EVALUATING THE IMPACT OF DESIGN DECISIONS ON THE FINANCIAL PERFORMANCE OF MANUFACTURING COMPANIES

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Doctor of Philosophy

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SUMMARY

Product design decisions can have a significant impact on the financial and operation performance of manufacturing companies. Therefore good analysis of the financial impact of design decisions is required if the profitability of the business is to be maximised.

The product design process can be viewed as a chain of decisions which links decisions about the concept to decisions about the detail. The idea of decision chains can be extended to include the design and operation of the 'downstream' business processes which manufacture and support the product. These chains of decisions are not independent but are interrelated in a complex manner. To deal with the interdependencies requires a modelling approach which represents all the chains of decisions, to a level of detail not normally considered in the analysis of product design.

The operational, control and financial elements of a manufacturing business constitute a dynamic system. These elements interact with each other and with external elements (i.e. customers and suppliers). Analysing the chain of decisions for such an environment requires the application of simulation techniques, not just to any one area of interest, but to the whole business, i.e. an enterprise simulation.

To investigate the capability and viability of enterprise simulation an experimental 'Whole Business Simulation' system has been developed. This system combines specialist simulation elements and standard operational applications software packages, to create a model that incorporates all the key elements of a manufacturing business, including its customers and suppliers. By means of a series of experiments, the performance of this system was compared with a range of existing analysis tools (i.e. DFX, capacity calculation, shop floor simulator, and business planner driven by a shop floor simulator).

The experiments demonstrated the superiority of the enterprise simulation approach; existing tools were deficient in their ability to analyse the chain of decisions, either to the necessary level of detail or across a sufficiently wide scope. Performing the experiments also confirmed the feasibility of enterprise simulation for the evaluation of design decisions and hence as a viable tool to support the product introduction process.

Key words: product design, costs, financial evaluation, simulation, enterprise simulation

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1 INTRODUCTION

1.1 The Importance of Design Decisions for Business

Product design is generally considered to be important to the financial performance of businesses in particular and to the economy in general. In the UK, the importance of design has been stressed for many years by design and engineering organisations, academics and government (Roy & Wield, 1986, pp. xii-xiv). The financial performance of a business is important for its short and long term survival. In the short term it must have cash to pay its debts; in the long term it must produce acceptable levels of profit. In either case, this involves having revenues greater than costs.

Revenues are the product of price and quantity sold but the decision to buy is dependent upon the price. There are many other factors that can affect the purchasing decision, for example superior design, trade-in-value, value for money, delivery performance, delivery speed, quality, responsiveness and product range (Rothwell & Gardiner, 1983; Hill 1993, chp. 3). The costs of a business are also affected by its operational performance. The way it organises and utilises people, machines, space, and the amount of inventory present will all affect the costs required to achieve the necessary operational performance. Therefore it can be seen that the financial performance of a business is, in part, determined by its operational performance.

The manufacturing costs of a business can be broadly classified as direct materials, direct labour and overheads. In general, materials are directly specified by the designer. Production processes may be directly specified (e.g. the use of a forging), but even where they are not, the material, shape, size, tolerance and finish of the component will influence the machinery and processes that can be used. This will affect the investment in plant required and the direct labour needed to operate them. It is not just direct costs, but also overhead costs which are considered to be affected by design decisions. Many workers in the field of Design For Manufacture (DFM) and Design For Assembly (DFA) claim that the design of the product has an effect beyond production and assembly costs; inventory, field service, floor space, capital requirement, and production support costs are some of the areas reported as being affected (Poli et al., 1986; Boothroyd & Dewhurst, 1988; Sprague and Wallach, 1988).

Product design decisions not only affect finances, they are also known to be a factor in the operational performance of a business. As design decisions influence the production processes and the processing time required, they will subsequently affect the shop floor performance (e.g. Galbraith & Green, 1995). The structure of the product (e.g. number of components, levels of the bill of materials, commonality) is known to affect the performance of the manufacturing planning and control system (Collier, 1981; Sum et al., 1993; Gupta & Brennan, 1995). Inventory levels are also known to be affected by product structure (Collier, 1982). All these factors will have some effect on the delivery performance of the business.

Making decisions which are good for the business therefore, can be seen to require an analysis of the operational as well as financial impact of design decisions.

1.2 The Place of Analysis in Design

Analysing the performance of a design is an important task in the design process. Figure 1.1 (adapted from Roozenburg & Eekels, 1995, p. 88) shows one view of the core tasks in design. Other similar views can be seen in Suh (1990, p. 7), Lawson (1990, p. 28) and Dym (1994, p. 28).

In the investigation stage the design problem is investigated to discover what are the requirements and constraints of the product. This should cover technical performance as well as non-technical aspects such as costs, ergonomics, maintenance, manufacturing, installation, etc. (Pugh, 1990, chp. 3). The output of this stage is a set of requirements, generally known as a design specification, which guides the design process and provides the basis for the criteria against which solutions can be compared. During the synthesis stage, solutions are generated which are aimed at satisfying the design specification. These designs are considered to be provisional as they have yet to be analysed and judged.

The term analysis is sometimes used to describe the investigation task, it is used here to describe the task of determining the behaviour or performance of the product (in the way that the term stress analysis is used). During the evaluation task, the 'goodness' of a design is determined and this involves a comparison of the predicted performance to the requirements. It will generally involve quantitative criteria (e.g. power consumption,

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Figure 1.1 Core tasks of design (after Roozenburg & Eekels, 1995)

costs) and qualitative criteria (e.g. aesthetics, user friendliness). It is likely that some aspects will be well satisfied and others not so well. This multi-criteria evaluation will therefore require judgement. The decision task will also require judgement. The first decision is to decide whether a design is acceptable, i.e. does it satisfy the specification. If there are a number of acceptable designs, there is the additional decision of deciding which is the best.

Besides providing the predicted performance of the product for use in evaluation, analysis also plays a role in improving designs. In an unacceptable design, the feedback from an analysis might identify those aspects which are the problem. In an acceptable design, it might prompt ways of making the design even better. Also, by comparing the performance of different designs and trying to incorporate the best and eliminate the worst aspects, an improved design might be created.

1.3 The Need For Quantitative Analysis

In discussing decision making and judgement in design, Ferguson (1992, p. 9) makes the point that:

> "... making wrong choices is the same kind of game as making right choices; there is often no *a priori* reason to do one thing rather than another, particularly when neither has been done before. No bell rings when the optimum design appears.".

Analysis is therefore required which is discriminating enough to indicate when good or bad decisions have been made. Without such an analysis, the best solution from a number of possible candidates might not be chosen, resulting in lower profit or market share. Conversely, the best candidate design may be chosen but is unacceptable in some respect, because the analysis failed to detect the flaw. This may result in a product which sells well but is unprofitable to make; in extreme cases the company could be forced into bankruptcy.

The use of rules and guidelines can be considered as a type of analysis. Pahl & Beitz (1988, pp. 273-281) give numerous examples of guidelines for different production processes; by specifying good practice such guidelines aim to reduce production difficulty and hence cost. One such guideline for casting is, 'provide tapers from the split-line'. A design therefore that does not have tapers is in a qualitative sense worse and hence should cost more than one that does. Where two designs both provide tapers, the guideline fails to differentiate between them. Some rules and guidelines can be more discriminating. For example in Design for Assembly (DFA) the guideline, 'minimise the number of parts', provides an ordinal measure of goodness. It is still limited for analysis because it cannot differentiate between two assemblies which have the same number of parts. Worse than this, it is quite possible that a product with fewer parts could cost more (D'Cruz, 1992). Even for a simple product, many rules and guidelines might be applied. This can lead to contradictions. For example, guidelines for production aim to simplify component parts, while the 'minimise the number of parts' guideline tends to create few, but more complex parts. While rules and guidelines can provide an indication of how the design might be improved, they are not a serious method of analysis.

Taking good financial and operational decisions therefore requires good quantitative analysis tools to support the design process.

1.4 Context and Focus of the Thesis

The work presented here is part of a series of research projects to develop an enterprise simulator, called the Whole Business Simulator (Love et al., 1992). The Whole Business Simulator is aimed at providing a comprehensive simulation of the business which can then be used for analysing a range of decisions, from product design, manufacturing systems design and operations. A number of elements of the system have already been developed: shop floor simulator (Ball, 1994), manufacturing planning and control (Boughton, 1995) and support departments (Jackson, 1996). A complete system has yet to be achieved. This thesis is not concerned with creating any of the missing elements. Its purpose is to demonstrate the need and capabilities of such a system in the analysis of product design decisions.

This thesis will focus on quantitative analysis tools which provide an assessment of the financial and operational impact of product design decisions. Although it is now well recognised that product design decisions need to be considered in a wider business context, the argument will be advanced that existing tools are lacking in their ability to provide a valid analysis. It will be further argued that the Whole Business Simulator possesses the necessary analysis capabilities; this will be supported by the building of an experimental system and comparing its performance with a number of alternative approaches.

2 THE DESIGN PROCESS AND ANALYSIS TOOLS

Consideration of the operational and financial impact of design decisions has generally been confined to the shop floor in terms of the impact on direct materials and direct labour. It is now generally recognised that design decisions can have an impact on a much wider range of operational and financial aspects and that these need to be considered.

Figure 2.1 Manufacturing costs driven by design (after Daetz, 1987)

Daetz (1987) has derived a chart of manufacturing costs driven by design decisions which was developed to aid designers and managers. A simplified version is shown in figure 2.1 (the original identifies whether the costs are material, labour or overhead). It can be seen that support functions such as purchasing are affected by design decisions. There are others who also consider design to have a wide impact. Many workers in the field of Design For Manufacture (DFM) and Design For Assembly (DFA) claim that the design of the product has an effect beyond production and assembly costs (Poli et al., 1986; Boothroyd & Dewhurst, 1988; Sprague & Wallach, 1988; Bakerjian, 1992). The following list has been derived from Bakerjian (1992, chp. 1 & 5) and lists the aspects on which the application of DFM could impact:

- Work-in-progress inventory

- Finished goods inventory
- Market flexibility and delivery
- Material overhead
- Machinery utilisation
- Throughput time
- Production rate
- Capacity
- Facilities and floor space
- Quality
- Development
- Set-up time
- Repair parts
- Inspection costs
- Field service
- Tools and equipment
- Systems (e.g. material planning)
- Maintenance
- Taxes and insurance.

Given that design does have such a wide impact, one might expect to find analysis tools which match this scope. This thesis will demonstrate that this is not the case. However, before reviewing existing tools, the design process will be briefly examined so that the tools can be put into context.

2.1 The Changing Organisation of Design

Figure 2.2 shows one view of the main phases involved in product design or product development (Pugh, 1990, chp. 1). Some authors also distinguish a phase between concept and detail design, called embodiment (e.g. Pahl & Beitz, 1988, chp. 3) but this distinction is not important here and will not be discussed.

In the market phase the user needs, competition, regulations, etc. relevant to the product being designed are investigated. From this investigation, a product design specification is

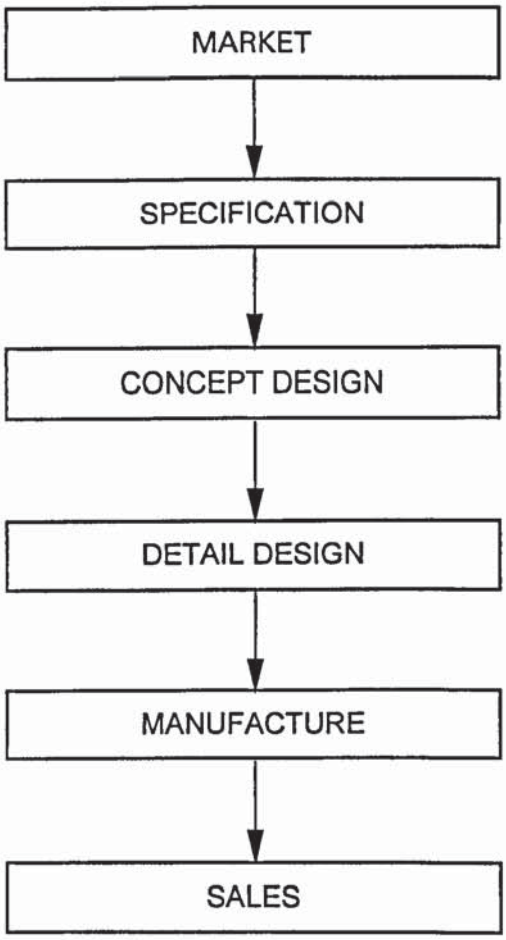

Figure 2.2 Main phases of design (after Pugh, 1990)

drawn up which defines the requirements and constraints for the product. Based upon this specification, conceptual designs are produced which satisfy the main requirements of the specification. What is included in a conceptual design is not fixed. It may include only the main working principles of the whole solution (Pahl & Beitz, 1988, p. 40) or it may include the means of major functions, spatial relationships and major dimensions (French, 1985, p. 1). Whatever the form, the conceptual design is then developed until a fully detailed design is produced. The output of the stage is usually a set of detail drawings, an assembly drawing and parts list. The detail drawings define such things as form, dimensions, tolerances, and material of each component so that it can be produced. An assembly drawing shows how the components go together to form the complete product, while the parts list basically defines the number of each component needed to create one product.

In the manufacturing phase, the fabrication and assembly systems and other support systems (e.g. manufacturing planning and control) are developed. For fabrication and assembly this will involve creating process plans and possibly machine layout. Process plans are developed from the detail and assembly drawings and define the operations and resources (e.g. machines and labour hours) that are required to make the part. The final part of the manufacturing phase will be to produce the product. In the selling phase the product is sold and delivered to the customer. Depending upon the business, the selling and delivery may be tied to a specific product that is being made, or the product might be sold from stock.

This simple diagram omits the many interactions between the various stages and feedback loops that characterise any real product development project. In its most extreme form the process is depicted as being entirely serial, with no communication between the design department and other functions. The design is only analysed for its functional performance and when complete, it is just 'thrown over the wall' to manufacturing (Riedel & Pawar, 1991; Evbuomwan et al., 1994). If consideration of downstream activities has been neglected it may lead to manufacturing costs which are higher than necessary, or a performance which is poorer that it might be. Alternatively, it could lead to delays in product development and an increase in development costs as upstream design activities and subsequent downstream activities have to be repeated to correct the poor design.

This problem is one of the reasons for a move to a product design process in which the impact of the downstream activities are considered during the product design phases. A number of such approaches are:

- Integrated Product Development (Andreasen & Hein, 1987)
- Total Design (Pugh, 1990)
- Life-Cycle Design (Alting, 1993)
- Concurrent Engineering/Simultaneous Engineering (Parsaei & Sullivan, 1993)
- Accelerated Product Development (Smith & Reinertsen, 1991).

Two main methods of achieving a wider consideration of the impact of design decisions are the use of multi-functional teams and tools for use by the designer.

Evbuomwan et al. (1994) in a review of concurrent engineering give a compilation of recommended team members derived from the literature, these are:

- marketing
- customers
- finance
- design or product engineering
- manufacturing engineering
- advanced purchasing
- internal company departments
- suppliers of components and parts
- suppliers of materials
- suppliers of manufacturing equipment

and in some cases

- insurance companies
- relevant government departments.

As this is a compilation, it is unlikely that every multi-functional team will be composed of all these members but it gives an impression as to the composition of such teams.

One aim of multi-functional teams is to be involved during the design of the product so that different team members can assess the design from their point of view (Dean & Susman, 1991). For example, manufacturing engineering may comment on the difficulties of fabrication and suggest a better way of manufacture. Similarly, the purchasing team member may note that a certain raw material will have a long delivery time. The design might then be changed so that it uses a more readily available material. Part of this assessment will involve considering what the downstream activities will be, before the design of the product is complete. In approaches such as concurrent engineering, the downstream activities are explicitly started before the product design is complete. The aim here is to purposely reduce the product development time by carrying out product design and 'downstream' activities concurrently or to be more accurate, overlap them. For example, the layout of the shop floor might be commenced before all the details of the components are known.

Tools for the designer in effect replace the role of different team members. There are many tools which provide a suggestion of what to avoid or what to improve (i.e. rules and guidelines). These rules and guidelines can be considered as part of the knowledge of the relevant functional team member. Their knowledge can also be captured and used in an expert system to provide the role of consultant (Rycher, 1985). When this is combined with a Computer Aided Design (CAD) system it can provide advice automatically or interactively as the design is developed (e.g. Mannion & Molloy, 1994). There are tools however, that provide a quantitative analysis (e.g. Design For Assembly). In this case, the designer and/or the tool makes decisions and assumptions regarding the downstream activities. The designer therefore, with the aid of the tool, carries out an analysis of the downstream activity earlier than would normally be the case.

Whether the team designs concurrently or not, the impact of the design on each functional area will need to be assessed if poor designs are to be detected before entering production. The analysis tools can be split into two broad classes, those generally for use by the designer and those generally for use by the functional personnel. The next two sections will respectively review these analysis tools. The aim of the review is to establish their range and capabilities.

2.2 Analysis Tools For the Designer

2.2.1 Parametric Methods

In the parametric method, an equation or relationship is derived which relates a product design parameter (or parameters) to the dependent variable of interest (Daschbach & Apgar, 1988). The relationships that are derived might be deterministic or statistical. For example, Stockton & Middle (1982) describe the use of a parametric method for estimating the job times and costs of cranes. The design parameters were such things as tonnage, span, motor size and brake size. The relationships were based on historical data about the manufacture of previous designs and were derived using multiple linear regression. By using overall design parameters it is possible to analyse a design in the earlier stages such as the specification and conceptual phases.

However, there are limitations to the technique (Stewart, 1982, p. 6). Where a design being analysed is very different to the designs from which the relationship was derived or if the underlying relationships have changed, then the answers given will be suspect. For example, in the case of Stockton & Middle (1988) above, job times and costs will be dependent upon the design and operation of the manufacturing system. As new products are introduced and production processes and systems changed, the previously derived relationships may no longer be valid. This problem may also mean that the parametric equations are specific to the company in which they were derived and so will not have general applicability.

A specific type of parametric costing is functional costing where the design parameters used are the functions that the design has to provide (Bradford & Culley, 1989; French, 1990). As French notes, the problem of gathering adequate data restricts the idea to components in highly competitive markets such as rolling element bearings, pneumatic cylinders, chain transmission systems. Example of functions in these cases are power, load capacity and speed. While the relationships should have general applicability, they will only be for a limited number of purchased components and systems.

2.2.2 Design For 'X' Tools

A large number of tools are covered by the name Design For 'X', where X is the aspect of interest, for example assembly, manufacture, quality. These tools have been specifically developed to be used by designers and are generally applicable during the detail phase when the product structure, shape, size, material, etc. have been decided. The most well developed of these tools are generally a combination of suggestion followed by analysis. The suggestion part is aimed at guiding the designer to improve a design by avoiding decisions which may cause problems downstream. This may be a set of rules or guidelines which the designer follows or knowledge engineering principles may be used to automatically identify problems and make suggestions. The analysis part of the tool is then used to confirm the appropriateness of the decisions taken.

Probably the most well used and widely available of these tools is Design For Assembly (DFA) (e.g. Boothroyd & Dewhurst, 1987). The procedure is generally as follows. From a drawing or sketch of the product the assembly time is generated based on tables for times of major assembly operations. As part of the analysis, a set of guidelines is used to assess which parts can theoretically be eliminated. From these two sets of information the designer is guided to seek ways to improve the design by either eliminating parts or improving the ease of assembly of the existing parts.

There are also many tools aimed at manufacturing processes such as injection moulding, casting and turned parts (e.g. Dewhurst & Boothroyd, 1987; Boothroyd & Reynolds, 1988; Allen & Swift, 1990). These are sometimes known as Design for Manufacture tools (DFM) but should be more appropriately named component-DFM (Boothroyd & Dewhurst, 1998). As with the DFA tools, the aim is identify features that are costly and so guide the designer into amending the component design to reduce production costs. Some techniques give an explicit processing time (Boothroyd & Reynolds, 1988) while in others, it is embedded in the evaluation. For example, Allen & Swift (1990) use knowledge engineering techniques in which the processing time is not explicitly available.

While these techniques give an estimate for a number of processes, they are all at present restricted to single manufacturing processes, multiple machines processes are not yet covered. The tool for turned parts (Boothroyd & Reynolds, 1988) is for CNC machines where it is assumed that all the processing is carried out on the one machine and only a single set-up is required.

These tools are specifically aimed at providing a cost. Ignoring the detail of some of the methods, the basis of the cost calculation used for DFA/DFM is generally as for traditional costing (see for example, Boothroyd & Reynolds, 1988 and Allen & Swift, 1990). However traditional product costing has a number of problems which will be discussed below in section 2.3.1.

To use these tools in the design process does mean that certain assumptions are made. For example, Dewhurst & Boothroyd (1987) in developing costing methods for use early in the design process assume that:

> "... manufacture will eventually take place under ideal processing conditions and that the final part design will be appropriate for the process.".

While this may be a necessary assumption given the stage in design when the technique is to be used, it assumes a set of circumstances that might not prevail when the product is made.

Quantitative analysis DFX tools for other aspects are not as well developed or are missing. Where they are being developed, they tend to be focused on the performance of the product rather than the impact it will have on the business e.g. human factors (Tayyari, 1993). It is not being argued that product performance factors are not important, but such tools do not analyse what the impact on the business might be. This concentration of analysis tools for assembly and piece part production is confirmed by Olesen (1992, p. 121).

One exception to the lack of tools is design for quality (DFQ) where an analysis tool is being developed (Swift & Allen, 1994). Based upon material, geometry, tolerance and surface finish, a manufacturing variability risk index is derived for components. While for assembly operations, an assembly variability risk index is based upon handling and fitting considerations. While the tool identifies risky components and assembly operations, it does not provide a basis for deciding whether a particular component or assembly operation is unacceptable. An overall rating for an assembly is not given, therefore judgement is required in deciding which of a number of designs is the better. The use of indices also means that trade-offs between cost and risk cannot be made.

To address these failings, the tool has been extended so that the probability of failure and cost of quality can be derived (Batchelor & Swift, 1996), but its validity can be questioned. Using Failure Modes and Effects Analysis (FMEA), acceptable limits for the probability of failure have been related to the manufacturing and assembly variability risk values (qm, qa) described above. This is shown in figure 2.3, for the special case where a fault will not be detected and where the presence of the fault will lead to failure. Approximate lines of equal cost (isocost) have then been plotted on the same graph and this is shown in figure 2.4, for the same special case.

