_954069051520
RESOURCE.Midendsection2_954069078540
RESOURCE.Midendsection2_954069078540
RESOURCE.Midendsection3_954069094530
RESOURCE.Midendsection3_954069094530
RESOURCE.Midendsection4_954069124570
RESOURCE.Midendsection4_954069124570
RESOURCE.Midendsection4_954069124570
RESOURCE.Midendsection1_954069342020
RESOURCE.Midendsection1_954069342020
RESOURCE.Midendsection1_954069342020
RESOURCE.Midendsection1_954069342020
RESOURCE.Midendsection4_954069436110
RESOURCE.Midendsection4_954069436110
```

Interactive SQL - Ford (dba) on DBServer

File Edit Command Window Help

Data

```
PROPLIST
site,buildings
xgeom,ygeom,xcoord,ycoord,avail,floors
xgeom,ygeom,xcoord,ycoord,avail,floors
xgeom,ygeom,xcoord,ycoord,avail,cells
xgeom,ygeom,xcoord,ycoord,type,avail,stations
xgeom,ygeom,xcoord,ycoord,type,avail,stations
xgeom,ygeom,xcoord,ycoord,type,avail,stations
xgeom,ygeom,xcoord,ycoord,type,avail,stations
xgeom,ygeom,xcoord,ycoord,type,avail,stations
xgeom,ygeom,xcoord,ycoord,type,avail,stations
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xgeom,ygeom,xcoord,ycoord,avail,resources,tools
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xgeom,ygeom,xcoord,ycoord,avail,power,quality,util,costrate,typeclass,company,prodrate,rough,flex,maxw,maxb,maxd,maxl
xgeom,ygeom,xcoord,ycoord,avail,power,quality,util,costrate,typeclass,company,prodrate,rough,flex,maxw,maxb,maxd,maxl
xgeom,ygeom,xcoord,ycoord,avail,power,quality,util,costrate,typeclass,company,prodrate,rough,flex,maxw,maxb,maxd,maxl
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xgeom,ygeom,xcoord,ycoord,avail,power,quality,util,costrate,typeclass,company,prodrate,rough,flex,maxw,maxb,maxd,maxl
xgeom,ygeom,xcoord,ycoord,avail,power,quality,util,costrate,typeclass,company,prodrate,rough,flex,maxw,maxb,maxd,maxl
```

Interactive SQL - Ford (dba) on DBServer

File Edit Command Window Help

Data

```
PROPLIST
xgeom,ygeom,xcoord,ycoord,avail,power,quality,util,costrate,typeclass,company,prodrate,rough,flex,maxw,maxb,maxd,maxl
xgeom,ygeom,xcoord,ycoord,avail,power,quality,util,costrate,typeclass,company,prodrate,rough,flex,maxw,maxb,maxd,maxl
xgeom,ygeom,xcoord,ycoord,avail,power,quality,util,costrate,typeclass,company,prodrate,rough,flex,maxw,maxb,maxd,maxl
xgeom,ygeom,xcoord,ycoord,avail,power,quality,util,costrate,typeclass,company,prodrate,rough,flex,maxw,maxb,maxd,maxl
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xgeom,ygeom,xcoord,ycoord,avail,power,quality,util,costrate,typeclass,company,prodrate,rough,flex,maxw,maxb,maxd,maxl
xgeom,ygeom,xcoord,ycoord,avail,power,quality,util,costrate,typeclass,company,prodrate,rough,flex,maxw,maxb,maxd,maxl
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xgeom,ygeom,xcoord,ycoord,avail,power,quality,util,costrate,typeclass,company,prodrate,rough,flex,maxw,maxb,maxd,maxl
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xgeom,ygeom,xcoord,ycoord,avail,power,quality,util,costrate,typeclass,company,prodrate,rough,flex,maxw,maxb,maxd,maxl
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xgeom,ygeom,xcoord,ycoord,avail,power,quality,util,costrate,typeclass,company,prodrate,rough,flex,maxw,maxb,maxd,maxl
xgeom,ygeom,xcoord,ycoord,avail,power,quality,util,costrate,typeclass,company,prodrate,rough,flex,maxw,maxb,maxd,maxl
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xgeom,ygeom,xcoord,ycoord,avail,power,quality,util,costrate,typeclass,company,prodrate,rough,flex,maxw,maxb,maxd,maxl
xgeom,ygeom,xcoord,ycoord,avail,power,quality,util,costrate,typeclass,company,prodrate,rough,flex,maxw,maxb,maxd,maxl
xgeom,ygeom,xcoord,ycoord,avail,power,quality,util,costrate,typeclass,company,prodrate,rough,flex,maxw,maxb,maxd,maxl
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xgeom,ygeom,xcoord,ycoord,avail,power,quality,util,costrate,typeclass,company,prodrate,rough,flex,maxw,maxb,maxd,maxl
```

Interactive SQL - Ford (dba) on DBServer

File Edit Command Window Help

Data