Figure 2.3 Limits of acceptable design (after Batchelor & Swift, 1996)

In the range $6 \leq S \leq 10$ (safety critical failures), the boundary of acceptable design is considered to be approximately equivalent to a cost of quality per product of 0.01% of the selling price of the product, while the boundary of unacceptable design is considered to be 1%. Batchelor & Swift (1996) give a basis for how the quality cost of non-safety critical failures (severity rating 1 to 5) can be derived. The cost of safety critical failures (severity rating 6 to 10) are discussed but no basis is given for how they were derived. The estimate of cost of quality provides a rough basis upon which to judge different designs but the basis of the costs means that this aspect is questionable.

Figure 2.4 Conformability map (after Batchelor & Swift, 1996)

2.2.3 Integrated CAD Based Tools

A number of tools are being developed, which link CAD to other systems thereby allowing the designer to analyse the fabrication and assembly aspects of the design at the CAD terminal. Generally, geometric (or feature), dimensional and tolerance data are extracted from the CAD system, and utilised by the linked system to provide an analysis of the design. Such systems are computer versions of DFA/DFM, Computer-Aided Process Planning (CAPP), Numerical Control (NC) program generation and cost estimation.

Many of the integrated systems are focused on either fabrication or assembly with the intention to expand into the missing area.

Maropoulos (1994) describes a system for the generation and analysis of discrete part process plans but which will be developed to handle subassemblies and eventually complete products. The system generates process plans that are not generic but based upon the existing manufacturing facilities, taking into account such things as location of machines and associated equipment. Lead times based upon the sum of the set-up time and total processing time ignores factors such as queuing and transport. As queuing can be a major proportion of the total lead time (Cunningham & Dale, 1983), such a calculation is questionable.

Bullinger & Richter (1991) describe an integrated design and assembly planning system (IDAP) which can generate and evaluate assembly aspects but has the ultimate aim of optimisation of product designs for production. After a DFA analysis, the designer is aided in developing an assembly layout, part of which includes a static capacity calculation. Analysis also includes a cost calculation using standard static calculation and a flexibility evaluation, the basis of which is not given.

As well as cost and quality of fabrication, the system of Chen et al. (1993) includes an aspect of manufacturing planning and control. From process plans of the design, available manufacturing resources and due dates, the feasibility of a production schedule can be checked. The system can then interact with the user and the scheduling system to investigate alternatives, such as looking at the impact of adding an extra machine at a bottleneck. It is not possible to comment on the schedule analysis tool as details are not given.

The claimed greater accuracy of activity based costing (ABC) compared with traditional overhead costing has led to ABC being used as the costing method of some systems. For example, Geiger & Dilts (1996) describe a system which utilises feature based CAD system, CAPP, coding and classification and ABC to provide a product cost. Coding and classification is used to find similar parts. These are used as a source of ideas for cost reduction or to provide a direct substitute if cheaper. Activity based costing is not without its problems and these will be discussed below with traditional costing.

2.3 Analysis Tools For Functional Areas

2.3.1 Traditional Product Costing and Activity Based Costing (ABC)

Costing can be used to determine the cost of the product after it is in production, and to estimate the cost before production. While the former use is not strictly relevant here, it will be discussed, as it will highlight the problems of estimating costs before production.

In traditional product costing the cost of a product is the sum of direct material costs, direct labour costs and overheads (indirect costs). In general, indirect costs are distributed in two stages, initially they are apportioned over a number of cost centres or allocated to a specific cost centre and then absorbed into the products, generally on the basis of direct labour or machine hour content of the product (Owler & Brown, 1984, chp. 1). Figure 2.5 shows a simple example of a factory which makes two products (A and B) and has two production cost centres, fabrication and assembly. The £400 indirect costs have been apportioned on the basis of floor area, while the craftsmen are specific to each cost centre and so have been directly allocated. The total overhead for A is then £14 (8+6) and for B is £8 (4+4).

Indirect costs (e.g. rates)		£400
Cost centre costs (craftsmen's wages)		
	fabrication	£500
	assembly	£600
Cost centre floor area (m^2)		
	fabrication	300
	assembly	100

	fabrication	assembly
Indirect costs (shared on basis of floor area)	£300	£100
Cost centre costs (craftsmen's wages)	£500	£600
Total	£800	£700
Production (total direct labour hours)	200	350
Overhead rate (overhead cost per labour hour)	£4	£2
Product (A) direct labour hours content	2	3
Overhead cost of product (A)	£8	£6
Product (B) direct labour hours content	1	2
Overhead cost of product (B)	£4	£4

Figure 2.5 Example of traditional two stage overhead costing

The implicit assumption is that overheads are directly related to production volume, e.g. a product which requires more direct labour hours has used more overhead resources. There are some overhead costs where this is not necessarily the case. For example, the cost of raising a purchase order is likely to be the same whether it is for 10 items or for 10,000 items. Therefore, assigning these costs on the basis of direct labour hours can be seen to give a distorted picture of product costs. This distortion of product costs has led to an alternative to conventional product costing, activity based costing (ABC) (Kaplan, 1984). Activity based costing uses multiple cost drivers to allocate all overhead costs (manufacturing and non-manufacturing) based on the activities that a product consumes. It uses the conventional two-stage method of allocating costs but uses cost drivers that are not just related to the unit-level (i.e. directly related to product volume) but also to other levels such as batch (e.g. set-ups) and product (e.g. number of parts). Therefore, there is a rate (e.g. cost per set-up) for each activity that is identified. The set-up costs of a product would then be the total number of set-ups required during manufacture multiplied by the set-up cost rate.

Activity based costing is resource-consumption based. Excess capacity of resources are not included as activity based costs and so not associated with products, but are charged as costs for the period (Cooper & Kaplan, 1988). The emphasis is to focus attention on costly activities and highlight areas where spending is not in line with consumption, rather than calculating the current spending of the company (Cooper, 1990). This highlights the fact that activity-based costing is not just aimed at more accurate product costing, it is also used as a means of costing the activities themselves (Innes & Mitchell, 1990).

The emphasis of ABC on tracing all business costs to the products produced has been questioned by Dugdale (1990). Its use in practice has suggested that there are costs which cannot be reasonably associated with a product. Dugdale says that it may be necessary to identify some of the costs as market, customer or order related costs.

Both traditional costing and ABC are based on the idea of allocation. Allocation occurs because in most factories there are a number of different products being manufactured which share the same resources e.g. land, buildings, men and machines. The problem is how to objectively allocate the costs of these resources to the products being made and, so arrive at a cost for a particular product. The general problem of allocation in accounting has been made most forcefully by Thomas (1975). One of his main conclusions is that allocations will always be arbitrary and incapable of verification whenever assets are being shared. This problem means that indirect costs assigned to a product will be questionable. If indirect costs are a minor part of a product's cost this would not be serious but this not likely to be the case. For example, a survey by New & Myers (1986), of 240 companies ranging from food processing to shipbuilding, shows the breakdown of costs as:

- direct material 1% to over 80%
- direct labour 1% to 60%
- overhead 1% to 80%.

For a much narrower range of products, i.e. electronics and computers, Daetz (1987) claims figures of:

- direct material 50% to 80%
- production labour 2% to 15%
- overhead 15% to 45%.

Besides the problems mentioned above there are additional problems when the techniques are used for estimating costs. When used for products which are in production the costs are calculated based on historical data, but when used for estimating cost of a product yet to be produced, these data do not necessarily exist. In the case of traditional costing, direct labour hours (or machine hours) would be available as part of the process plans. The current overhead rate would then be used, but this might not be appropriate because the introduction of a new product may affect the overhead rate of the company. For example, utilisation levels may increase which would mean that the fixed costs of the factory would be apportioned over more direct labour hours and so reduce the overhead rate. In the case of ABC, the driver cost rates would in theory be unaffected by volume changes if they are based on resource consumption. The difficulty would arise in estimating the quantity of each driver. Take the example of estimating the number of set-ups per product. This will not be simple if shop floor policies are: split batches across all available machines in a work centre and group similar waiting batches at work centres.

As ABC is resource-consumption based it has a further problem; the estimated costs (whether product or activities) will not necessarily equate to actual expenditure. The difference will be significant in cases where the quantum nature of the resource causes a significant cost variance. For example, the increase in load due to the introduction of a new product may require the purchase of additional plant and equipment, or in an extreme situation a new building.

2.3.2 Computer-Aided Cost Estimating

Traditional cost estimation is a labour intensive process and relies upon individual experience and judgement. This can lead to inconsistencies and errors in the results. For these reasons the traditional process has been partially automated using computer based systems (e.g. Lee & Ebeling, 1987). These systems generally provide the same analysis as traditional cost estimating; one exception is the system proposed by Randhawa et al. (1991) which is described below.

Based on the user's inputs, material and process data are extracted from a database and fed into a simulation module. The manufacturing operations are then simulated and can be altered by the user to perform a sensitivity analysis. The simulation module provides economic and operational evaluation. Certain factors such as worker productivity and compatibility with existing production equipment are included in the overall evaluation as qualitative factors and not as a part of the simulation. The economic and operational factors are rated and weighted, and combined with the qualitative factors to provide an overall rating. The operational sequence does not take account of the actual manufacturing environment, e.g. the loading on machines due to other products.

It could be argued that the use of qualitative judgements merely indicates a deficiency in the capabilities of the technique used. The use of subjective assessments may be justified where quantitative judgement is impossible or impracticable. However if such factors are truly significant then their influence must, eventually, work through to the financial performance of the company and thus demonstrate a quantified effect.

2.3.3 Manufacturing System Analysis Tools

In manufacturing systems design, two major stages are steady-state design and dynamic design (Parnaby, 1986). In steady-state design resources are identified based on average requirements, while in dynamic design the variations in system performance due to disturbances and uncertainty are determined.

To assess the static design a capacity calculation can be carried out which provides an estimate of the average utilisation of the machine and labour. It is a calculation that is well suited to a spreadsheet. The calculation requires routing and process data (e.g. set-up times, processing times, machine type) for each component to be fabricated or product to be assembled; also required is average demand and batch sizes. With this information the total average amount of machining capacity and labour required at each work centre can be determined. From this information the number of machines and amount of labour can be determined. The utilisation of plant and labour can then be calculated (i.e. the required processing time divided by the total available processing time). Depending upon the user the calculation may include factors for breakdowns, maintenance and operator efficiency. The capacity calculation enables a number of manufacturing factors to be considered, however, the assumption of average values will undermine the validity of the calculation due to the dynamic nature of shop floor operations.

The dynamics of shop floor operations are generally analysed using either analytical techniques such as queuing models (Suri et al., 1995) or discrete event simulation (Law & Kelton, 1991). Similar data as for the capacity calculation are required but shop floor policies decisions can also be modelled. Examples include, sequencing rules for processing the next batch of work and priority rules for multi-skilled workers. Variability and stochastics can be included, for example, variable processing times, variable demand and random breakdowns. The simulation can provide performance measures such as utilisation, throughput time, WIP levels. Bottleneck operations can also be identified. Therefore, as well as providing what should be a more valid analysis, dynamic tools also provide a wider range of inputs and outputs than a capacity calculation.

From the review of Banks (1993) shop floor simulators do not appear to include the wider aspects of manufacturing planning and control except for scheduling (e.g. FACTOR). This lack of planning and control elements has been noted by other authors (e.g. Ball et al.,1994).

2.3.4 Business Process Modelling Tools

There are a number of graphical tools aimed at modelling business processes such as manufacturing planning and control, purchasing and sales. Common techniques are SADT (Structured Analysis and Design Technique), IDEF0 (ICAM Definition Method) and the GRAI method (Graphes de Résultats et Activitiés Interreliés) (Vernadat, 1996, chp. 4).

Techniques such as SADT and IDEF0 provide a well documented record of the activities required for a given process and can highlight where activities are missing or where there is mismatch of inputs and outputs. Such techniques are only descriptive and consequently lack the ability to provide quantified measures of the performance (Busby & Williams, 1993). The GRAI method concentrates on the decision making aspects of business processes but is similarly descriptive and lacks any quantitative analysis capability.

The lack of quantification makes these techniques unsuitable for the type of analysis that is argued for here. Gladwin & Tumay (1994) also give lack of quantification as a reason why simulation tools are required to model business processes. They describe a tool (ServiceModel) which appears to be focused on the serving of people, although it claims to model entities such as orders. Other instances of simulation for the modelling of business processes are Ketcham (1991) and Davies (1994), both of which modelled administrative and office processes in the financial service industry.

While these tools are not directly focused on manufacturing support functions, such simulation tools could in principle be used and would provide similar performance measures to a shop floor simulation. What must be pointed out is that these tools model the business processes in the same way that shop floor simulators model the production processes, i.e. as a time to complete each task. These simulators can model the capacity of staff to process a certain quantity of orders, but not the actual activities. Therefore, a business process simulator modelling the planning function would not model the details of a material requirements calculation, nor what effect this might have on the operational of financial performance of the business.

2.3.5 Financial Modelling - Business Planners

Financial modelling can be for specific purposes such as profit forecasting, cash flow analysis, taxation, acquisitions, and are normally built using a spreadsheet (Berry & McLintock, 1991). Of interest here are business planning models which can be used to assess the financial implications of introducing a new product.

Business planners provide a comprehensive model of the finances of the business and include such aspects as revenues, costs (material, labour, overhead), interest, taxation, dividend and assets. When these aspects are modelled over a number of time periods, with appropriate lags for payments and receipts, the cash flow can be derived. The modelling over time is generally approximated by having a 'static' model for each time period under consideration (e.g. monthly) and computing the expected values at each period. Such models are in effect a model of the financial accounts of the business and so can provide most financial reports such as profit & loss, balance sheet, cash flow as well as financial performance measures e.g. return on capital employed.

While business planners encompass the whole business they tend to be at an aggregate level (Bhaskar et al., 1982) which undermines their validity. The financial model will generally include financial accounting identities which model the financial accounts, and behavioural equations which represent operational aspects of the business. While the former should provide a valid model of the financial accounts, the latter may be inadequate in representing the operational aspects. Berry & McLintock (1991) point out that many financial models use behavioural equations which just include proportions. For example, the costs of products might be based on a fixed variable split, with the variable costs being derived as a proportion of sales (e.g. variable cost = 0.45 * revenue). Other inputs to business planners are WIP levels and stock levels for each period being modelled. Ideally these are aspects which ought to be outputs of a model.

2.3.6 Investment Appraisal Methods

Introducing a new product is an investment and so can be assessed using investment appraisal methods. Well known methods are pay-back, rate of return, Net Present Value (NPV) and Internal Rate of Return (IRR) (Davies & Hughes, 1977). Although the methods are different, they require as an input a cash flow model of the investment (i.e. the costs and revenues of each period being considered). From this information a measure of the investment is derived. For example, the NPV method takes each future period cash flow and discounts their value back to the start of the project. This is based on the idea that a pound now is worth more than a pound later, since a pound now could have been invested and earned interest. The summation of all these discounted cash flows gives the net present value.

Investment appraisal methods, provide a measure of 'goodness', but do not model the operational or financial behaviour of the business. As they are based on cash flow, they are just another performance measure that could be derived from a business planner and hence not considered to be an analysis tool.

2.4 Range and Capabilities of Analysis Tools

From the above review, a summary of the range and capability of the analysis tools is given in table 2.1. This shows that neither the designer nor all the functional areas has a range of tools that can provide a complete operational and financial analysis.

Simulation and queuing models provide good operational analysis of shop floor and business processes (e.g. throughput time of entities). What is lacking however are the tools to model the impact that many functional areas (e.g. manufacturing planning and control, purchasing, sales, distribution) will have on the operational and financial performance of the business

The costs and financial performance aspects appear well supported. There are a number of tools aimed at deriving products costs, which is not surprising given the importance of product costs to the business. Activity based costing can take a process, as well as product cost view. Hence it can be used to provide the cost of many operational activities. There

Analysis Tool	Range and Capability	Comments
Tools for the designer		
Parametric modelling	Product cost	Assumes underlying business does not change
Functional costing	Purchase cost of component/sub-system	
DFM	Fabrication cost of component	Assumptions about downstream processing
DFA	Assembly cost of product	Assumptions about downstream processing
Integrated CAD tools	Fabrication & assembly cost of product; Some shop floor operation performance measures	
Tools for the functional personnel		
Standard costing	Product cost	
ABC - product	Product cost	Requires input of activities
ABC - process	Cost of operational activities	Requires input of activities
Capacity calculation	Utilisation of fabrication & assembly work centres	Limited performance measures
Shop floor simulation & queuing model	Wide range of operational performance measures of fabrication & assembly	
Business process simulation	Wide range of operational performance measures of business processes	Not specifically designed for manufacturing businesses
Business planner	Finances of business	Poor operational model, aggregate inputs

Table 2.1 Range and capability of existing analysis tools

are question marks over costing tools because of the need to allocate costs. This is not a problem with a business planner which should provide a good model of the finances of the business. However, a business planner contains a poor operational model of the business which will undermine the validity of the financial results.

Therefore, if product design does have the wide impact it is generally considered to have, there are some gaps in the analysis tools available and some of their capabilities are questionable. A possible remedy to some of these problems is to use the operational output of the simulation tools as the source of activity drivers in an activity based cost model and to provide the WIP data for the business planner. The cost output of the ABC model could then be used as the cost input for the business planner.

Before looking at whether this is what is required it is necessary to examine the nature of design decisions and the extent to which they affect the business. This is the subject of the next chapter.

3 THE NATURE OF DESIGN DECISIONS

If product design really does affect many areas of the business there must be a link between what the designer decides and the impact on the functional areas. This will be investigated below and from it, some implications for the analysis of design decisions derived.

3.1 Design Decision Chains

Although there is not a universally accepted view of the design process (see for example Hubka & Eder, 1988; Pahl & Beitz, 1988; Pugh, 1990; Suh, 1990, for differing views), there are some common features which are relevant here. The process of design can be thought of as generating a complete description of the product (e.g. detail drawings) which satisfies a set of requirements and constraints. The process generally moves from the abstract to the concrete and is seen as hierarchical. The solution on one level becomes part of the requirements and constraints on the next level. Suh (1990, chp. 2) calls it a mapping process between a functional domain and the physical domain. The functional domain contains the set of functional requirements (the aims) that the design has to fulfil while the physical domain contains the physical embodiments (the means) that can satisfy the requirements. The functional requirements and physical embodiments are seen as hierarchical and interrelated. Suh gives as an example a lathe, figure 3.1 shows some of its functional requirements and figure 3.2 shows the corresponding physical embodiments. Suh argues that you cannot simply construct the whole of the functional hierarchy without referring to the physical embodiment at the corresponding level. So for example, once having decided to use a tailstock, the functional requirements of tool holder, positioner and support structure can be stated. Hence the functional requirements on one level are satisfied by a physical embodiment, this physical embodiment is then used to derive the next level of functional requirements.

This view of design therefore lends itself to the idea of a chain, where one level is linked to the next. The idea of a chain is put forward by others, for example, Tjalve (1977) describes the design project as a long chain of problems. Hansen (1995) also sees the design process as decision chains.

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Figure 3.1 Functional hierarchy of a lathe (after Suh, 1990)

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Figure 3.2 Physical hierarchy of a lathe (after Suh, 1990)

Suh (1990, chp. 8 & 9) applies his principles of design to the design of manufacturing processes, production schedules and, organisational and manufacturing systems. Therefore, he does not see any fundamental difference between the design process as applied to a product and that applied to processes and systems. Olesen (1992, chp. 5), also

Figure 3.3 Graph of process choice against production volume (after Hill, 1993)

takes this view and argues that the design of products is no different to the design of what he calls the production-oriented systems (e.g. fabrication, assembly, quality & production planning, transport system, sales & marketing and distribution). Accepting this similarity, the process of design for the systems that support the product will also be hierarchical and therefore involve a chain of decisions.

The product and the supporting systems are not independent. It is well known that the product has a major influence on the design of the fabrication and assembly areas. The product volume will be a major factor in determining the manufacturing process, i.e. project, jobbing, batch, line and continuous process (Hill, 1993, chp. 4). Figure 3.3 shows very broadly the relationship between volume and manufacturing process used. While the designer can affect the volume of the product by reducing its cost or adding features, there are some situations in which the designer will have little influence on volume. For example, specialist capital equipment such as large machine tools, printing presses, etc. are unlikely to be demanded in large numbers even if the price was low. But even in these situations, the product could be designed such that even though the product itself is low volume, the component parts are of a much higher volume (e.g. by using the principles of modularity and commonality). Similarly the design of the sub-assemblies and component parts will have an influence on the type of production processes (e.g. turning, milling, casting, etc.), labour requirements (numbers and skills), tooling, jigs and fixtures, etc..

The manufacturing planning and control (MPC) system of a business will be affected by the design of the product. For example, Mather (1986) considers the relationship between product design, bills of materials and forecasts to be very important, especially when product variants are involved. Many companies must base part of their manufacturing orders on forecasts because the total lead time for the product is longer than their customer delivery time. The extent to which companies have to forecast varies, in the case of consumer goods virtually all of their Master Production Schedule (MPS) planning horizon might be forecast, while manufacturers of machine tools may only have to forecast a portion of it.

Mather gives an example of a hoist which is made in quantities of 50 per week with a 15 week lead time and a customer delivery time of 4 weeks. The hoist comprises a motor (30), drum (10), gearbox (4) control pendant (2) and hook (1). The number of varieties of each item is shown in brackets. Assuming each combination is feasible, there are a total of 2400 combinations. Trying to forecast which 50 variants out of a possible 2400 will be demanded is an almost impossible task and stocking enough of each combination is not an attractive proposition. Instead of 2400 bills of materials it is possible, by arranging them into modular structure, to reduce the forecasting problem to a set of 47 bills of materials with a much reduced need to carry large amounts of inventory. The freedom to arrange the bill of materials to achieve the best situation is greatly affected by the design of the product. Therefore, the simplicity of the MPC system can be directly affected by the design of the product.

Designing the product to be modular, using few unique parts and more standard components will all affect purchasing. Modular structures might lead to increased volumes for component parts and so enable improved prices and delivery to be negotiated. Fewer unique parts will require fewer suppliers which will have implications for the effort required in managing the purchasing function. The use of standard parts will reduce involvement with suppliers to ensure that the particular requirements can be met.

Policy decisions will have a major impact on the spares and repair function, e.g. repair by replacement, return to base. The ability to implement such policies and the effort required will be affected by the design of the product. The technologies used in the product and the way it is structured will have implications for the skills required to repair it, and for the test and repair equipment requirements.

The type of product itself will be a factor in distribution e.g. small domestic goods will not require the same distribution as large scale one-off pieces of capital equipment. Nevertheless the design of the product can have implications. Modularity may allow large equipment to be shipped in pieces and assembled on site rather than being shipped complete. This may also affect handling and storage requirements as many smaller items may be more readily moved and more compactly stored. The transport equipment requirement may be similarly affected.

Therefore, the requirements and constraints for the design of these systems will be partially derived from the products they have to support. Suh (1990, p. 128) takes this view but in a narrow way. As well as functional domain and physical domain, Suh also defines a process domain which covers the fabrication and assembly of the product. Designing then becomes a mapping from the functional to the physical and from the physical to the process. The choices in the process domain are required to satisfy the product design (i.e. the physical domain). This mapping will not be confined to the production area but to all the relevant support systems. Consequently the chain of decisions about the design of the product will extend to a chain of decisions about the design of support systems.

3.1.1 Chains Extend to Operational Decisions

The chain of decisions does not stop when the product and its support systems have been designed, there are many decisions still to be taken before the product can be manufactured and sold. While these decisions might not be considered design decisions, they are nevertheless related to the design of the product and hence are part of the decision chain. For example, on the shop floor, there might be decisions of policy about splitting batches and labour allocation. In the production control system, for each component, subassembly and assembly there will be decisions about the batch size, lead time offset and safety stock level. Similarly in the purchase department, decisions will be required about who is to supply raw materials and components, and what are acceptable price and delivery terms.

The design of a new product may well incorporate existing components and subassemblies. Similarly, the existing support systems might not be redesigned, it being assumed that they can support the new product. In this case the product will now be constrained by these existing areas. Operational decisions about the new components within existing systems will still need to be taken as discussed above. But even where components and subassemblies already exist, the policies for these components might need to be reviewed. For example the use of an existing component may increase its overall demand and lead to a review and possible changes in batching and lead-time offsets in the production control system. In addition, there may be changes within the departments themselves, additional staff or office space may be required to deal with the extra workload generated from the new product.

3.1.2 Implementation Actions

From the above discussion a range of representative decisions has been derived and is shown in table 3.1. The decisions have been called implementation actions and cover both design and operational decisions. The table lists the different business systems that are typical of manufacturing companies. There are those that deal with the physical handling of the products (goods inwards, fabrication, assembly and distribution) and those that deal with the control and processing of the work (finance, sales & marketing, manufacturing planning and control, purchasing). The implementation actions have been split into those that relate to physical entities (e.g. machines) and those that relate to systems, policies or data (e.g. MPC type, routing data). This is not meant to be a comprehensive list but gives an idea of the decisions that might have to be taken to implement a design.

BUSINESS SYSTEMS	Physical	Systems, Policies & Data
FINANCE	personnel	payment terms
	office space	investment policy
	equipment	wage rate
		working procedure
PURCHASING	personnel	quantity/price/delivery agreement
	office space	vendor control
	equipment	order release policy
		working procedure
MANUFACTURING PLANNING & CONTROL	personnel	production planning method
	office space	master production schedule method
	equipment	capacity planning method
		material requirements method
		manufacturing lot sizing
		purchase order lot sizing
		lead time offset
		order release policy
		routing data
		process operation data
		BOM data
		working procedure
SALES & MARKETING	personnel	forecasting method
	office space	discount policy
	equipment	quoted product delivery time
		product price
		working procedure
GOODS INWARDS	personnel	inspection methods
	floor space	working procedure
	storage system	
	internal transport	
FABRICATION	personnel	shift pattern
	floor space	work pattern
	machine/processes	schedule method
	tooling	sequencing rule
	jigs & fixtures	routing data
	consumables	process operation data
	internal transport	
ASSEMBLY	personnel	shift pattern
	floor space	work pattern
	machine/processes	schedule method
	tooling	sequencing rule
	jigs & fixtures	routing data
	consumables	process operation data
	internal transport	
DISTRIBUTION	personnel	distribution method
	floor space	working procedure
	storage system	
	internal/external transport	

Table 3.1 List of representative implementation actions

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Figure 3.4 Chain of decisions for design of component

Using these implementation actions as a basis, the idea of the chain of decisions can be represented for a number of individual decisions. For example figure 3.4 shows what the chain might be for the design of a component. This will involve a number decisions that are taken to fully implement the upstream design decision. The detail implementation actions that might be taken along the decision chain are shown as greyed in boxes in the relevant sub-systems. Figure 3.5 shows the same information for a more complex set of design decisions and is based on the case study of Janson & Lundborg (1992). They describe how a manufacturer of sewing machines redesigned them for improved fabrication and assembly. This involved changing the product structure to reduce variants, and changes to components to use sintering and injection moulding processes. Obviously the figure does not show all of decisions and actions that took place, but it gives a good

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Figure 3.5 Complex chain of design decisions

idea of the range of decisions and implementation actions that is likely to occur for real design projects.

3.2 Interdependency of Decisions

The idea of decision chains presented above has been largely a hierarchical one, with the product design decisions cascading down to the supporting systems. This idea is shown in figure 3.6. It has been assumed that the implementation of the design will be acceptable and not cause any problems. This may not be the case, the interdependency of design decisions means that the impact of a decision can have consequences beyond what was expected and in areas outside its immediate implementation.

Figure 3.6 General idea of chain of decisions

An obvious interdependency is between the fabrication of components and the assembly of them. For example the assembly time of a product might be improved with the intention of reducing work-in-progress and offering better customer service. One way to do this is to amalgamate a number of separate components into a single, more complicated one. These more complicated components might lead to longer fabrication times or to longer delivery times if they are made by a subcontractor. The increased fabrication time may require an increase in component stocks or the installation of extra machining capacity to meet the intended customer delivery performance. Similarly, for purchased components, extra stocks might have to be held due to the longer delivery times or an increased price paid to ensure quicker delivery. Consequently efforts to improve the performance in one area, may lead to a degradation of performance in another area. This may then require corrective actions which were not initially considered.

The significance of this is discussed by other authors. For example, Haas (1987) lists eight kinds of manufacturing decisions, such as product design, process design, and facility and plant configuration. She argues that properly linked decisions in these areas can deliver what she calls a strategic breakpoint (i.e. a significant improvement), but warns that if their interdependencies are not taken into account it can pose strategic barriers. However, Haas does not indicate how these interdependencies can be assessed.

The need to express the interdependency between the design of the product and the systems to support it, is recognised by Dolinsky & Vollmann (1991). In evaluating the effect of product design decisions on the overhead costs of processing transactions they suggest that the consequences need to be thought through and developed into what they call 'scenarios'. These scenarios could be viewed as decision chains. As an example of a scenario they give:

> "An improvement to a customer service feature may dictate a change in certain quality specifications. For example, one alternative for achieving a desired quality level may involve a change in parts that may require a change in technology. This, in turn, may involve a change in layout and work centres; which then dictates a revision in the number of required operations. At the same time, the new technology can give rise to changes in throughput time, yield expectations, inspection needs, and reporting system requirements.".

In general therefore, it can be seen that a decision in one area which is intended to affect a given performance measure, might:

- affect other measures of performance in the same area
- affect the same or other measures of performance in other areas.

This has implications for the analysis of design decisions. A complete analysis is required in which all relevant functional areas and performance measures are included.

3.2.1 Theory of Dispositions

The above ideas and arguments have also been made by Olesen (1992) with the idea of a dispositional mechanism. Olesen (1992, p. 53) describes a disposition as:

> "... that part of a decision taken within one functional area which affects the type, content, efficiency or progress of activities within other functional areas.".

He argues that the parameters (i.e. decisions to be made) for the design of the product and for the design of each supporting system can be viewed as a hierarchy of four levels: range, concept, structure and component. This is shown graphically in figure 3.7. It is then proposed that, for each level, there are dispositions between the parameters in each area (i.e. product, and each supporting system) which can have a significant influence on the

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Figure 3.7 Design decisions levels of Olesen

performance of the product and supporting systems. Therefore, it is these dispositions that need to be handled well if a good result is to be obtained.

This theory, if found to be true, offers a way to structure the decision making process.

3.3 The Cost of Early Decisions

It is a widely reported fact that product design decisions determine the majority of costs (e.g. Daetz, 1987; Sheldon et al., 1990; Aldersey-Williams, 1996). I have questioned this claim (Barton et al., 1991); the estimates of how much product design determines business costs are supported by anecdotal evidence. In many cases authors just assert the claim , but where it is supported by references to published work, the references are to authors who themselves provide no proof to support their claims.

The results of a Rolls-Royce study (Symon & Dangerfield, 1980) have been erroneously used to support such a claim. A team of designers, detail draughtsmen and production engineers assessed the source of unnecessary cost of 2000 components. The team discovered that 20% of unnecessary cost could have been avoided by production engineering changes, 30% of unnecessary cost by detail drawing changes and 50% of unnecessary cost by design schemes changes. No figures were given for the level of these unnecessary costs as a percentage of total costs, or how these unnecessary costs compared to other areas of the business, so the significance of the unnecessary cost is unknown. Whitney (1988) and Smith & Reinersten (1991, p. 225) use the study to argue that design determined 80% of the final production costs of 2000 components. This is to misunderstand the difference between total cost and unnecessary costs.

Apart from Barton et al. (1991), Ulrich & Pearson (1993) are the only ones to have questioned such statements and some of the logical inconsistencies that follow. They say that one widely held interpretation is that when the product design is complete, the minimum possible manufacturing cost is 80% of the maximum manufacturing cost, irrespective of how the manufacturing system is designed and operated. Ulrich & Person (1993, p. 2) question, how there can be a maximum manufacturing cost. To avoid this and other flaws they set out to estimate how much product design and manufacturing system design influences the manufacturing cost.

The analysis is based upon the concepts of a design range and a manufacturing range. They defined the design range as the set of possible designs and the manufacturing range as the set of possible manufacturing systems to make those designs. They then assessed what the manufacturing cost of the product would be for each combination of product design and manufacturing system design by using a cost model. The cost range for a given product design gives the influence that the choice of manufacturing system can have and the cost range for a given manufacturing system gives the influence that the choice of product design can have. They choose as their product range, 18 commercially available drip coffee makers. The manufacturing range was taken as representing the best and worst systems that could reasonably be considered for manufacture of the product. The manufacturing system's parameters were derived from the literature and their own previous research. A total of 6 manufacturing system configurations were considered.

The results of the cost analysis are that for drip coffee makers, the product design range is 47% of the average manufacturing cost and the manufacturing system design range is 65% of the average manufacturing cost. In this instance, design is not 80% of manufacturing costs.

3.3.1 A Lower Bound View

Many text books on design will make the point that a flawed or poor concept cannot be remedied by excellent detail design. This could lead to a view that conceptual design decisions are more important than detail design decisions. But the same books will quickly point out that an excellent concept can be easily ruined by poor detail design (e.g. Pugh, 1990, p. 102). That later decisions can ruin a good concept is not restricted to these two major areas of design.

In the various views on the process of design the common theme has been its hierarchical nature, with one level being satisfied by the next level. Therefore, while it is by definition true that a lower level must 'logically' satisfy an upper level for the upper level to work, there is no law of nature that says that it will satisfy the upper level. It is the job of the designer to constantly ensure that each level will deliver what is required. This idea is applicable to the design chain, right down to the implementation. All along the chain decisions are being taken which are meant to deliver the requirements of those above it but could at any time lead to a less than ideal outcome.

The implications of this can be illustrated by a very simplified and idealised situation. Imagine a project in which a specification exists, the task is to design a product and implement it in the company. This idealised project has three points at which a decision must be taken, the outcome of the final decision completes the implementation. At each decision point there are two possible outcomes which therefore leads to a total of eight possible implementations. This scenario is illustrated in figure 3.8 as a decision tree with each outcome labelled with a letter. When the final decision is taken, only one particular product will have been implemented and the impact on the business (e.g. cost) will be a fact. The impact on the business of each implementation is assumed to have the value shown on the right of figure 3.8.

Each decision has two possible outcomes and these can be considered in pairs e.g. G and H are the outcome of decision C. Therefore, working back along the tree the minimum implementation values of each pair can be found and is shown in the figure. The root of the tree shows the overall minimum possible implementation value of 0.37 for L, the final implementation. It can be seen therefore, that whatever path is taken, the value of the

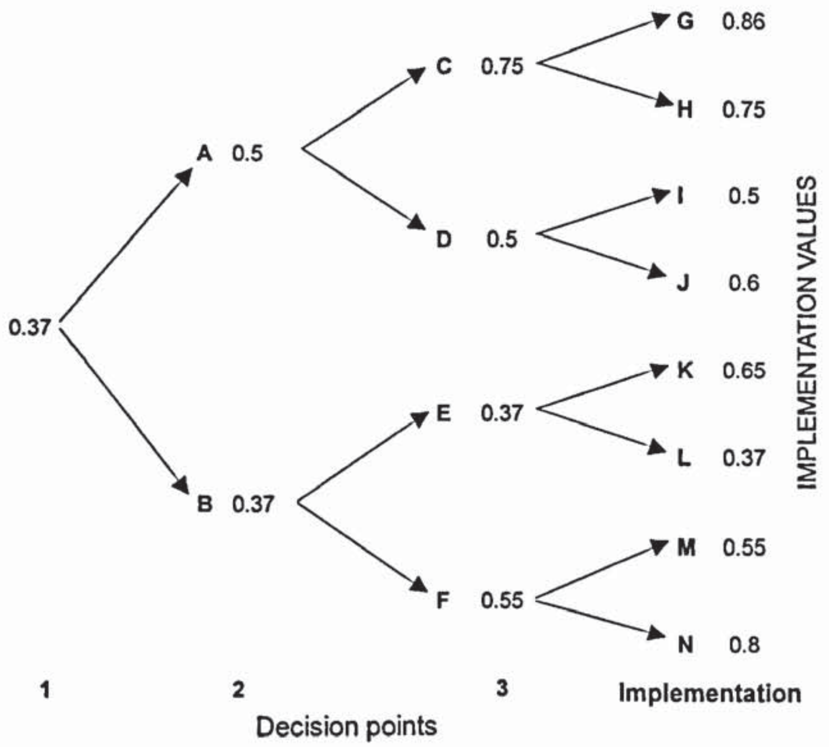


Figure 3.8 Design decision tree with implementation values

implementation that can be achieved cannot be better than is given by the minimum implementation value at that decision point. So for example, choosing outcome A at decision point 1 means that the best that can be achieved will be an implementation value of 0.5. If we then choose outcome C the minimum value has risen to 0.75 and no matter what we do, the next decision cannot improve it. This view of decisions fits the ideas of a poor concept not being saved by good detail (decision path ACH) and a good concept spoilt by poor detail (decision path BEK).

A good project therefore will not be about making good decisions at any one phase of the process, but is about making good decisions through the whole process, right down to the implementation.

As Pugh (1990, p.102) makes clear with respect to product design:

> "Good, sound detail design is as important in the overall design activity as conceptual design - indeed, all stages are of equal importance. This theme will be reiterated throughout this book.".

Good decision making can be helped by good analysis. It would be ideal therefore, if there were good analysis tools at all stages of the process.

3.4 Implications For Analysis

From the above discussion it can be seen that product design does have an impact across many functional areas through a chain of interconnected decisions.

The interdependency of decision chains has been argued to lead to the need to carry out a complete analysis i.e. an analysis that encompasses virtually the whole business and considers the impact on many performance measures. The point has also been made that it would be ideal to have good analysis tools at all stages of the product development process.

Except for very simple cases, a complete analysis would probably be too onerous for a product designer (or product design team) as it would involve carrying out the whole of the product development process. The analysis could be simplified but the level of simplification required is likely to lead to serious questions of validity. Using computers to fully automate the downstream activities would involve the need for automated designing. Automating even very narrow design activities is very difficult (e.g. Jones et al., 1993) and therefore full automation is unlikely to be possible in the very near future. If such sophisticated software were available, then there would be no need for the product designer either.

To carry out a complete and valid analysis will therefore require input from the various functional areas. This does not necessarily mean that it has to be done as a team or concurrently. One could imagine a set of tools which can analyse the supporting systems and output the necessary performance measures. To use the set of tools, the implementation actions from each functional area would be entered into the various tools. When all the functional areas had made their decisions, the analysis would be performed and the results fed back to each area. Each area could then assess the impact of their decisions and decide on any improvements or corrections.

Working concurrently as a team has a number of benefits. Delays in analysis due to the failure of any one functional area not entering their actions can be avoided. Many obviously poor decisions can be avoided by discussing each others intentions, and so reduce the number of iterations. The interaction of decisions and complexity of most businesses means that solving problems or aiming for improvements is likely to be achieved more readily with a team than with individuals working in isolation. For practical purposes therefore, a team approach is required if the best is to be obtained from such an analysis tool. This would match current trends in product development with the emphasis on the use of multifunctional teams.

Evaluating the impact of product design decisions therefore requires a complete analysis that supports the product development team in assessing its decisions making. The next chapter will look at the requirements for such an analysis and compare this with existing tools. In this way the basis of a suitable tool will be derived.

4 DERIVATION OF ANALYSIS TOOL REQUIREMENTS

An analysis tool can be viewed as a modelling process which transforms a set of inputs into a set of outputs (figure 4.1) This view can be used to compare an existing tool (or tools) to a given set of requirements. Therefore if the requirements for the proposed analysis are derived, the capabilities of existing tools can be assessed and any deficiencies used to define the additional analysis required.

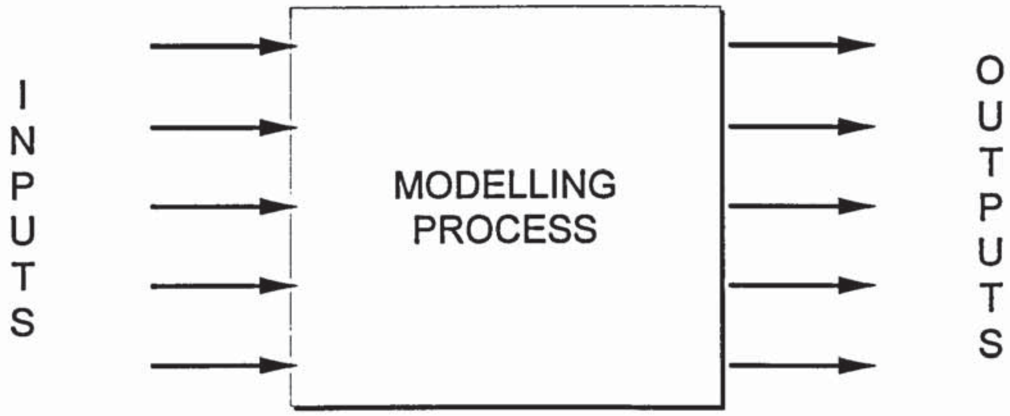


Figure 4.1 View of analysis tool as input, modelling process and output

4.1 Derivation of Inputs

The tools for use by the designer (e.g. DFA) make assumptions about the downstream activities and so limit the decisions that can be explored within a given area. The lack of accuracy which accompanies such restrictions is acceptable and is necessary if the product designer is to carry out the analysis. However, this restriction on decisions that can be input does mean that such tools do not allow the relevant functional team member to implement their actions.

If the impact of different downstream implementations are to be investigated and fully assessed, the analysis needs to provide inputs which match the implementation actions for each relevant functional area. In this way a particular team member could make their decisions and input them into the analysis tool. Table 3.1 in chapter 3 indicated the range and detail of inputs required. The implementation actions that have been identified contain many detailed decisions. This implies that an analysis that supports this level of detail could only be used towards the end of the product development process. This would obviously limit its utility.

Having detailed inputs does not necessarily mean that the analysis tool must be used when all the detail implementation actions have been decided. Data can be made available by either using default values or estimates. Alternatively, multiple levels of analysis could be presented to the user, in which less data are required by using an approximate analysis. The use of multi-level modelling has been suggested and used by others for shop floor simulators (e.g. Comly et al., 1982; Bridge, 1990).

The simulator ATOMS, developed by Bridge (1990) has three modelling levels: department, centre and station. The amount of data required and the level of modelling increases on each level. For example, at the centre level, individual machines and operators are not modelled, only the overall capacity of the work centre is modelled. The modelling levels in ATOMS are the same throughout the model but it would be an advantage if different parts of a model could be at different levels. This form of multi-level modelling would allow certain areas which were considered critical or of interest, to be modelled in detail while other areas are at an aggregate level. This has the advantage that effort would be concentrated where it is required and allow quicker analysis. For example, the redesign of a major sub-assembly might have a major effect on certain areas of the business; it would be these areas which would be modelled in detail while other areas would be modelled at an aggregate level. This form of multi-level modelling was the intention of Bridge (1990, p.180) and was also suggested by Comly et al. (1982).

The four levels of decisions (range, concept, structure and component) proposed by Olesen (1992) and already mentioned in chapter 3, may also be a way of structuring the model views, although ideally one would not want to predetermine the levels.

Using default values, estimates or multi-levels will explicitly or implicitly introduce elements to the modelling which will reduce the accuracy of the results. The lack of accuracy due to assumptions was a criticism of some of the tools discussed in chapter 2 (e.g. business planner) and would apply here, as a loss of accuracy is to be expected as the modelling becomes more aggregate. However, it is argued here that the analysis should be able to support the detail when and where required. This is in contrast to an analysis that has a limited range of inputs which can never allow the more detailed decisions to be implemented.

The scope and detail of the input requirements for the analysis are therefore the relevant implementation actions in each of the support systems.