```
VALUE
NewtonAycliffe,2
201,142,120,0,True,1
100,142,0,0,True,1
201,142,0,0,True,11
90,7,0,0,Cell,True,5
77,7,0,0,Cell,True,5
94,13,0,0,Cell,True,7
74,13,0,0,Cell,True,7
84,10,0,0,Cell,True,2
89,10,0,0,Cell,True,6
10,10,0,0,True,2,2
10,10,10,0,True,2,2
10,10,20,0,True,2,2
10,10,30,0,True,0,4
10,10,40,0,True,1,4
10,10,50,0,True,2,2
10,10,60,0,True,2,2
13,13,0,0,True,2,2
13,13,13,0,True,2,2
13,13,26,0,True,1,5
13,13,39,0,True,1,5
13,13,52,0,True,2,2
13,13,75,0,True,2,2
10,10,40,0,True,3,2
10,10,50,0,True,2,2
10,10,60,0,True,2,2
10,10,70,0,True,3,2
15,10,0,0,True,2,2
15,10,15,0,True,2,2
20,10,30,0,True,4,2
20,10,50,0,True,4,2
20,10,70,0,True,4,2
20,10,30,0,True,4,2
2,11,1,1,True,1000,20,70,5897,Injection Moulding,UNKNOWN,60,1,50,1,1,1,1
2,11,1,1,True,1000,20,70,58.97,Injection Moulding,UNKNOWN,60,1,50,1,1,1,1
2,11,5,1,True,800,25,70,45.93,Compression Moulding,UNKNOWN,60,1,50,1,1,1,1
2,11,5,1,True,800,50,70,4593,Contact Moulding,UNKNOWN,60,1,50,1,1,1,1
2,11,5,1,True,800,30,70,45.93,Injection Moulding,UNKNOWN,80,1,50,1,1,1,1
2,11,2,1,True,800,80,50,45.93,Blow Moulding,UNKNOWN,80,1,30,1,1,1,1
2,11,2,1,True,500,50,50,35.52,Injection Moulding,UNKNOWN,80,1,30,1,1,1,1
```

Interactive SQL - Ford (dba) on DBServer

File Edit Command Window Help

Data

VALUE
2,11,1,1,True,1000,20,70,58.97,Injection Moulding,UNKNOWN,60,1,50,1,1,1,1
2,11,5,1,True,800,25,70,45.93,Compression Moulding,UNKNOWN,60,1,50,1,1,1,1
2,11,5,1,True,800,50,70,4593,Contact Moulding,UNKNOWN,60,1,50,1,1,1,1
2,11,5,1,True,800,30,70,45.93,Injection Moulding,UNKNOWN,80,1,50,1,1,1,1
2,11,2,1,True,800,80,50,45.93,Blow Moulding,UNKNOWN,80,1,30,1,1,1,1
2,11,2,1,True,500,50,50,35.52,Injection Moulding,UNKNOWN,80,1,30,1,1,1,1
2,11,6,1,True,500,50,50,3552,Injection Moulding,UNKNOWN,80,1,30,1,1,1,1
2,11,2,1,True,550,50,50,35.52,Injection Moulding,UNKNOWN,60,1,30,1,1,1,1
7,2,9,1,True,270,40,70,23.58,Injection Moulding,UNKNOWN,80,1,60,1,1,1,1
2,11,2,1,True,500,50,50,35.52,Injection Moulding,UNKNOWN,60,1,30,1,1,1,1
2,11,6,1,False,500,50,50,35.52,Injection Moulding,UNKNOWN,60,1,30,1,1,1,1
2,11,6,1,True,650,50,50,35.52,Compression Moulding,UNKNOWN,60,1,30,1,1,1,1
2,11,2,1,True,650,50,50,35.52,Injection Moulding,UNKNOWN,60,1,30,1,1,1,1
2,11,2,1,True,750,50,50,45.75,Injection Moulding,UNKNOWN,40,1,30,1,1,1,1
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2,11,2,1,True,550,30,80,35.52,Injection Moulding,UNKNOWN,50,1,30,1,1,1,1
2,11,6,1,False,550,30,80,35.52,Injection Moulding,UNKNOWN,50,1,30,1,1,1,1
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2,11,6,1,True,820,30,80,31.60,Injection Moulding,UNKNOWN,60,1,30,1,1,1,1
2,11,6,1,True,190,30,80,22.35,Injection Moulding,UNKNOWN,80,1,30,1,1,1,1
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7,2,1,6,True,270,40,70,23.58,Injection Moulding,UNKNOWN,80,1,60,1,1,1,1
7,2,9,6,True,270,40,70,23.58,Injection Moulding,UNKNOWN,80,1,60,1,1,1,1
7,2,1,1,True,380,40,70,27.58,Compression Moulding,UNKNOWN,80,1,60,1,1,1,1
7,2,1,1,True,250,40,70,25.58,Injection Moulding,UNKNOWN,60,1,60,1,1,1,1