4.2 Derivation of Outputs

4.2.1 Global Measures

The examples of interdependencies between design decisions and the manufacturing business have illustrated the complex way in which design decisions can affect a number different functional areas and performance measures. Concentrating on any one area may lead to a deterioration in another. While a single global measure of goodness would ease the evaluation of decisions, such a measure does not exist at present. The lack of any one single measure means that in assessing the performance of a business a wide and varied range of measures, financial and operational, are used (Parnaby, 1986; Hill, 1993, chp. 3; Gelders et al., 1994). Parnaby (1986) lists:

- stock turn ratio
- ratio of indirect staff to direct
- sales/value added per employee
- manufacturing lead time
- return on investment (same as ROCE)
- delivery on time.

If an analysis is going to assess the impact of design decisions on the performance of the business, it ought to provide or be able to provide, the financial and operational performance measures that are normally used and generally accepted.

Ideally the analysis should not restrict the performance measures that are provided. One way is to provide every possible measure, but as there are numerous performance measures, this does not seem sensible. It is further complicated if the user requires non-standard measures. A better way is to provide the basic data and outputs that the performance measures are based upon; in this way the performance measure can be derived to suit the particular purpose. The basic data and outputs are the ones which match those of the actual business (e.g. quantity sold, product price, cost of machines, number and type of employees, required date for customer order, actual delivery date of order, physical stock levels).

4.2.2 The Need For Transparency and Local Feedback

It was argued in chapter 3 that using local measures of performance may not lead to a global improvement due to the interdependencies of decisions. This does not mean that local measures and local feedback are not useful. If a particular global performance measure is poor, then without local output, users would find it difficult to understand the reasons for the problem and consequently be handicapped in suggesting ways to improve matters. This would obviously limit the utility of the analysis. A poor global performance is likely to involve a number of functional areas and output data. For example, the total lead time for a product may be too long. Local feedback may identify that the lead time in fabrication is too long. Further investigation may reveal that the utilisation is high at a particular work centre. Alternatively, long lead times may be due to the lead time offset being set too high in the MRP system.

A related point to feedback is that of confidence in the analysis. A user is likely to be suspicious of an analysis if he is forced to regard its workings simply as a 'black box'. By providing feedback, the user can confirm that his actions are having the expected effect and so reinforce his view of the workings of the analysis. If outcomes do not conform to expectations then the feedback needs to be of sufficient detail to provide valid explanations.

The same argument for global performance measures can be applied to local feedback i.e. by providing basic data and output that matches that of the actual business, the user can derive local performance measures as desired. This level of feedback would also seem appropriate to provide valid explanations.

From the above argument, a representative sample of basic output data is shown in table 4.1 for the different areas of the business. The data generally relates to physical resources (e.g. people, machines), the entities being processed (e.g. parts, orders, invoices) and the details of the entities (e.g. quantity, price and customer on an invoice).

BUSINESS SYSTEMS	Basic Output Data
FINANCE	personnel (e g. time processing, etc.)
	physical resource (e.g. utilisation)
	financial entity (e.g. throughput time)
	details of invoices raised
	details of payments received
	details of invoices received
	details of payments made
	details of wage payments
	details of capital purchases
	details of bank balance
PURCHASING	personnel (e.g. time processing, etc.)
	physical resource (e.g. utilisation)
	order entity (e.g. throughput time)
	details of purchase orders
MANUFACTURING PLANNING & CONTROL	personnel (e g. time processing, etc.)
	physical resource (e.g. utilisation)
	order entity (e.g. throughput time)
	capacity plans
	material requirement plans
	details of works orders sent
	details of GRN's received
	details of scrap notes received
	stock record for each item
SALES & MARKETING	personnel (e.g. time processing, etc.)
	physical resource (e.g. utilisation)
	order entity (e.g. throughput time)
	forecasts
	details of customer purchase orders
	details of sales orders
GOODS INWARDS	personnel (e g. time processing, etc.)
	physical resource (e g. utilisation)
	order entity (e.g. throughput time)
	part entity (e.g. throughput time)
	details of goods received
	details of goods in stock
FABRICATION	personnel (e.g. time processing, etc.)
	physical resource (e.g. utilisation)
	order entity (e.g. throughput time)
	part entity (e.g. throughput time)
	details of components in progress
	details of works orders
	details of scrap notes raised
ASSEMBLY	personnel (e.g. time processing, etc.)
	physical resource (e.g. utilisation)
	order entity (e.g. throughput time)
	part entity (e.g. throughput time)
	details of components in progress
	details of works orders current
	details of scrap notes raised
DISTRIBUTION	personnel (e g. time processing, etc.)
	physical resource (e.g. utilisation)
	order entity (e.g. throughput time)
	part entity (e.g. throughput time)
	details of goods in stock
	details of goods sent

Table 4.1 List of basic output data

Operational Performance Measures
supplier delivery reliability supplier lead-time supplier returns
raw material stock levels (value)
manufacturing lead-time production rates operator absenteeism operator utilisation machine reliability machine utilisation change over times WIP levels (value) scrap rate
finished goods stock levels (value)
customer delivery reliability customer lead-time customer returns
overall lead time

Table 4.2 Derived operational performance measures

Table 4.2 lists some of the operational performance measures that might be derived from the basic data. For example, with details of the customer required delivery date (from the customer purchase order) and details of the actual delivery date (from the despatch note), the delivery performance can be assessed.

It should be noted that some of the operational performance measures are aspects which would normally be defined as an input to many models. For example, in a shop floor simulation, the scrap rate would be an input parameter for a machine. Therefore in some cases the output data and performance measures will be things which are not derived from the model but which can only be set to investigate what the effect might be. Using the example of scrap rates, a product may be changed which should reduce the scrap rate. Existing shop floor simulators would not enable the input of the product parameters which should bring about the reduction in scrap, the scrap rate will be an input, derived from some other model or be an estimate based on experience.

Table 4.3 lists cost and financial performance measures that could be derived from the basic data. The financial measures have been arranged into generally accepted groups

Cost and Financial Performance Measures
Cost
cost of component/product cost of process/activity
Financial
profitability ROCE (profit/capital employed)
margins profit margin (profit/sales)
turnover ratios asset utilisation (sales/assets) stock turnover (cost of sales/average stock)
turnover periods customer credit period
value added value added margin (value added/sales)
liquidity current ratio (current assets/current liabilities)
productivity turnover per employee value added per employee
capital structure capital gearing
Investor ratios earnings per share (EPS) dividend yield

Table 4.3 Derived cost and financial performance measures

based on Reynolds (1992, chp. 9). Only one or two examples for each group are given as there are numerous measures in each. The cost measures could be derived, using either traditional or ABC techniques. For example, to use ABC the overall costs could be combined with the activity data from the operational areas to derive the required cost per activity or product cost. The financial performance measures could be derived by taking the details of the basic outputs (e.g. invoices, payments, value of assets, WIP values) and processing them in a business planner or financial accounting system.

4.2.3 The User View

Many of the inputs and outputs derived above can be seen to match the user's view of each functional area. Having a close match between the model and the way that the user would normally view the real world, brings a number of advantages. The translation required between the model and the actual system is reduced, this eases:

- inputting of decisions
- judging the performance of the modelled business
- understanding why a particular outcome occurred and what to do next
- implementing the desired decisions in the real world.

These benefits are observed by a number of authors (McKenny, 1965; Little, 1970; Comly et al., 1982; Suri et al., 1995).

4.3 Derivation of the Modelling Process

A manufacturing business can be viewed as a system that uses personnel, land and capital equipment to transform materials and energy to produce outputs of products and waste. As well as material and energy flows, there are information (e.g. purchase orders, sales orders) and financial flows (e.g. invoices, payments).

Figure 4.2 is a simplified view of a manufacturing business with some of the major flows and resource inputs. For established products, orders from customers will trigger the manufacture of the product using the labour and equipment of the business. Customer orders also trigger the purchase of materials from suppliers. On delivery of the product,

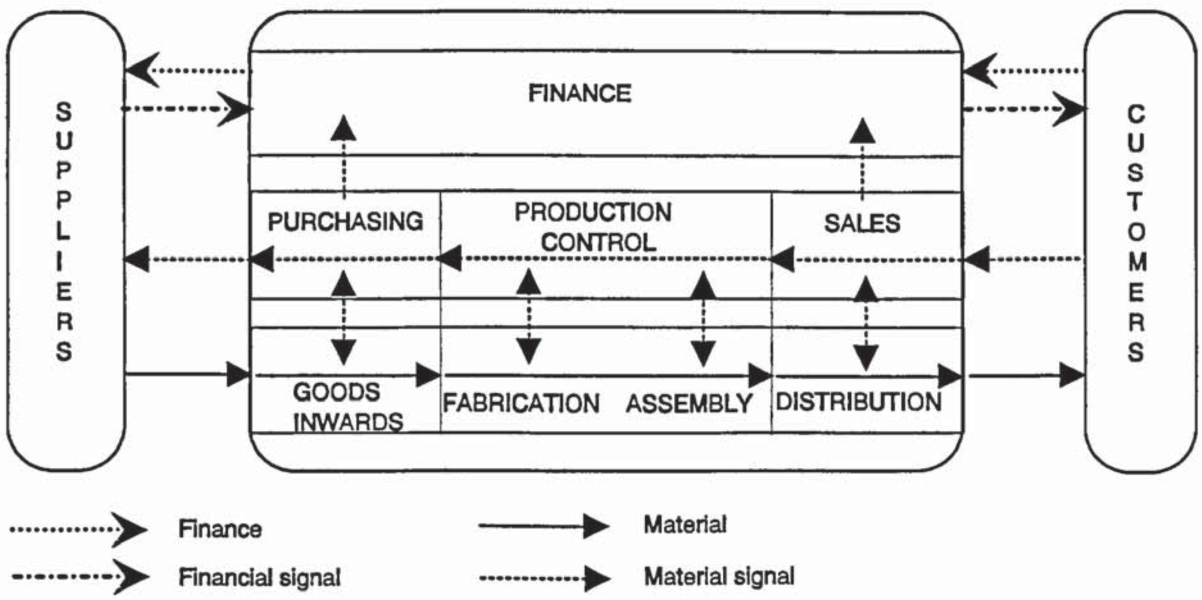


Figure 4.2 Simplified view of a manufacturing business

the customer is invoiced and after some delay payment is received. The company is similarly invoiced and makes payment for its purchases.

The flows of material, information and money can be seen to link the business with its suppliers and customers. With a steady demand of orders, these flows will be relatively stable. This view of manufacturing is simplistic, normally there are a number of different products being produced at the same time, each with varying demand patterns. This situation must be managed at the same time as a number of planned interventions occur, Lanigan (1992, p. 421) lists at the product-level:

- enhance established products
- introduce new products
- phase out old products

and at the process-level:

- periodic maintenance and/or servicing of the machinery
- the introduction of new machines
- modifications to process procedures and techniques aimed at improving efficiency.

Not all interventions are planned though, the business is also subject to a variety of random disturbances, Lanigan also lists:

- parent company, profit short fall, wants 10% cut in overheads
- delivery failure of supplier
- critical machine breakdown
- rush order
- urgently needed product definition data is incomplete
- specialist stock is now obsolete due to cancelled order
- irate workers due to time & motion study.

Rather than being a dynamic system in steady state, the effect of disturbances is more likely to make a manufacturing business a dynamic system which might never reach steady state.

The point has already been made that the interdependency of design decisions means that the performance of the whole system must be considered, not any one area. In saying this, it was implicitly assumed that the performance of the whole system could be taken as being the sum of each part of the business. However, the dynamic interaction between different parts of the business invalidates this assumption. For example, delivery performance requires more than knowing that on average suppliers, fabrication and assembly can each deliver or produce the required quantities of material, components and finished goods. Variability in quantities and timing can seriously affect overall delivery performance. In each area, planned and unplanned disturbances may mean that the actual quantities may be less or the actual delivery date may be later than required. These factors may lead to an overall delivery performance which is much worse than expected by just examining the individual areas. The manufacturing planning and control system could also be a major factor as it interacts with suppliers (via purchase orders), and fabrication and assembly (via works orders) to control the flow of materials. If this control system is not matched to the systems it is trying to control or cannot react appropriately to disturbances then it could make matters worse. For example, MRP (Materials Requirements Planning) systems assume infinite capacity but it is known that the throughput time for components will be dependent upon the load on the shop floor. The need to model the MPC system and the shop floor as an integrated system has been observed by others (e.g. Boughton, 1995)

While not often considered, dynamic interactions can be seen to exist between the performance of the shop floor and the ability of the support functions to handle the transactions that are generated as part of the normal planning and control of a manufacturing business (Jackson & Love, 1995). Jackson & Love argue that decisions such as make or buy (a decision which is related to the design of the product) will affect the work load of support departments. This may lead to extra staff being required and consequently to extra wage costs. Alternatively, the performance of the support department could feedback to affect the performance of the shop floor. For example, the processing of purchase and works orders is an element in the overall lead times for raw materials and components. Delays in processing orders therefore may affect the overall delivery performance of the manufacturing system. In addition there may be direct consequences on cash flow if the service level provided by the accounts department deteriorates so that it causes delays in invoicing and hence recovery of payments.

The manufacturing system therefore is complex in the way that Simon (1960, p. 86) describes complex systems as:

> " ... a large number of parts that interact in a nonsimple way. In such systems, the whole is more that the sum of its parts, not in an ultimate metaphysical sense, but in the more important pragmatic sense that, given the properties of the parts and the laws of their interactions, it is not a trivial matter to infer the properties of the whole.".

A manufacturing business therefore, is a complex dynamic system in which the design of the product and how it is implemented can significantly affect the business performance. The elements of a business system interact in complex ways, consequently, modelling one element in isolation can lead to invalid results.

Valid modelling therefore, requires a dynamic modelling process, with the ability to model as an integrated system all the interacting elements of the business, including its customers and suppliers.

Having described the inputs, outputs and modelling process requirements, existing tools can now be compared to them.

4.4 Comparison of Modelling Inputs and Outputs

The existing tools could be compared to the inputs using a table with all the inputs as rows and the tools as columns. By identifying when a tool met an input, the gaps in the tools would be seen. The same could be done for the outputs. The inputs and outputs as presented are not ideally suited for comparison. By arranging the inputs and outputs to match the basic views taken by the existing tools, any discrepancy will be readily identified.

The model of the manufacturing business given in figure 4.2 can be viewed in terms of three processing systems: material processing (goods inwards, fabrication, assembly, distribution), order processing (purchasing, manufacturing planning and control, and sales) and financial processing. The material processing system can also be seen to handle some of the orders (e.g. goods received notes, works orders).

For each of these systems the inputs can be arranged into three data types: resource, routing and process.

Resources are entities required to do the processing of either the material, material information (e.g. purchase orders, works orders) or financial information (e.g. invoices and payments). They are such things as people, machines, tools, work stations, computers, desks and space. These were identified in the list of inputs as physical resources.

Routing data define how material, material information and financial information are moved between processes. This includes where it should be processed, with which resources and how long each process will take. It also includes policy decisions of how to deal with the routing of the items being processed. For example, a shop floor policy decision could be to group similar batches, a MPC department policy could be to deal with all goods received notes at the end of each week.

The routing data as defined above specify the time required to process the item (i.e. material, order information, financial information) but not the details of the processing. This is in effect an arbitrary abstraction of reality and matches the views that existing tools take. For example, a business process modeller could be used to look at the effect on throughput time of invoices, payment, etc. due to an increase in business. In this case, it would be considered that the detailed processing of the data (e.g. posting of values to ledgers) does not need to be modelled. For this reason the items in the model will not normally carry the data required for this detailed processing. Similarly if the ability to deal with works orders, etc. was being assessed, the details of the material requirements method would not normally be modelled. In the processing of material, the details of the operation (e.g. face off, turn to diameter 20 mm) are not normally modelled and so data that might be required to do this are not included in the model.

There is in principle no problem in modelling the details of the processes as they are in general algorithmic processes. The level of detail could be taken further. For example, the processing of materials could be taken to the level that physical process is modelled. For example Jaques et al. (1994) describe a model which can simulate the forming of metallic fastenings. Therefore, it is not that the detail could not be modelled but that for the purpose of the particular analysis it is generally considered unnecessary.

The data of table 3.1 have been rearranged using the above classification and are shown in table 4.4.

The outputs can also be viewed as three types: resource, routing and process data. Each one generally matching the three types of input discussed above.

BUSINESS SYSTEMS	Resource Data	Routing Data	Process Data
FINANCE	personnel	routing instructions	double entry book keeping
	office space		financial accounting
	equipment		payment terms
			investment policy
			wage rate
PURCHASING	personnel	routing instructions	quantity/price/delivery agreement
	office space	order release policy	vendor control
	equipment		
MANUFACTURING PLANNING & CONTROL	personnel	working procedure	production planning method
	office space	order release policy	master production schedule method
	equipment	updating policy	capacity planning method
			material requirements method
			manufacturing lot sizing
			purchase order lot sizing
			lead time offset
			routing data
			process operation data
			BOM data
SALES & MARKETING	personnel	routing instructions	forecasting method
	office space		discount policy
	equipment		quoted product delivery time
			product price
GOODS INWARDS	personnel	routing instructions	detail inspection methods
	floor space		
	storage system		
	internal transport		
FABRICATION	personnel	routing data	detail process operation data
	floor space	shift pattern	
	machine/processes	work pattern	
	tooling	schedule method	
	jigs & fixtures	sequencing rule	
	consumables		
	internal transport		
ASSEMBLY	personnel	routing data	detail process operation data
	floor space	shift pattern	
	machine/processes	work pattern	
	tooling	schedule method	
	jigs & fixtures	sequencing rule	
	consumables		
	internal transport		
DISTRIBUTION	personnel	routing instructions	
	floor space	distribution method	
	storage system		
	internal/external transport		

Table 4.4 Classification of input data

The resource output relates to the physical resources and includes such things as time in various states (e.g. processing, broken down, idle), size of queues and reject work produced. Routing output data relates to the items (parts, orders, invoices etc.) that were processed and gives information such as, time in various states (e.g. being processed, waiting) and total throughput time. Process outputs are the details of 'live' items and any records of the data that were processed. For material information it includes details of such things as sales orders, works orders and purchase orders. For example a customer purchase order might include customer, part number, quantity required, price and date required. The process might be a forecast and have records of each forecast produced. Similarly, for financial information it covers details of invoices and payments. The processes might be the double entry accounting system in which there were records of the transactions. Process data for material items could include its detailed processing history and current state of the material properties. While there is generally a real world record of data for information in the processes (e.g. computer accounting system record of each transaction) the same does not apply to process of material items such as machines. If required one could record such data in a model. Using this classification the output data have been rearranged as shown in table 4.5.

Using the three broad areas, the existing tools can be compared to the inputs and outputs. Table 4.6 shows how well existing tools match the input requirements identified above. Where a cell has not been filled in it is because it is considered that the tool is not applicable. On the right-hand side of the table is a column labelled 'Best Match'. This identifies the best match for each input. If there are question marks then this identifies an input for which there is no match.

Business process simulation and shop floor simulation (or queuing models) can be seen to provide a good match to inputs for resources and the routing data across the business. The business planner provides a medium match to the detailed financial processing that is required but there are no tools identified which match the processes for the ordering system. Nor do shop floor simulators generally provide the ability to model the detail of production processes.

BUSINESS SYSTEMS	Resource Data	Routing Data	Process Data
FINANCE	personnel (e.g. time processing, etc.)	financial entity (e.g. throughput time)	details of invoices raised
	physical resource (e.g. utilisation)		details of payments received
			details of invoices received
			details of payments made
			details of wage payments
			details of capital purchases
			details of bank balance
PURCHASING	personnel (e.g. time processing, etc.)	order entity (e.g. throughput time)	details of purchase orders
	physical resource (e.g. utilisation)		details of goods received
MANUFACTURING PLANNING & CONTROL	personnel (e.g. time processing, etc.)	order entity (e.g. throughput time)	capacity plans
	physical resource (e.g. utilisation)		material requirement plans
			details of works orders sent
			details of GRN's received
			details of scrap notes received
			stock record for each item
SALES & MARKETING	personnel (e.g. time processing, etc.)	order entity (e.g. throughput time)	past forecasts
	physical resource (e.g. utilisation)		details of customer purchase orders
			details of sales orders
GOODS INWARDS	personnel (e.g. time processing, etc.)	order entity (e.g. throughput time)	details of goods received
	physical resource (e.g. utilisation)	part entity (e.g. throughput time)	details of goods in stock
FABRICATION	personnel (e.g. time processing, etc.)	order entity (e.g. throughput time)	details of components in progress
	physical resource (e.g. utilisation)	part entity (e.g. throughput time)	details of works orders
			details of scrap notes raised
ASSEMBLY	personnel (e.g. time processing, etc.)	order entity (e.g. throughput time)	details of components in progress
	physical resource (e.g. utilisation)	part entity (e.g. throughput time)	details of works orders current
			details of scrap notes raised
DISTRIBUTION	personnel (e.g. time processing, etc.)	order entity (e.g. throughput time)	details of goods in stock
	physical resource (e.g. utilisation)	part entity (e.g. throughput time)	details of goods sent

Table 4.5 Classification of output data

Interestingly, the costing tools provide a poor match to the inputs identified. While ABC has a wide range of inputs, the match is poor because the inputs are generally of the type that are normally seen as outputs, e.g. number of set-ups, number of works orders.

Table 4.7 is a similar table for the outputs. Again, business process simulators and shop floor simulations can provide a good range of basic output data relating to the resources and entities. The business planner provides a low match to the basic outputs because its outputs are generally aggregated and provide limited details of the data that generated them. Also the aggregation occurs in time, as there are generally only 12 or 13 periods recorded during a year. In terms of outputs, the costing methods do not really provide any basic output, they just provide a cost of the product or cost of activities. While they do not provide the basic output, cost tools and the business planner provide a good match to the derived financial and cost performance measures identified earlier in table 4.3 above.

		Capacity Calculation	Shop floor simulation / queuing model	Business Planner	Traditional Product Costing	ABC - Product	ABC - Process	Business Process Simulation	Best match
Financial	Resource							high	high
	Routing					low	low	high	high
	Process			medium					fair
Order	Resource							high	high
	Routing					low	low	high	high
	Process								???
Material	Resource	medium	high	low					high
	Routing	medium	high		low	low	low		high
	Process								???

Table 4.6 Comparison of analysis tools and inputs

		Capacity Calculation	Shop floor simulation /queuing model	Business Planner	Traditional Product Costing	ABC - Product	ABC - Process	Business Process Simulation	Best Match
Financial	Resource							high	high
	Routing							high	high
	Process			low					low
Order	Resource							high	high
	Routing							high	high
	Process								???
Material	Resource	low	high						high
	Routing	low	high						high
	Process								???

Table 4.7 Comparison of analysis tools and outputs

4.5 Modelling Process Comparison

A key requirement of the modelling process is its ability to handle the dynamics of the business. Of the tools considered, only simulation and queuing models have a dynamic modelling capability. The other tools are static in nature. Consequently, even if static techniques could match many of the inputs and outputs required, they would still be unsuitable in terms of their modelling process. While static techniques can give an indication of the performance of a dynamic system, they are invalid as a means of assessing its dynamic performance.

As well as dynamic capability, modelling the elements as a single integrated model is a further requirement. Therefore, modelling each particular aspect using a dynamic model is not enough, they must be able to function as a single model. The dynamic capability does not necessarily mean that all the elements are dynamic but that the elements are part of a dynamic model. For example, a business planner on its own is a static model but the financial aspects of a business planner would provide one way of modelling the financial accounting system of a business. Similarly, many of the processes that have been identified as missing (e.g. forecasting, material planning) are static calculations.

A model which contained a shop floor simulation, a MPC model and a financial accounting model in which the orders, invoices, payments, etc. were modelled, would look similar to the business model of figure 4.2 above. It would of course require models of the suppliers and customers to complete it. This model would be able to model the basic functional aspects of a business, it would include the interactions between the MPC system and the shop floor, and could provide the financial output required. Such a model could therefore be used to investigate the impact of product design decisions.

This basic model does not contain the resource constraints of the supporting departments, in the extreme it assumes that orders, etc. are processed without any resources or time. Modelling of these aspects needs a dynamic modelling ability such as provided by business process simulation. However, this type of tool treats the orders, invoices, etc. that are being processed, as entities. Also required is the inclusion of the data that are normally associated with these documents (e.g. part number, quantity, date required, price).

The above discussion gives the outline of the modelling tool required, if a multi-functional team is to be able to fully analyse the impact of design decisions on the operational and financial performance of the business.

4.6 Summary

From a comparison of the inputs, outputs and modelling processes it has been shown that existing tools do not satisfy all the requirements. While many of the tools can provide a good match to the inputs and outputs, the need to have a fully integrated model means that using each tool in isolation is not acceptable. From this, the basic structure of the required model has also been described, specifically the requirement of a dynamic modelling capability. There are a number of dynamic modelling techniques available; the suitability of these will be discussed in the next chapter.

5 COMPARISON OF DYNAMIC MODELLING TECHNIQUES

Dynamic modelling techniques can be split into two major types: analytical and simulation.

Analytical techniques are intended to solve a set of equations. The equations that describe the dynamics of a manufacturing system are not trivial but analytical techniques do exist. These techniques provide answers, such as the amount of work-in-progress in the system or the throughput time of a component.

Conway et al. (1959) noted that simulation is a widely used term, meaning different things to different people. The situation is no different today. For example, in a recent book on product design, Roozenburg & Eekels (1995, chp. 8) use the term to mean any modelling technique used to predict the properties of the design (e.g. analytical, physical models). As with Conway et al. the term will be used here in a much narrower sense using the description of Evans et al. (1967, p. 6):

> "... given a system and a model of that system, simulation is the use of the model to produce chronologically a state history of the model, which is regarded as a state history of the modeled system.".

Therefore the production of a chronological state history differentiates simulation from analytical techniques, which provide a solution. In a simulation the model is run and the performance parameters of interested recorded as the simulation progresses.

The techniques relevant to manufacturing systems analysis will now be discussed in more detail.

5.1 Analytical Techniques

The most well developed of the analytical techniques for analysis of dynamic manufacturing systems is Queuing Theory (Papadopoulos et al., 1993) and a promising technique is Petri nets (Moore & Gupta, 1995). These two techniques can determine steady state performance measures such as machine utilisation, throughput time and work-in-progress.

5.1.1 Queuing Theory

Queuing theory deals with the performance and analysis of generic queues and servers, and since many shop floor activities can be viewed in this way, it has found wide applicability. By combining a number of queue/server systems, the output of one being the input of another, a network of queues is formed which allows larger systems to be modelled.

To obtain exact solutions of queuing networks, a number of assumptions have to be made (e.g. service times are exponentially distributed, random routing of jobs); these assumptions make the solutions invalid for many real situations (Jackman & Johnson, 1993). Approximate solutions allow a relaxation in these assumptions (e.g. actual service time distributions, specified routings), albeit at some loss of accuracy; 10% is claimed (Suri et al., 1995). These improvements meant that queuing theory based models found wider applicability, but mainly for early 'rough-cut' analysis. There are still features and assumptions however which limit the use of queuing network models.

Queue buffers are assumed to be infinite but buffers are important in many production situations where blocking is likely to occur (e.g. in kanban controlled systems). Queuing networks cannot, inherently, model assembly operations. The assumptions of first-come-first-served queue control means that many scheduling or shop floor control strategies cannot be modelled. The static control logic of queuing networks also means that conditional branching is not possible (Jackman & Johnson, 1993).

5.1.2 Petri Nets

Petri nets are not constrained by many of the assumptions of queuing network models, hence they can model:

- finite buffer sizes
- control logic (e.g. sequencing and priorities)
- assembly type operations
- the sharing of common resources.

Various classes of Petri nets have been developed to enable the modelling of a wide range of domains, e.g. Stochastic Petri nets can model random events. While the modelling features have advanced, the ability to analyse them has not kept pace (Moore & Gupta, 1995).

5.1.3 Summary of Analytical Techniques

Queuing network models provide useful performance analysis but have limited application; Petri nets have potentially wide application but limited performance analysis. Notwithstanding these limitations there is a more fundamental limitation.

As was mentioned above, these tools provide an analysis of steady state performance. In principle, transient performance analysis is possible but in practice it is not, due to the intractability of the solution (Papadopoulos et al., 1993, p. 48). Therefore, for all practical purposes, these techniques are unsuitable for the analysis of transient situations. This will limit their use in the analysis of design decisions as the introduction of a new product involves a significant transient for a manufacturing company.

Queuing networks are generally used as a 'rough-cut' modelling technique but for detailed steady state and transient analysis, simulation is recommended (Jackman & Johnson, 1993 and Papadopoulos et al., 1993, p. 48). Simulation, therefore, would appear to offer the ability to model richer and more complex situations and provide a wider range of performance measures than is possible with these techniques.

5.2 Simulation

Simulation has been described above as the generation of a state history and it is this which is the key to the power of simulation. As long as operational rules for each element of the model can be described, the generation of the state history is then 'merely' a matter of executing the rules. The size and complexity of most manufacturing simulations means that this process is carried out by computer. This gives simulation the potential to model a wide range of dynamic systems.

There are two major classes of simulation which are based on opposite views of the world: continuous and discrete. In a continuous simulation state variables change continuously with respect to time while in a discrete simulation state variables change instantaneously at separate points in time. This does not necessarily mean that continuous simulation can only be used to model continuous systems and vice versa (Law & Kelton, 1991, p. 7).

5.2.1 Continuous Simulation - Systems Dynamics

There are a number of continuous simulation techniques but of relevance here is systems dynamics (originally called industrial dynamics) (Forrester, 1958). Systems dynamics was originally developed as a tool to simulate industrial feedback systems such as the production-distribution system. The system modelled is viewed in terms of flows, levels (i.e. accumulations of flows), delays to flows and control of flows. The continuous variables of the system are approximated by difference equations which are evaluated at fixed time intervals. Hence, non-linear changes in variables are approximated by small linear changes (Pidd, 1992, chp. 14 & 15).

Systems dynamics models are generally of the company in its immediate environment (i.e. the company is the system being modelled) (e.g. Kriebel, 1971; Thiel, 1996) or multi-company distribution chains (e.g. Forrester, 1958; Mohanty & Marthe, 1985). Sub-systems are generally modelled in an aggregate manner, for example Thiel (1996) modelled the fabrication of two parts in which their assembly was represented by a rate equation for each element. Also, the flows are likely to be aggregations, e.g. a number of different products represented by a single flow.

5.2.2 Discrete Event Simulation

In discrete event simulation the system is modelled in terms of entities, the states they can possess, the events which define the point in time when the entities change state and the activities which determine how entities change state (Pidd, 1992, chp. 3). Therefore a machine (an entity) might have the states of idle, running and broken down. It might be in a state 'running' when an event occurs and the activity 'break down' is initiated which changes the state to 'broken down'.

Discrete event applications in manufacturing are generally concerned with at most a few manufacturing subsystems and generally concentrated on the shop floor. Discrete event models tend to be at a detailed level, modelling individual machines, operators, control logic, etc.. Similarly, different types of components are likely to be modelled separately, in contrast to systems dynamics.

5.3 Comparison of Systems Dynamics and Discrete Event Simulation

Thiel (1996) remarks that:

> "... discrete and continuous simulation approaches can have a complementary use, allowing a hierarchical modelling of production systems, where continuous simulation can describe long-term or global phenomena, and discrete events simulation will be appropriate for representing details of the systems, short-term phenomena and rough transitions.".

This approach though has potential problems. The introduction of a new product, as has been argued, could have major effects company wide and so in principle, the model should encompass them. However, the aggregation of systems dynamics models at this level means that significant translation and aggregation of data would be required. This introduces the possibility that the translation could lead to significant effects being missed. The results of such a model will also be at an aggregate level and this leads to the problem of implementing any suggested changes at the detail level (Love, 1980, chp. 12). An idea of the problem can be gained by considering a discrete event model in which the purchased components are modelled individually because they go into the product assembly at different levels of the bill of materials. Delivery problems of the components would have different effects depending at what level they are assembled. For systems dynamics model all purchased components would be one flow. If acceptable parameters of the systems dynamics model have been determined, and it is required to produce a discrete event model, how should the delivery performance of the single flow be translated into the parameters of each material in the discrete event model? Conversely, if an acceptable discrete event model has been produced, and the wider implications are to be tested, how should the delivery performance of each component be combined into a single flow?

An integrated model, which has a kernel of a discrete event simulation model and a shell of continuous simulation might appear to be a fruitful approach. Note that this approach is not the same as combined discrete-continuous simulation systems such as SIMAN, SIMSCRIPT II.5 and SLAM. These systems are more a mixture of discrete and continuous simulation elements which allow interactions between discrete and continuous state variables (Law & Kelton, 1991, p. 112). What is required is not an interaction between discrete and continuous state variables but a mapping, i.e. the ability for a continuous state variable to be transformed into a discrete variable and vice versa. This approach has the same problem of aggregation and disaggregation of flows as mentioned above, only this time it happens during the model execution and not between the building of the models.

One way round the problem is to increase the number of flows of the systems dynamic model to match the number of individual items being modelled by the discrete event model. However, this increase in detail of the systems dynamics model takes away the advantages of aggregation which is a feature of systems dynamics.

An integrated model therefore, of discrete event and systems dynamics does not seem to be a solution. Either discrete event simulation should be expanded to cover the scope required or systems dynamics should be made to match the detail required. The viability of these two options are discussed below.

There is a basic limitation with systems dynamics which is its inability to model the discreteness of manufacturing. This is not a problem of discrete changes. Systems dynamics can approximate step changes and in any case this could be handled by using a traditional combined discrete-continuous simulation system. The problem is that discrete entities are modelled as homogeneous flows. Where the need to identify a discrete item is important, the use of system dynamics will be invalid. For example, controlling specific orders or batches is not possible with systems dynamics (Baines et al., 1994). This puts a limitation on the valid domains of systems dynamics.

Notwithstanding this limitation of validity, systems dynamics models are considered to have quicker model build and run times than discrete event models. These advantages are partially to do with the level of detail in each model but where the level of detail is the same, the differences may not be so significant. Experiments by Baines et al. (1995) showed that discrete event models require about 40% more time to build than comparable systems dynamics models; the differences in execution times were not given.

The trade off therefore, is a shorter build time and execution speed of systems dynamics against the validity of discrete event. Model build times are of the same order of magnitude and the problem of execution speed can always be overcome by 'brute force' but inherent problems of validity cannot be readily dealt with. The problem of execution speed will also become less significant as the cost of computer processing power continues to decrease over time. On this basis it is considered that discrete event simulation is the better choice for modelling dynamics.

5.4 Summary

Discrete event simulation has been argued to be the most suitable technique for modelling the dynamic aspects of a manufacturing business. The application of discrete event simulation is usually limited to a single sub-system of the business (e.g. shop floor or a business process). The need to model all the relevant areas of the business means an application of the technique not normally seen. The ability and feasibility of discrete event simulation to model the wider business is the subject of the next chapter.

6 ENTERPRISE SIMULATION

It has been argued that existing tools for the analysis of design decisions are inadequate and that a discrete event simulation is the required modelling approach. This chapter will show that it is possible for discrete event simulation to cover the scope and detail required. The modelling requirements will be shown to be provided by a simulation system, the Whole Business Simulator. Similar systems will be shown to lack all the necessary capabilities.

From here on, the term simulation will be taken to mean discrete event simulation.

6.1 Extending Simulation

Although simulation in manufacturing is mainly focused on modelling of shop floor operations it has been used in wider operational and financial applications. These will be discussed below.

6.1.1 Models of Wide Operational Scope

The modelling of the manufacturing planning and control systems using simulation is not new although published work is not extensive. In a review of six volumes (1989-1994) of the International Journal of Production Research, Boughton (1995, chp. 6), noted that of 196 articles which related to planning and control issues, 45 (23%) involved discrete event simulation. The most popular issues for the studies were scheduling rules, lot sizing policies and determining the number of kanbans. Boughton makes the point that many of the simulations did not include the higher levels of planning and control such as the Master Production Schedule (MPS). This paucity is due to the focus of the investigators and not an inherent limitation of the technique. For example Umeda (1992) describes a simulator which can model MRP, kanban or a mixture of the two.

An interesting application of simulation is a system in which a commercial MRP system was integrated with a detailed shop floor simulator (Gooden, 1988; Clarke, 1988). This system therefore is not limited to just batching policies but can include decisions about the higher level planning and control functions. The inclusion of real systems also has other significant benefits as pointed out by Love et al. (1992):

- reduces validation problems (it is the real system so it must be valid)
- eases data management problems (the data has already been loaded)
- provides a familiar user interface (the user could be in the real world)
- allows direct translation of model findings into new policies (the model and real system parameters are identical).

An extensive simulation of the business with the operational scope required, but lacking financial elements, is described by Mujtaba (1994). It included the shop floor, planning and control, sales and purchasing, and external elements (suppliers and customers). The simulation was of a single site of Hewlett-Packard but no details of its size are given. It was used to investigate delivery delays and excessive inventory but also had the aim of showing that the application of simulation at the broader level of the enterprise was feasible.

There is sufficient evidence therefore to consider that extending simulation to cover the required operational areas is feasible. It interesting to note that both Clarke (1988, p. 292) and Mujtaba (1994) suggest the inclusion of financial elements. This aspect will be covered next.

6.1.2 Including Finance in Simulation Models

Different approaches have been suggested for including cost as part of a simulation (see for example Patton-Stallman & Blank, 1984; Gogg & Mott, 1992, chp. 10). The least integrated approach is to post-process the results of the simulation using an external program (e.g. spreadsheet cost model). The most integrated approach is to implement the cost aspects as part of the simulation itself and so accumulate costs, etc. as the simulation proceeds. The systems discussed below generally use the latter approach. The integrated approach is required if decision and control aspects of the business are related to the financial state of the business, although this in not mentioned by those using an integrated approach.

A number of simulators with a costing aspect have been reported in the literature. While some use a fairly traditional cost approach (e.g. Haider & Blank, 1983; Falker & Garlid, 1986) the majority adopt an ABC approach (e.g. Christy & Kleindorfer, 1990; Hugan, 1994; Fernihough et al., 1995; McLeod & Burns, 1995). Whether traditional costing or ABC, the general principle is one of linking the cost calculation to the actual sites and activities involved (Christy & Kleindorfer, 1990). In this way, the total cost or product costs are built up as the simulation proceeds. As well as tangible costs such as material and labour, less tangible costs such as inventory carrying cost is generally included. These approaches will have the problem of costing discussed in chapter 2, e.g. valid allocation of costs to derive cost rates, resource consumption not equating to actual spending. There is also the problem of costs which cannot be directly associated with certain activities such as idle machine time, idle labour time, and unused facility space (Zuk, 1990).

A unique approach is that of Son (1993) who has proposed a new cost model he calls simulation-based manufacturing accounting (SBMA). This cost model aims to include tangible costs (e.g. material and labour) and intangible costs (e.g. flexibility) and is based on the concept of opportunity cost. Opportunity can be thought of as the benefit or cost of using a resource in an alternative way. Therefore, the opportunity cost of equipment idle time might be based on the profit that could have been made were the machine running and producing products. This approach is even further removed from the actual finances of the business than traditional costing or ABC. This will bring with it problems. The users may have difficulty because the financial picture does not match the business. Even if the user accepts it, there will be the problems of convincing management of the validity of the financial benefits.

All these approaches are not without problems and are missing the point. What is important is the impact on the finances of the business and not some notional allocation of costs or opportunity cost. If the operations of the business (e.g. shop floor, manufacturing planning and control, purchasing, sales) are being modelled to the detail argued, then there will be operational transactions for the sale of goods (i.e. sales orders) and for the purchase of raw materials and components (i.e. purchase orders). If the corresponding financial transactions are also modelled (e.g. invoices and payments) then this will provide a valid

Financial element	Traditional	Proposed
Labour costs	labour rate and processing hours	wages paid to each person employed
Raw material and component costs	material cost rate and the consumption of material	material delivered against purchase orders, the supplier will send an invoice and after a delay the corresponding payment will be sent to the supplier
Revenues	price of the product and the production rate	products delivered against customer purchase orders, customer invoiced then customer payment after a delay
Machine costs	cost rate based on amortised cost of machine and processing time	machine is purchased with a loan, periodic payments to the bank

Table 6.1 Examples of traditional and proposed financial modelling

financial basis. The difference in the approaches discussed above and what is proposed here, can be seen in the examples given in table 6.1.

Modelling in this way matches the actual financial transactions of the business. These transactions, with their respective delays, provide a valid model of the cash flow of the business. They are also the financial transactions required for input into a model of the financial accounts. In this way, the financial impact of design decisions can be seen, without the distortions or inconsistencies of cost models. The case for avoiding distortions of cost models is made by O'Loughlin et al. (1990) but they do not suggest modelling of the financial transactions in the way described here.

The global nature of the financial accounts and the way they might be organised may mean that they are not suitable as a source of suggestions for improvement in a particular situation. For this reason, a cost model might be constructed. A cost model in this case is different from those discussed above in that the purpose of the cost model is one of investigation and suggestion, and not as a measure of the overall financial impact. The impact of decisions based on the cost model would be assessed by looking at the cash flow and financial accounts. If the decision did not deliver the improvement expected then the logic of the decision and the cost model would need to be assessed.

Therefore, the implementation of valid financial modelling proposed here should be no more complex than existing approaches, should avoid their problems and should be feasible to implement.

6.2 The Whole Business Simulator

A simulation system, the Whole Business Simulator (WBS), has been proposed which has the required operational and financial modelling (Love et al., 1992). The system includes the following elements:

- the shop floor operations (goods-inwards, fabrication, assembly, distribution
- the manufacturing planning and control function
- purchasing
- sales
- accounts.

As well as elements internal to the business, the external elements of customers and suppliers are also required to provide a valid evaluation of business performance.

Together these would form the basis of a core model as shown in figure 6.1. For simplicity, the sales and purchasing functions are assumed to be part of the manufacturing planning and control function, and goods inwards and distribution are assumed to be part of the shop floor operations.

6.2.1 Operation of the Whole Business Simulator

The operation of the simulation is similar to the flow model described in chapter 4. Purchase orders from the customer model trigger sales orders to be raised in the material requirements planning (MRP) system. Based on the actual and forecast demand the master production schedule (MPS) is updated and forms part of the MRP calculation. The suggested works and purchase orders are passed to the factory simulator and supplier model respectively. Local planning or scheduling rules would be applied in the factory module that simulates production, goods-inward and distribution activities. Stock movements are posted to the MRP system, as are completed works orders, shipments to

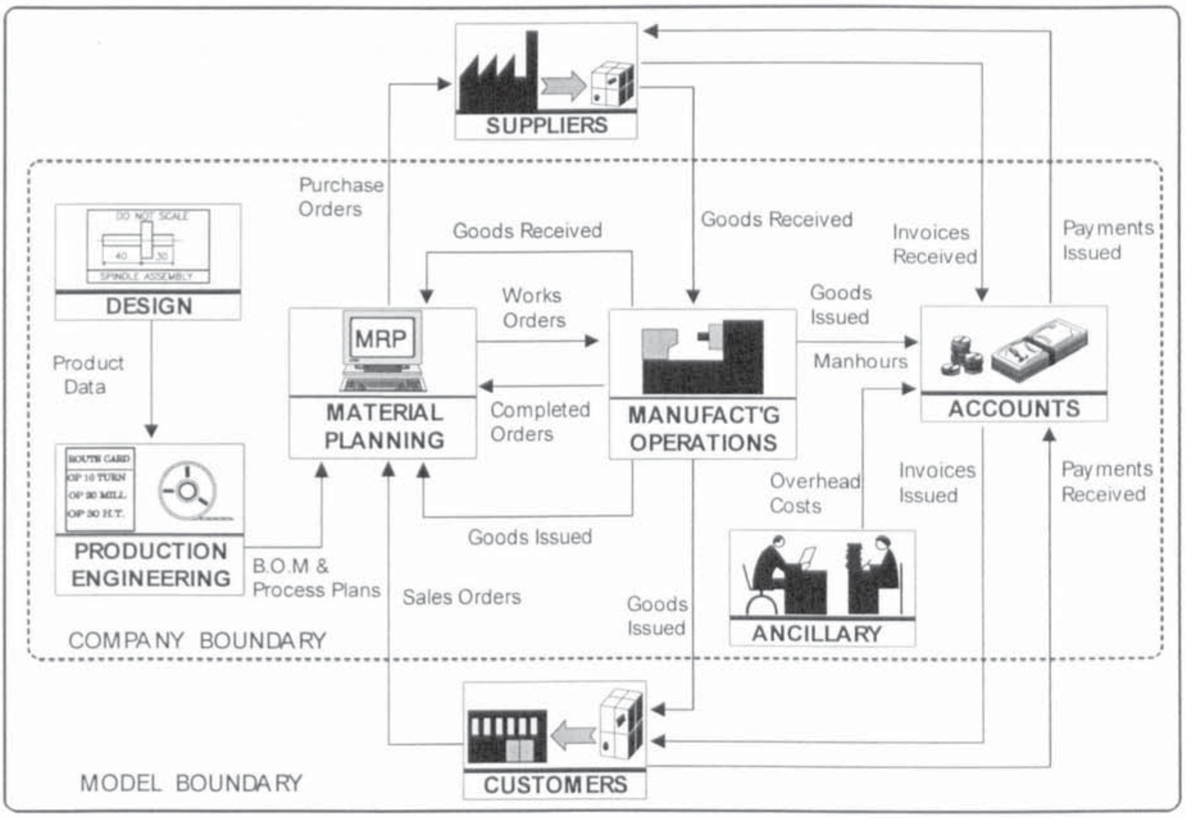


Figure 6.1 Core elements and transaction of the Whole Business Simulator

customers and deliveries from suppliers. Standard accounting transactions are generated from events that occurred in the operational elements of the simulation. For example, sales orders and deliveries lead to invoices being issued to the company's 'customers'. After a suitable delay the invoices will be paid and the ledgers in the accounting system updated. A similar technique deals with purchased items. Wages are paid to the people reported as 'employed' by the factory simulator, with due adjustment for absenteeism and overtime working. Not every activity would necessarily be modelled to the extent that the financial transaction could be driven from them. In these cases the appropriate financial transaction could be generated from simple models. For example, higher business administration activities would probably be handled this way.

6.2.2 Generation of Reports and Performance Measures

The model described above could generate a variety of reports and performance measures to suit the particular interest of the user. The financial accounting system, having recorded the time phased financial transactions could be used to view the cash flow of the business over the period of the simulation run. It could also be instructed to produce a set of accounts, i.e. profit & loss and balance sheet, at the end of each accounting period. More detailed information (e.g. individual nominal accounts such as wages) could also be generated to investigate specific areas of interest. A similar procedure would apply to operational measures. If delivery performance was of concern, the MRP could produce reports of orders delivered late. The reasons for poor performance could then be investigated, for example by looking at the shop floor model to see if there was a capacity problem. In this way it can be seen how members of a multi-functional team could be provided with reports and performance measures that they would normally use. They could readily confirm that their actions had had the desired effect or investigate any problems that may have occurred.

6.2.3 Links to Engineering Functions

While not essential for modelling the impact on the business, automated links to the design and production engineering functions and their systems offer some interesting possibilities. This ability would allow translation of the design into manufacturing data that define the product which could then be input into the core model. To do this requires links to a number of systems, e.g. Computer Aided Design (CAD), the Numerical Control (NC) programming aspects of Computer Aided Manufacture (CAM) and Computer Aided Process Planning (CAPP). With an automated process it could be imagined that the CAD system would pass the product specification to the CAPP and CAM systems which would automatically generate all the manufacturing data and instructions. These would then be passed to the MRP system as bills of materials (BOM) and process plans. Manufacturing data would also be passed to the shop floor, sales and purchasing simulation systems. Even in such an automated process it is likely that manual intervention might be required to revise any operational policies (manning, batching policies, etc.) that are deemed necessary.

6.3 Enterprise Modelling and Enterprise Simulation

There is a major area of research that comes under the heading of enterprise integration modelling (Petrie, 1992) or enterprise modelling and integration (Vernadat, 1996). Enterprise modelling has the broad aims of a better understanding of the business, supporting the design of new parts of the business, and modelling to control and monitor the business. Enterprise integration has the aims of enabling communications amongst functional entities, coordination of functional entities and interoperability of information technology (Vernadat, 1996, p. 20).

A wide range of tools come under the enterprise modelling umbrella. These tools are focused on modelling the functional, information, decisions and dynamic aspects of business. Models for the dynamic aspects of a business would seem, in principle, applicable to the task here. The dynamic models are generally graphical descriptions of the dynamic aspects of the business in the same way that IDEF0 is a graphical description of the functional aspects. For example IDEF2 (Bravoco & Yadav, 1985) can be analysed using simulation but Vernadat (1996, p. 136) states that it has now been abandoned. Other graphical modelling tools can be analysed using Petri nets (e.g. CIMOSA, Vernadat, 1996, p. 169), but the limitations of this technique have already been discussed in chapter 5. Therefore the dynamic models of enterprise modelling are limited.

The simulation model of Mujtaba (1994) was described above, but an earlier report (Mujtaba, 1992) differentiates between the terms enterprise model and enterprise simulator. The former is used to represent the static aspects of the enterprise (structural and functional definitions) whilst the latter describes the simulator that generates the dynamic behaviour. This would seem an appropriate differentiation, given the focus of the tools which are generally used for enterprise modelling. The whole business simulator would then be classed as an enterprise simulation. Using this definition, there are some examples of enterprise simulations that appear to have been built for a similar purpose to WBS. Early work on an enterprise simulation (although it was not called that then) is that of Comly et al. (1982) which was aimed at factory automation rather than the analysis of product design decisions. It is interesting in that Comly et al. advocated providing financial output in the form of standard financial reports which match those that are normally reported by the plant. The system does not appear to have been developed further as a search of the literature has found no further references to it.

Chan et al. (1993) describe an Enterprise Modelling System being developed by the National Research Council of Canada and a consortium of companies. The objective of this system is said by them to provide:

> " ... a comprehensive set of tools for the creation of structural and process models of the business as well as production operations within an enterprise, with capabilities specifically aimed at continuous process improvement and evaluating decision-making alternatives.".

Elements of the model have been built using object oriented technology and implemented in Smalltalk as a self-contained system. The scope of the system appears comparable with that of WBS, but the functionality as described could not support typical product design decisions. The impact on the enterprise can be judged using a variety of local or global measures but the financial measures are based upon the use of a conventional cost model rather than a simulation of the finances of the enterprise.

6.4 Summary

The Whole Business Simulator has been presented as a tool that has the required capabilities for the analysis of design decisions. If the arguments for this tool are valid then it should have advantages over the existing tools that have been described. An experiment to test these claims is the subject of the next chapter.

7 EXPERIMENTAL RATIONALE

7.1 Initial Considerations

It has been argued that enterprise simulation as described in the previous chapter ought to support a multi-functional team in analysing the impact of design decisions. It has also been argued that current tools are inadequate and that enterprise simulation should provide a better analysis. There is a major problem in testing such claims at present, as the prototype of the Whole Business Simulator has not yet been completed, even in a limited form. This fact highlights a basic point, that the building and use of such models has not been investigated even in a laboratory setting.

A laboratory setting would allow the relaxation or omission of many of the aspects required of a system for industrial use (e.g. completeness, ease of use, robustness, speed). It was therefore considered that a laboratory based version of the Whole Business Simulator could be built and used to investigate the benefits of enterprise simulation in advance of the prototype system. This laboratory system became known as the 'WBS demonstrator' or demonstrator, for short.

Since this is the initial work in this area, the work was aimed at the functional aspects of the tool, i.e. can it be done and does it deliver? As such it was not intended to answer other important questions such as, is it practicable and practical in industry, at what stages in the design process is it applicable and what methodology is required for its use?

It was decided for a number of reasons that two alternative designs should be analysed rather than just one. Having two designs parallels in a simple way what a team would do in comparing a number of possible designs. Analysis tools are used in deciding between alternatives as well as predicting their absolute performance. Therefore, as well as looking at the absolute results, having two designs allows a comparison based on how the tools ranked the designs i.e. do the tools always favour the same design or are there differences? The basis of the experiment is therefore:

- produce two solutions to satisfy a design requirement
- analyse each design using a number of existing tools
- analyse each design using enterprise simulation.

Besides the improved validity of the analysis, the arguments for enterprise simulation have focused on the capacity to input the decisions of a multi-functional team to bring about the successful implementation of a product design. Part of this ability requires the output of accepted performance measures. It has also been argued that a good analysis tool needs to provide local feedback rather than just being a 'black box' if it is to assist in discovering why a particular set of decisions has produced the results it has. Therefore when comparing analysis tools, criteria will include not only the accuracy and validity of the answer, but also the ability to input decisions to achieve a successful implementation and the degree of feedback provided when bringing about any improvements.

With this view of analysis, a measure of successful implementation of the product design is required if the tools are to be compared. To keep the experiment simple it was decided to use a single measure of success, delivery performance was chosen as it is considered to be an important business target (Hill, 1993, chp. 3; New & Meyers, 1986, p. 26).

To test the ability of the analysis tools to assess the robustness of the solutions, two levels of demand (normal and high) will be used.

The experiment must be discriminating enough to give confidence in the results. This requirement affects the features of the demonstrator system and the scope and detail of the case (i.e. the context of the experiment). The two are interrelated. An important aspect of the proposed tool is that it will allow decisions in different functional areas to be implemented. Without the experiment it is difficult to decide what range of actions might be needed to implement the two designs. This implies that the demonstrator system will have to be reasonably comprehensive and detailed to cover a wide range of possible actions (as it would in reality). It might also be expected that it is in the range and detail of implementation where differences between the demonstrator and existing tools would be seen. This range and detail of the demonstrator implies a case which is of limited size if it is not to become too burdensome. A case study (known as Mandrill) was available, part of which could form the basis of a suitable experiment.

7.2 Context of the Experiment - The Mandrill Model

The Mandrill model is an expanded and extended version of a systems dynamics model called Alterfax (Parker & Mackness, 1986). Alterfax was designed for the training of foremen and potential production managers to give them a deeper understanding of the complexities of running a factory. It is based on a real alternator factory and includes sufficient complexity and richness to be typical of a real factory, but not so much as to overwhelm the trainee. While the product range only includes four types of alternators, the model includes enough detail to allow the trainee to make decisions about manning, machine maintenance programmes, inventories, materials provision, quality levels, scheduling, machines capacities, etc.. Feedback of decisions made are provided by operational and financial reports that the model produces. The model is not run by the trainee directly, but the trainee's decisions are implemented in the model by the trainer.

The Mandrill model has as its case study the production of four types of electric hand drill of increasing power output. The smallest is based on the Black & Decker model H501 which has a single speed and hammer action. The other 3 sizes are assumed to be scaled up versions of this. The electric motor of the drill replaces the alternator of the Alterfax model, extra machines have been added for the manufacture of gears, spindle, housings, etc. that comprise the drill, and additional assembly lines have also been included. In addition, the reporting facilities of the Mandrill model have been extended to include full financial accounting reports (e.g. balance sheet and profit & loss). The scale of the Mandrill model can be appreciated from the following statistics:

- over 300 direct personnel
- over 100 machines
- 3 assembly lines
- £30 million turnover.

The author has been involved in the use of this model for training and is aware that even with the relatively narrow product range, experienced operations management personnel do not find it a trivial situation to manage.

While only the bottleneck machines are modelled, the data available to the trainee cover virtually all the details that one might expect to find in a real factory. For example manning, machine types, process routings, processing times, set-up times, transfer quantities, etc. are available. The data are realistic and are derived from a factory about 10 years ago. The machines, processes and cost data reflect that era but this does not invalidate its use here.

A major part of the Mandrill model (spindle manufacture and assembly) satisfies the requirements for the experiment. It provides many aspects which are representative of manufacturing and products in general, while being of a suitable size. A schematic of the spindle manufacture and assembly area is shown in figure 7.1. The figure shows the material flow and work centres. Drawings of the gear, spindle and spindle assembly with a product structure are shown in figures 7.2, 7.3, 7.4 and 7.5 respectively. The basic operations are given in figure 7.6.

There are four sizes of spindle assemblies, designated A, B, C & D in order of increasing size. Each spindle and gear is unique and each is made from a unique raw material, so there are 24 unique items.

Although relatively simple the product includes raw materials, component manufacture and final assembly, and so covers the major features of more complex products. The component manufacture involves multi-machine processes which is also representative of actual components.

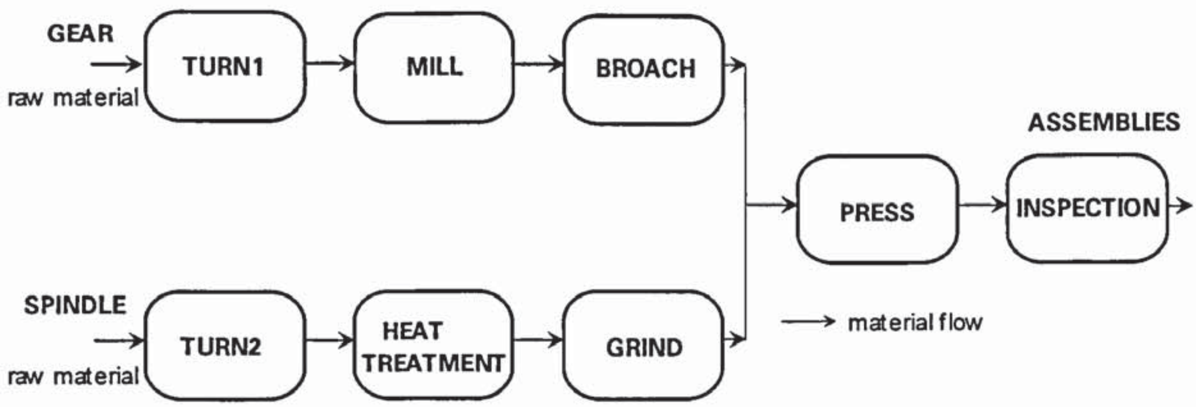
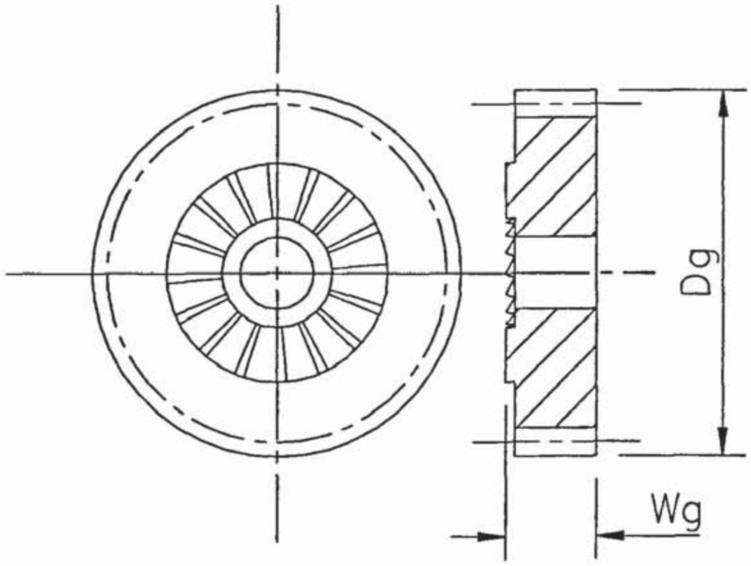
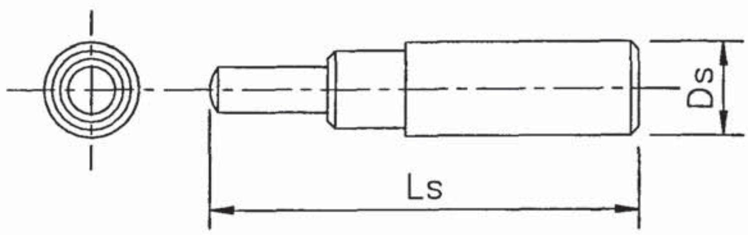


Figure 7.1 Material flow and work centres of spindle assembly area



	Width Wg (mm)	Diameter Dg (mm)
GEAR_A	10	40
GEAR_B	11	45
GEAR_C	13	50
GEAR_D	14	55

Figure 7.2 Drawing of gear



	Length Ls (mm)	Diameter Ds (mm)
SPINDLE_A	65	12
SPINDLE_B	66	14
SPINDLE_C	68	16
SPINDLE_D	69	18

Figure 7.3 Drawing of spindle

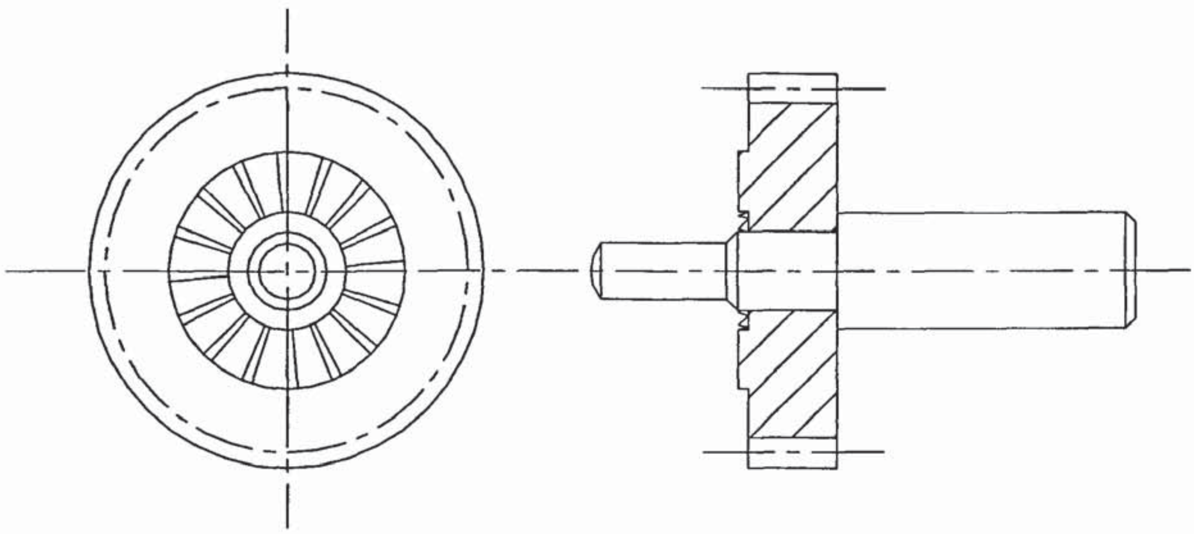


Figure 7.4 Drawing of spindle assembly

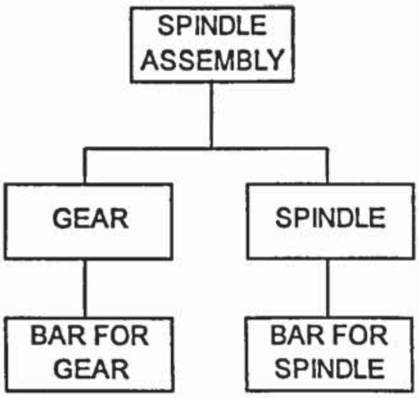


Figure 7.5 Product structure of spindle assembly

Gear	
OP No.	Operation
10	Turn outside diameter and drill and ream bore
20	Mill hammer action teeth
30	Broach gear teeth

Spindle	
OP No.	Operation
10	Turn outside diameter
20	Heat treat surface
30	Grind bearing diameters and interference diameter

Assembly & Inspection	
OP No.	Operation
10	Press gear onto spindle
20	Inspect

Figure 7.6 Basic processing operations of gear, spindle and spindle assembly

An alternative to this spindle assembly was designed and utilises a tolerance ring which is a corrugated cylindrical strip of metal (figure 7.7.) It has a number of uses, one of which is in areas where there is an interference fit. The corrugations act like a series of small springs which are designed to have a force-deflection curve which is much flatter than the mating parts themselves. The tolerance ring is placed between the two mating parts and allows a narrow range of interference force to be achieved using relatively wide tolerances (figure 7.8). To achieve the same narrow range of forces using a standard interference fit would require much tighter tolerances.

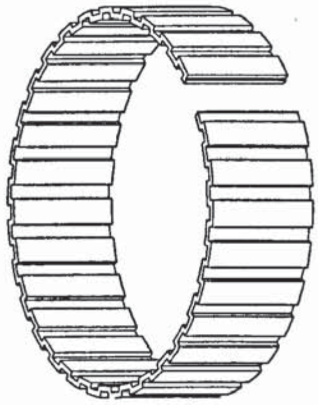


Figure 7.7 Drawing of tolerance ring

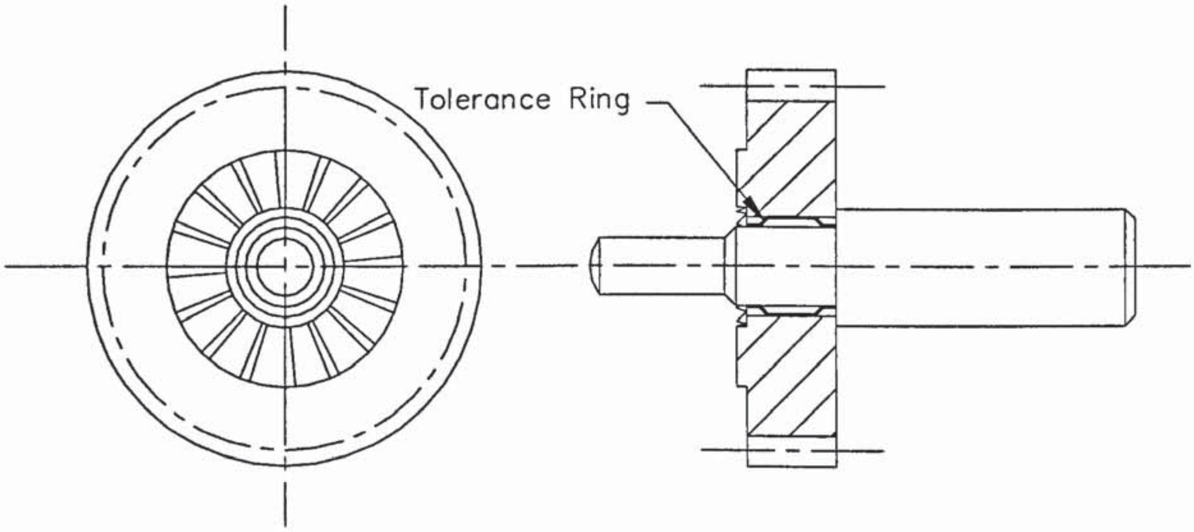


Figure 7.8 Drawing of spindle assembly with tolerance ring

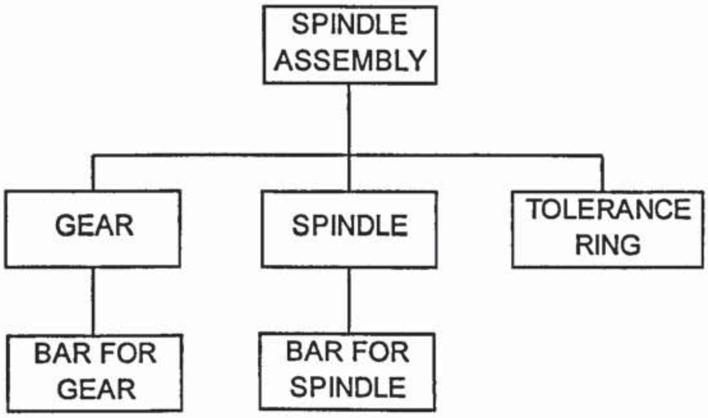


Figure 7.9 Product structure of spindle assembly with tolerance ring

The use of a tolerance ring has a number of implications. An additional component will require provisioning. This changes the product structure (figure 7.9) so that a component now enters at the assembly stage. The wider tolerances that the tolerance ring allows will reduce the amount of grinding required for the spindle and eliminate the need to ream the bore of the gear. The tolerance ring will increase the assembly time and affect the scrap rates. The elimination of the reaming operation, the reduced grinding and the lower press force are assumed to reduce the scrap rates at these operations. Therefore, this relatively simple alternative will affect purchasing, component manufacturing, assembly, and manufacturing planning and control. To differentiate the two designs, the standard interference fit design will be called the 2-piece design (spindle and gear), while the new design will be called the 3-piece design (spindle, gear and tolerance ring).

7.3 Scope and Detail of the Demonstrator

The demonstrator system needs to cover the minimum functional areas discussed in section 6.2 and shown in figure 6.1 namely:

- shop floor (goods-inward, fabrication, assembly and finished goods store)
- material planning and control (including forecasting, MPS, batching etc.)
- accounting (recording of transaction as well as financial reporting)
- external elements i.e. suppliers and customers

The effort required to model a range of manufacturing planning and control systems would be considerable, therefore the decision was taken that the type of planning and control in the demonstrator would be fixed, but that within the system, detail decisions must be catered for. This is obviously a constraint on the decisions that can be taken but it was considered necessary, to make the development of the demonstrator possible. For the case being used, material requirements planning was considered a suitable system because it is a common system used in batch manufacturing and is applicable to the products used in the case study (Vollmann et al., 1988, chp. 1).

For the experiment, it was decided that customers and suppliers need not be at the same level of detail as the business itself. The customer demand could be created from an order stream generator and suppliers could be represented as a delay in deliveries by sampling from a distribution.

Modelling the major functional areas identified above must, as a minimum, include the mechanics of the processes that these areas carry out and allow changing of policies. For example, in the factory this could be machining of a component, in the materials planning and control function such a process might be an MRP calculation, while in the accounting function it might be entering a payment in the nominal ledger. Without these processes the model would be invalid. Manning issues can be an important factor in the operation of the shop floor. The design of the product will be a major factor in the design of the shop floor and this might carry through to manning issues. For example one product design might require more machines than another, but the extra machines might also lead to the need for extra personnel to do set-ups and carry out maintenance. If the people are not modelled, then the increase in costs or the reduction in performance of the shop floor will be missed. The modelling of direct and indirect shop floor personnel will therefore be included in the shop floor model. While the same argument can be applied to the support functions it was not considered necessary for this experiment to include them. Although not all personnel in the business will be modelled to a detailed level, the costs of all people will be included.

7.4 Range of Existing Tools to be Used

From the discussion in chapter 2 and chapter 6 the following tools were identified:

- design for 'X' (DFX)
- integrated CAD
- capacity calculation
- shop floor simulator
- process modellers
- cost models (traditional & ABC)
- business planner
- shop floor simulator + cost model.

DFX tools and CAD based tools are aimed for use by the designer and not functional personnel. They were included, since it will be a useful comparison to the downstream tools.

The majority of DFX tools (e.g. DFA, DFM) and the integrated CAD tools assess the impact on the business generally through estimations of process times. Therefore, rather than use a range of tools to cover the possible production processes used, the following logic was applied. As the actual processing times to be used in the shop floor simulator and the demonstrator will be known (and be the same), these can be used as though they were the output of an imaginary tool. This removes any problem of being unfair as any real evaluation tool will of course never be better than this. These 'perfect' times can then be used as the basis of a cost calculation similar to that used by these type of tools. In this way DFM, DFA and integrated CAD tools can be included.

The use of capacity calculations is included as it is a typical calculation that manufacturing engineers perform to determine the resources required (number of machines, manning, tooling, etc.).

Although not used universally (Simulation Study Group, 1991), shop floor simulation will be included for the following reasons. The demonstrator is a simulation based tool and therefore comparing it only with static tools could rightly be seen as biased. It has been claimed that more than just the shop floor should be simulated, therefore by including shop floor simulation this claim can be tested. As was mentioned above, the processing times in the shop floor simulator will be identical to those in the demonstrator.

Cost models have in effect been included as part of the design costing described above and so will not be included as a separate analysis.

A number of different financial models driven by shop floor simulations have been described in chapter 6, e.g. standard costing and ABC. Although ABC is been advocated by many, the decision not to include detailed modelling of the majority of support personnel does not allow a comparison to be made. Because the demonstrator uses financial accounting, it is more appropriate to compare it to a business planner. Therefore a business planner driven by a shop floor simulator will be included.

As mentioned earlier, modelling of support personnel is not part of the experimental model therefore process modelling tools will not be included in the comparison.

The analysis tools to be used in the experiment are therefore:

- design costing
- capacity calculation
- shop floor simulator
- business planner driven by shop floor simulator.

The basic scope of the intended demonstrator system and the existing tools to be used for the comparison have now been defined. The details of the demonstrator, its construction and features, along with the details of the other tools for comparison are discussed in the next chapter.

7.5 Details of the Case Data

All the details of the case data considered necessary to appreciate the experiments are described here. Other details are given in appendix 1.

7.5.1 Target Delivery Performance

Although 100% deliveries on time is an aim for some (Parnaby, 1986) this is not the reality for many. In a survey by New & Meyers, 1986 (table 3.6) the performance of most of the businesses was much worse, with only 46% of them meeting between 76% to 100% of orders on time. While 100% deliveries on time could be used as target, to achieve this might involve many adjustments and iterations to the model. Therefore the target delivery performance was set at an average 95% of deliveries on time.

7.5.2 Customer Demand Pattern

Weekly demand for the four spindle assemblies is shown in table 7.1, with the high demand being 5% greater than the normal demand. Average levels are generally based on the Mandrill case and range from low (spindle assemble A) to high (spindle assembly C). The demand pattern in the Mandrill case is fairly complex, with each product having out of

Spindle Assembly	Weekly Demand	
	Normal	High
A	2040	2142
B	9960	10458
C	9000	9450
D	8520	8946

Table 7.1 Average weekly product demand levels at normal and high demand

phase periodic cycles and randomness. The demand was simplified for the experiment to a level demand but with random variations of +/- 20% so that it includes a reasonable amount of variability.

7.5.3 Batching and Safety Stock Levels

The batching policy is to have batch sizes which are equal to the average weekly demand for each type of component. For raw materials and purchase parts the reorder quantity was set to what were considered to be the minimum purchase quantities. For the raw material this was a 3 metre bar of material and for the tolerance ring this was a box of 500 items.

Safety stock levels for finished goods and components are zero as it is expected that the batching in the MRP system would cover any differences between customer demand and forecast demand; it will also account for the small amount of scrap that will occur. For raw materials and purchase parts a safety stock level was set based on conventional stock control calculations to cover variability in delivery and demand (appendix 1, section A1.2.3).

7.5.4 Financial Aspects

The profits of a business are likely to be put to use, either earning interest or being reinvested in the business. For the experiment interest is to be paid on cash balances. Overdrafts will also attract interest but at a higher rate.

The Mandrill model does not have selling prices for spindle assemblies. The prices were set so that the retained profits would give a reasonable return to the share holders funds. The same prices were also used at high demand.

7.6 Experimental Procedure for Simulation Based Tools

A number of factors need to be considered to have confidence in the results of a simulation based experiment: number of replications or batches, starting conditions, and run-in period. These are discussed below.

7.6.1 Replications and Batching

The output of a stochastic simulation are random variables which give an estimate of the actual performance of the model under investigation. Statistical analysis of the output is required to assess the confidence that can be placed on the results. Law & Kelton (1991, p. 284) consider that all simulation outputs are correlated, i.e. within each simulation run, a given output is affected by other variables. By definition correlated output are not independent, therefore, statistical techniques which are based on the assumption of independent and identically distributed data are not strictly applicable. Two approaches to deal with the problem are replication and batching (Law & Kelton, 1991, chp. 9 and Pidd, 1992, chp. 13)

Replication involves repeating the simulation with the same starting conditions but with different random number streams. Although the outputs of a given replication are correlated, outputs across replications are not. Replication therefore increases confidence in the output, both by increasing the quantity of data and by allowing simpler statistical techniques to be applied.

Having one long run also increases confidence in the results but the outputs are still correlated. Splitting the run into a number of batches reduces the effect of correlation between batches; with a large batch size the outputs of each batch can be treated, for practical purposes, as independent (Law & Kelton, 1991, p. 554). Large batches are therefore equivalent to replications and a small number of large batches is considered better than a large number of small batches (Conway, 1963).

In both approaches the initial period of the simulation (i.e. run-in period) should be deleted to reduce the effect of the initial conditions biasing the results. With replication there is the disadvantage that time is wasted with each replication, while batching carries a risk of correlation.

For the shop floor simulation, batching is easier to apply and so will be used. For the demonstrator, replication is the most appropriate method because of the effect of depreciation. Depreciation reduces the assets of the business over time and this will affect some measures of financial performance, e.g. profitability. Therefore measures of performance will be changing purely due to the passage of time and will not be stationary. Non-stationarity is an assumption of classical statistical analysis, i.e. the distribution that the data are being sampled from does not change over time. As long as the calendar time periods from which the measures are taken are the same across both alternatives, then each will be affected in a similar way. Therefore, for the purposes of the experiment it was considered acceptable to ignore this assumption as long as the measures were from corresponding calendar periods. Batching, compared with replications, would involve a much longer period over which the effect would act, therefore replications will be used.

Further confidence in the results can be achieved by applying variance-reduction techniques which attempt to improve the efficiency of the simulation by achieving a higher confidence with a given set of data or conversely a given level of confidence with less data. A simple method which will be applied here is common random numbers (Law & Kelton, 1991, chp. 11). The use of common random numbers destroys the independence of the simulation output therefore to analyse results the paired t-test will be used as it does not require the output to be independent (Law & Kelton, 1991, p. 587).

The number of replications (or batches) required depends upon the confidence required. For this experiment, differences which are of practical rather than just statistical significance are of interest. This will therefore tend to reduce the number of replications required because minor differences will not be of interest. As a rule of thumb, it is recommended that a minimum of three to five replications are carried out (Robinson, 1994, p. 163). Therefore, as a starting point, five replications will be used and if found to be insufficient the number will be increased.

A run length of 52 weeks (one year) was chosen as acceptable for the demonstrator. This length matches the financial accounting year used and is long enough to ensure that the most infrequent events, in this case machine breakdowns, have occurred a reasonable number of times. Robinson (1994, p. 165) recommends at least 10 to 20 occurrences but the grinding machines have about 7 breakdowns per year (all the other machines have more than 10 per year). This is considered acceptable as it is the effect on capacity at the work centre which is important. At the work centre there will be on average about 29 breakdowns per year for the 2-piece design and 21 breakdowns per year for the 3-piece design (this is based on the shop floor designs to be discussed in chapter 9). For the shop floor simulation it was decided to have 5 batches of 50 weeks each. The use of 50 weeks instead of 52 weeks was purely a matter of convenience for operation of the simulator and collection and processing of results.

The same number of replications and batches has been set so that the paired t-test can be used for the analysis of results between the shop floor simulator and the demonstrator without wasting simulation output.

7.6.2 Starting Conditions

Starting conditions can bias the results. For a terminating simulation typical starting conditions must be chosen but for a non-terminating simulation, such as this, there also exists the option of using a simple but untypical starting condition (usually empty and idle) and a run-in period to eliminate the transient. The end of the run-in period is in effect a typical steady-state condition. Even where typical starting conditions are chosen this does not necessarily eliminate the need to have a run-in period but it should shorten it compared with empty and idle. The former approach has the advantage of simplicity whereas the latter has the advantage of saving simulation time (Pidd, 1992, pp. 222-224).

Where two or more systems are being compared there is also the problem that the starting conditions will favour one or other of the systems. With regard to this problem Conway (1963) points out that the investigator has at least three choices with respect to the starting conditions:

- each empty and idle
- each with a common starting condition that is a compromise between them all
- each with its own reasonable starting conditions.

Conway recommends avoiding the third option because of the inherent bias it might introduce. He favours the second option because although constructing a good compromise starting condition is not a trivial task he considers that almost nothing could be worse than empty and idle and so any effort will allow some reduction in computing time.

Whether using empty and idle, or typical starting conditions, there is no guarantee that either will lead to a steady-state condition (if it exists). The main reason for avoiding empty and idle is therefore to shorten the computing time, but where powerful computing is relatively cheap this becomes much less of a concern and may lead to situations where the time involved in setting up typical starting conditions could outweigh the gains.

In the case of the shop floor simulator there is the facility to set WIP and so start with a more typical condition but because of the relatively short time for the simulation to stabilise it was not considered advantageous. For the demonstrator there is a problem of setting starting conditions and so the only choice is to start empty and idle, and use a run-in period.

While the starting condition of the demonstrator simulation is to be empty of orders and all machines idle, it does not mean that there will be no stock in the system. If the system was totally empty, it could lead to the problem of back orders, unless the MRP system was fed by an MPS before the demand starts. This would build up stock in advance of the actual demand. It is simpler to have starting stock (raw materials, components and finished goods) and allow the MRP system to issue orders as the stocks fall to the reorder level. The same amount of stock was set for the 2-piece and 3-piece design.

As mentioned above, the financial performance is dependent upon the elapsed time but it is also dependent upon the starting conditions. For example, financial ratios which relate profit to capital (e.g. return on assets, return on investment) will be affected by the amount of capital required. If there is unnecessary capital in one alternative compared with the other then this would lead to bias. The capital required will be affected by the requirements for the building, machines, stocks and money at the bank. The building and machines will be derived from the factory designs and so any differences in requirements will be a reflection of actual differences in design. As the simulations are being started with stocks then there needs to be some recognition that money would have been spent to generate them. It was therefore decided to use the stock valuation as a proxy for the money required. Although the amount of starting stock is the same in each case, the differences in overhead rates and standard time means that the stock valuations will be different in each case. The configuration of a particular business will also affect the amount of money required at the bank to cover working capital. Estimating what is a valid amount is not easy. A simpler option is to give each alternative a nominal amount of money in the bank and let the businesses go overdrawn for a temporary period. The interest payments during this transient period are then a reflection of the amount of money that might have been required.

7.6.3 Run-in Period

Although algorithms do exist for certain situations the simplest, generally accepted method of determining the run-in period is a graphical method developed by Welch (Law & Kelton, 1991, p. 545). This involves plotting the moving average of the output variable of interest and using judgement to decide when it has levelled out. The number of data points covered by the moving average is defined by 2.w + 1, where w is known as the window. The size of the window is chosen, using trial and error, so that high frequency oscillations are eliminated but lower frequency ones are not.

The level of WIP is a good measure of the stability of the factory and so this was plotted. For the shop floor simulation, the moving average was based on a single run and a window of 10 was found to be suitable. Figure 7.10 and 7.11 show typical plots for the 2-piece and 3-piece design respectively and shows that beyond about 16 weeks the WIP has levelled out. For the demonstrator, the moving average was based on the average of 5 replications and a window of 20 was found to be suitable. Typical plots are shown in figures 7.12 and 7.13 for the two designs. It is considered that at least 20 to 30 weeks are required before the WIP has levelled out.

Pidd (1992, p. 223) recommends determining a run-in length for each replication rather than determining one length in advance and using it for all the replications. The latter

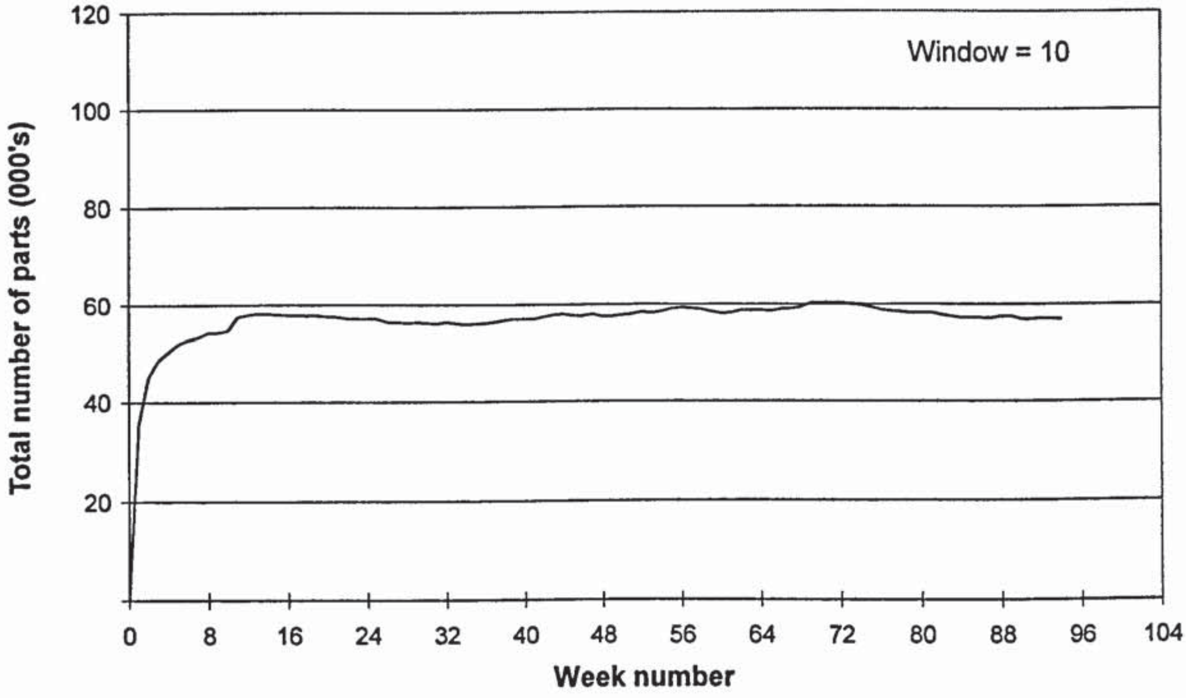


Figure 7.10 Shop floor simulator WIP moving average for 2-piece design (w=10)

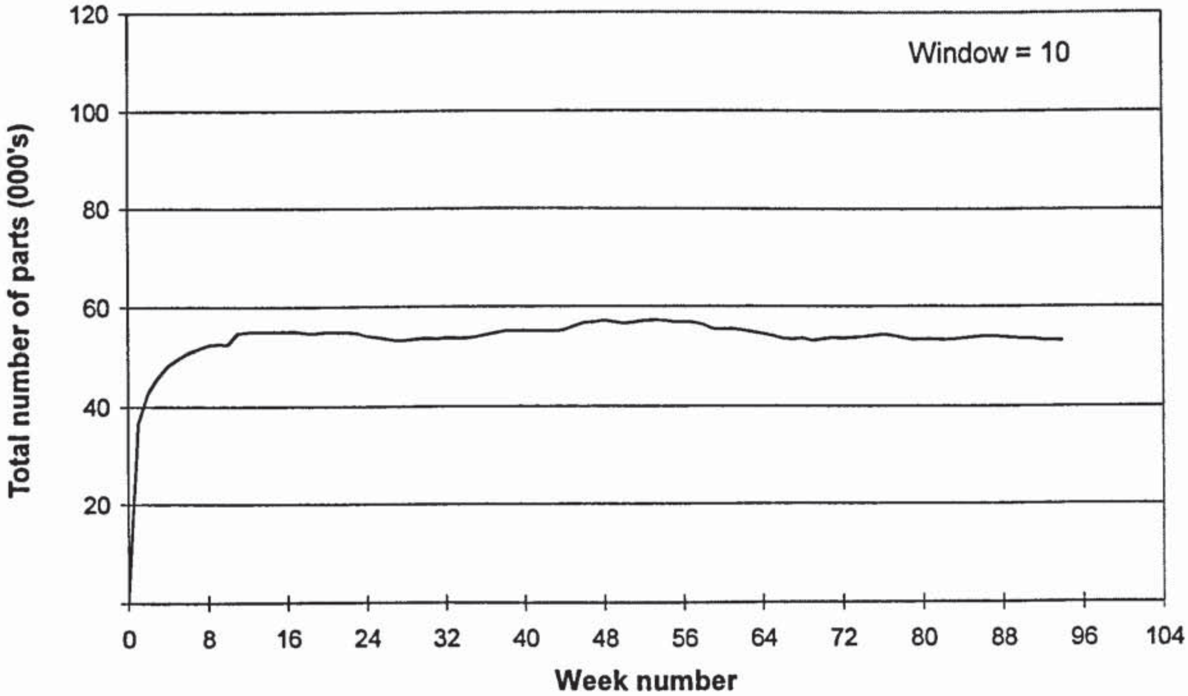


Figure 7.11 Shop floor simulator WIP moving average for 3-piece design (w=10)

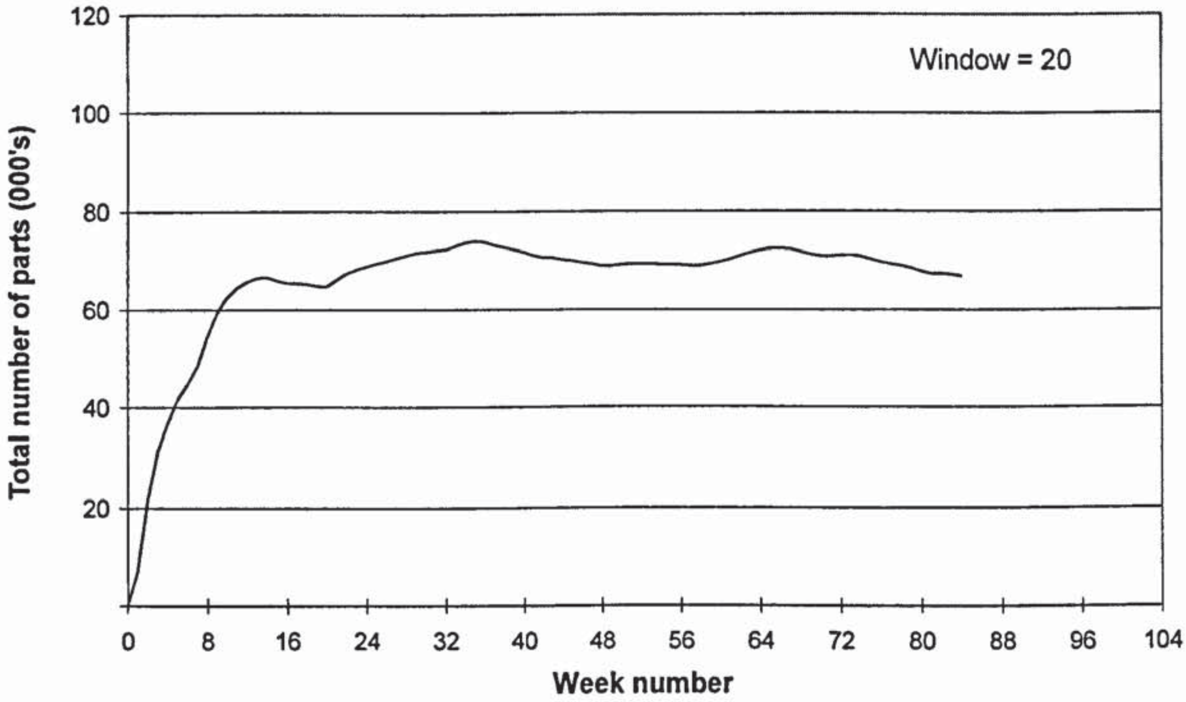


Figure 7.12 Demonstrator WIP moving average for 2-piece design (w = 20)

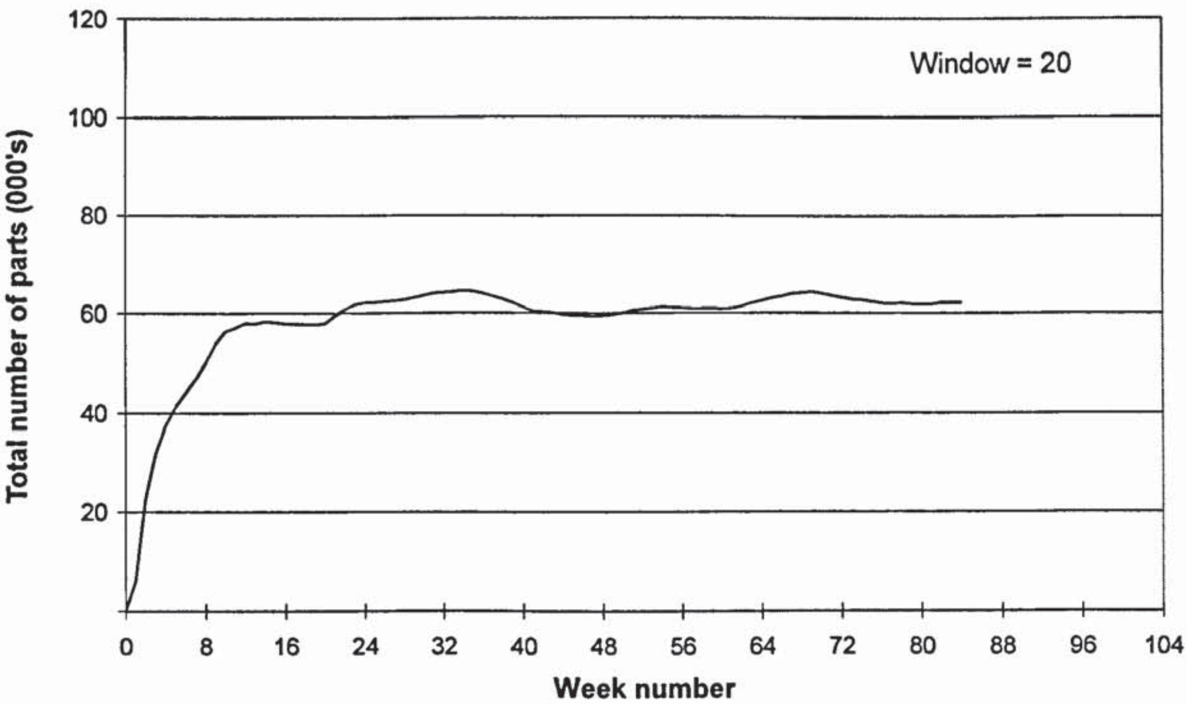


Figure 7.13 Demonstrator WIP moving average for 3-piece design (w = 20)

approach will be used here because of the need to take financial measurements from the same elapsed time periods.

For the demonstrator, a run-in period of 52 weeks was chosen. This is beyond that suggested by the plots and allows a full financial year to be completed which eases the use of the demonstrator. For the shop floor simulation, 50 weeks was chosen, this is more than that suggested by the plots and again makes it operationally simpler.

The simulation procedures for the shop floor simulator and demonstrator are now complete and are summarised below.

Shop floor simulation:

- single replication
- run-in period of 50 weeks
- data collection period of 250 weeks, split into 5 batches of 50 weeks each
- use common random numbers.

Demonstrator:

- 5 replications
- run-in period of 52 weeks
- data collection period of 52 weeks
- use common random numbers.

8 DESCRIPTION OF TOOLS USED IN THE EXPERIMENT

This chapter will describe the details of the tools that are to be used in the experiment: a design cost model, a capacity calculation, a shop floor simulator, a business planner driven by a shop floor simulator, and the demonstrator enterprise simulation system. The chapter concludes with the verification and validation procedures that were carried out.

8.1 Design Cost Model

Ignoring the detail of some of the methods, the basis of costs calculation used for DFA/DFM is as for traditional costing, i.e. component cost is the sum of material and processing costs. Processing cost includes direct labour and overheads. See for example Boothroyd & Reynolds (1988) and Allen & Swift (1990). The material costs tend to be based either on volume or mass usage. Processing costs are generally based on the processing time but may also include tooling costs. As tooling costs are not to be considered here, only the processing time costs will be included. As explained in section 7.4 the processing time to be used will be the same as those used in the shop floor simulator and the demonstrator. The overheads that are included as part of the processing costs will depend upon what explicit costs have been included. For example, Boothroyd & Reynolds (1988) in costing for CNC machines have an explicit cost for set-up of the machine, and separate overhead factors for the machine and labour. As set-ups are generally included as part of manufacturing overheads, this means that their overhead factors must ensure that set-ups are excluded to avoid double costing. For the calculation here the overhead rate will include the set-up costs.

An average overhead rate of £7.79 per hour (£0.1298/min) has been used in the cost model. This is an average value derived from the business planner at normal and high demand.

8.2 Capacity Calculation

The capacity calculation is based on the set-up times, processing times and down time at each work centre on a weekly basis. Table 8.1 gives an example of the format of the spreadsheet used for the calculation and is discussed below.

The set-up time has been estimated as follows. The shop floor policy is to have a transfer quantity of 1500 and to split batches amongst all available machines at a work centre. Set-ups are not required when the following batch is of the same item. Sales orders are weekly, hence, it is assumed that this will generate, on average, one works order per item per week. Although an order will be split into smaller transfer quantities, it is assumed that the whole order goes through together. At each work centre, all the machines are assumed to be set-up once for each order, i.e. each machine will be set-up once per item, per week. For example, in table 8.1 the set-up time at the TURN1 work centre for GEAR_A is 240 minutes, there are 2 machines, therefore the set-up time for GEAR_A at the work centre is 8 hours (2*240/60).

Processing time is based on the mean processing time for the item multiplied by the quantity to be processed per week. Where there is a load and unload time, this has been included in the processing time, by dividing the load or unload time by the respective load or unload quantity. The effect of scrap on the processing time has been included by increasing the quantity to be processed (e.g. the number of spindles to cover scrap will need to include the scrap of spindle assemblies). As the scrap rates are small, the effect of cumulative scrap has been included by summing the individual scrap rates rather than using the exact solution. The difference is minor and simplifies the spreadsheet, for example, the largest cumulative scrap rate is for gears at the TURN1 work centre of the 2-piece design, summing the scrap rates gives 5.8% compared with 6.0% for the exact solution.

The two sources of losses, planned and unplanned, are shown separately. These have been calculated in the following way. The period between the machine being stopped is a function of processing time. Therefore the number of stoppages at the work centre is assumed to be the total processing time divided by the mean processing time between stoppages. The number of stoppages is then multiplied by average time to carry out the maintenance (or repair) to give the total losses at the work centre. For example, at TURN1, the total process time is 110.35 hours, the machine planned losses are 5 minutes and occur every 16 hours of processing. The loss per week in minutes is therefore (110.35/16)*5 = 34.48 minutes, which is 0.57 hours. No losses have been included for

Work Centre Name	No. of m/cs	Product Code	Set-up Time (mins)	Set-up Time (total) (hours)	Process Time (each) (mins)	Quantity Required (per week)	Scrap %	Cumulative Scrap %	Total Quantity (per week)	Process Time (total) (hours)	Planned Losses (per week)	Unplanned Losses (per week)	Total Losses (per week)	Total Time Required (per week)	No. of Operators Shift 1	No. of Operators Shift 2	Total Time Available (per week)	Load % (of actual)
TURN1 (Automatic)	2	GEAR_A	240	8.00	0.212	2040	0.6	5.80	2158	7.63								
		GEAR_B	240	8.00	0.212	9960	0.6	5.80	10538	37.23								
		GEAR_C	240	8.00	0.212	9000	0.6	5.80	9522	33.64								
		GEAR_D	240	8.00	0.212	8520	0.6	5.80	9014	31.85								
				32.00						110.35	0.57	4.41	4.99	147.34			160.00	92%
MILL (Manual)	4	GEAR_A	15	1.00	0.473	2040	1.40	5.20	2146	16.92								
		GEAR_B	15	1.00	0.473	9960	1.40	5.20	10478	82.60								
		GEAR_C	15	1.00	0.473	9000	1.40	5.20	9468	74.64								
		GEAR_D	15	1.00	0.473	8520	1.40	5.20	8963	70.66								
				4.00						244.82	1.02	1.63	2.65	251.47	4	3	280.00	90%
BROACH (Manual)	2	GEAR_A	30	1.00	0.240	2040	0.90	3.80	2118	8.47								
		GEAR_B	30	1.00	0.240	9960	0.90	3.80	10338	41.35								
		GEAR_C	30	1.00	0.240	9000	0.90	3.80	9342	37.37								
		GEAR_D	30	1.00	0.240	8520	0.90	3.80	8844	35.38								
				4.00						122.57	0.51	0.82	1.33	127.89	2	2	160.00	80%
TURN2 (Automatic)	3	SPINDLE_A	240	12.00	0.304	2040	0.9	5.4	2150	10.89								
		SPINDLE_B	240	12.00	0.304	9960	0.9	5.4	10498	53.19								
		SPINDLE_C	240	12.00	0.304	9000	0.9	5.4	9486	48.06								
		SPINDLE_D	240	12.00	0.304	8520	0.9	5.4	8980	45.50								
				48.00						157.64	0.82	6.31	7.13	212.77			240.00	89%
HEAT (Automatic)	1	SPINDLE_A	15	0.25	0.115	2040	0.5	4.5	2132	4.09								
		SPINDLE_B	15	0.25	0.115	9960	0.5	4.5	10408	19.95								
		SPINDLE_C	15	0.25	0.115	9000	0.5	4.5	9405	18.03								
		SPINDLE_D	15	0.25	0.115	8520	0.5	4.5	8903	17.06								
				1.00						59.13	0.25	0.39	0.64	60.77			80.00	76%
GRIND (Manual)	4	SPINDLE_A	15	1.00	0.545	2040	1.1	4	2122	19.27								
		SPINDLE_B	15	1.00	0.545	9960	1.1	4	10358	94.09								
		SPINDLE_C	15	1.00	0.545	9000	1.1	4	9360	85.02								
		SPINDLE_D	15	1.00	0.545	8520	1.1	4	8861	80.49								
				4.00						278.87	1.94	4.46	6.40	289.26	4	4	320.00	90%
PRESS (Manual)	2	SPDL_ASY_A	30	1.00	0.233	2040	0.9	2.9	2099	8.15								
		SPDL_ASY_B	30	1.00	0.233	9960	0.9	2.9	10249	39.80								
		SPDL_ASY_C	30	1.00	0.233	9000	0.9	2.9	9261	35.96								
		SPDL_ASY_D	30	1.00	0.233	8520	0.9	2.9	8767	34.05								
				4.00						117.96	0.70	1.18	1.88	123.84	2	2	160.00	77%
INSP (Manual)	1	SPDL_ASY_A	2	0.03	0.100	2040	2	2	2081	3.47								
		SPDL_ASY_B	2	0.03	0.100	9960	2	2	10159	16.93								
		SPDL_ASY_C	2	0.03	0.100	9000	2	2	9180	15.30								
		SPDL_ASY_D	2	0.03	0.100	8520	2	2	8690	14.48								
				0.13						50.18	0.00	0.00	0.00	50.32	1	1	80.00	63%

Table 8.1 Example of capacity spreadsheet (2-piece design at normal demand)

waiting for personnel to carry out the work, it being assumed that labour will be available when required.

The total of set-up time, processing time and lost time has then been called the time required at the work centre. The time available at the work centre is the lower of either the machines hours or labour hours. For example, at the MILL work centre there are 4 machines with 4 operators on the first shift and 3 operators on the second shift. With a 40 hour shift, the machine time at the MILL work centre is 4*2*40 = 320 hours, while the labour time available is (4+3)*40 = 280 hours. Therefore the time available is 280 hours. Where a machine is automatic, i.e. only requires loading and unloading, the number of operators is not given by the capacity calculation and therefore the available time has been based on the number of machines. Utilisation is calculated as the time required at the work centre divided by the available time at the work centre.

8.3 Shop Floor Simulator - ATOMS

The ATOMS simulator was specifically designed to be used by manufacturing systems engineers for the design of batch manufacture systems. The view given to the user is in manufacturing terms such as work centres, operators, parts, routings, breakdowns. ATOMS is purely data driven and includes most of the features that exist in a batch manufacturing environment, such as shift working, multi-skilled operators, priority working and transfer batches. It supports three levels of modelling: department, centre and station. Station is the lowest level and models individual work stations and operators in detail. This is the level that has been used in the experiment for both the shop floor simulation and the demonstrator.

ATOMS was designed to be run in periods, which are measured in days and can contain non-working days. Hence a normal working week of 5 days with a weekend is a 7 day period with 2 non-working days; non-working days are skipped in the simulation. To use ATOMS as part of the demonstrator it is necessary to edit ATOMS to reflect the delivery of raw materials on a daily basis. ATOMS was therefore set to a period of 1 day with zero non-working days. This was also the configuration when ATOMS was used on its own.

ATOMS provides a wide range of reports, relevant aspects of which are discussed below.

In ATOMS, work-in-progress is the total load (in number of components) on the system. This load includes actual physical components being processed or waiting, as well as any orders that have been released but not started. The number of components reported as output is updated only when a works order is completed. Therefore, a works order which is just short of being completed in one week will show up as output in the following week, when it is completed. Where there are a large number of small works orders that only take a short time to complete the difference will be small. In this study there are only 12 orders per week so the output is likely to show a greater variability than would occur in reality.

For each work station ATOMS reports: set-up time, processing time (including any load and unload time), repair time and down time. Repair time for the work station is the time the work station spent in the state of 'repair' and is the sum of planned and unplanned stoppages. Down time is reported for a work station when it has stopped for planned and unplanned stoppages. It is the calendar time for waiting to be repaired (waiting time) plus repair time. In this study the shop floor is working two, 8 hour shifts per day, 5 days per week. Therefore if a work station is stopped during the second shift and is not repaired until the next shift, down time will include the 8 hours between shifts. As ATOMS is being run every day, weekends are not skipped, therefore if a machine is stopped at the end of the second shift on a Friday, the whole of the weekend will be counted in the down time. Because of the way that ATOMS is implemented for the demonstrator, the reporting of repair time is also affected in this way. The ATOMS results have therefore been processed to eliminate any down time and repair time that is reported during the weekend, but it has not been possible to eliminate these during the working days. This can lead to the reported figures of down time, repair time and utilisation being marginally higher than they actually are.

To allow easier comparison between the capacity calculation and the ATOMS results, the same format is used to summarise the work centre results of both. An example is given in table 8.2. Set-up time and process time are self-explanatory. Down time is as defined above. Total time is the sum of set-up, process and down time. Available time and utilisation are as defined for the capacity calculation. ATOMS does not report waiting time, it has therefore been calculated as down time minus repair time.

Work Centre	Set-up Time (hr)	Process Time (hr)	Down Time (hr)	Repair Time (hr)	Waiting Time (hr)	Required Time (hr)	Available Time (hr)	Utilisation
TURN1	29.82	112.16	11.01	5.73	5.29	153.00	160.00	96%
MILL	3.20	244.71	10.37	2.92	7.45	258.28	280.00	92%
BROACH	3.70	122.43	5.09	1.46	3.62	131.22	160.00	82%
TURN2	40.20	158.50	14.21	8.09	6.12	212.91	240.00	89%
HEAT	1.01	59.69	2.20	0.83	1.37	62.90	80.00	79%
GRIND	3.12	280.03	22.25	7.37	14.88	305.40	320.00	95%
PRESS	3.72	119.04	7.51	2.03	5.48	130.27	160.00	81%
INSP	0.15	49.75	0.00	0.00	0.00	49.90	80.00	62%

Table 8.2 Example of work centre utilisation report format

8.3.1 Assumptions of the Shop Floor Model on its Own

The shop floor model on its own does not include high level planning and control elements, suppliers or customers. Therefore a number of assumption were made and are discussed below.

The lack of material planning and the effect of scrap losses, mean that the spindle assembly can not include the effect of gear and spindle deliveries, i.e. it is assumed that there are sufficient gears and spindles available. Similarly, the lack of suppliers means that raw materials are assumed always to be available. A general assumption made was therefore that the MRP system would handle correctly the ordering of materials, components and finished goods. The main requirement therefore, of the shop floor simulation, is to ensure that there is enough capacity available.

Although the components and assembly were in effect being modelled independently, the simulation still modelled the shared resources such as the auto-lathe operators, craftsmen and transport personnel.

The simulation was run with an order stream for the assemblies, spindles and gears. The average demand included an additional load to account for scrap in the same way as described above for the capacity spreadsheet. Since scrap rates are different, the same demand pattern was not used for both designs. Each average demand was then factored by a +/- 20% random uniform distribution to account for the variability in the demand. The orders were released at the beginning of each week but in a random sequence which will eliminate effects due to a repeating pattern of order release.

8.4 Business Planner Driven by Shop Floor Simulator

From the discussion in section 7.4 it was argued that rather than a cost model, a business planner would be used. Upon further investigation, it was realised that there were problems in doing this.

A business planner is a model of the business finances for each accounting period. The intention was that the shop floor simulator (ATOMS) would replace the crude operational model used in the business planner and provide some of the inputs, e.g. stock valuation. While the shop floor simulator provides the level of WIP it does not supply the levels of raw material stocks, intermediate parts, and finished goods. There is also a problem of determining what the typical opening balances of the business are, specifically the bank, stocks, debtors and creditors. Again these are not supplied by the shop floor simulator.

Even without the problems above, many financial details (e.g. stock valuations) need to be derived from the operational output of the shop floor simulator using a spreadsheet since the business planner requires financial input. Therefore, it was decided to build a financial model by extending this spreadsheet, rather than using a business planner. The financial model will be as valid as the business planner and will remove much formatting and manual transfer of data. Using the case data, information supplied by the shop floor simulator and a number of assumptions, a financial model of the business was built.

The components of the profit & loss account were derived in the following way.

Sales revenue is the annual average demand multiplied by the selling price.

The lack of material planning in the shop floor model meant that the material usage was calculated based on the average demand for each item and included scrap. Material costs are then calculated from the unit costs of each item. Direct labour costs were calculated based on the number of people derived from the shop floor simulator and the wage rate.

Production indirect wages are based on the inspectors, craftsmen and transport personnel. Machine power consumption costs are based on the processing times and machine power ratings and unit power costs. Depreciation costs are based on the total machines values and the depreciation rate. All other overheads are fixed costs.

The stock movement cost is assumed to be zero since the demand is, on average, level.

Sales, technical and Administration costs were a part of the case data and used directly.

The balance sheet values were derived as follows.

Fixed assets are given as part of the case data. From the depreciation rate, the remaining plant value can be calculated.

WIP levels are given by the shop floor simulator; stock levels have to be estimated. It was assumed that on average the level of stocks would be half the weekly demand, plus any safety stock set in the MRP system. The stocks are valued on the same basis as the demonstrator, i.e. including direct costs and production overhead.

The debtors value was estimated based on payment days. Since there are 56 payment days (8 weeks), the debtor amount on average will be 56/364 of the yearly sales.

To estimate the bank value and the interest payments a simple cash flow model was developed using 13 periods for the year. The relevant income and expense were offset by 2 periods to account for the 56 payments days. The interest for each period was based on half the value of the beginning and end period bank balances.

Creditors were estimated in the same way as the debtors but were based on yearly purchases. As raw materials (56 payment days) and machine power costs (28 payment days) were the only purchases being modelled with appropriate payment delays, only these have been included as creditors.

8.5 WBS Demonstrator System

In the previous chapter some of the basic requirements for the system have been defined. To make the development feasible, a number of simplifications were decided, namely, the customer model to be an order stream, the supplier model to provide a delivery delay sampled from a distribution, and not to model support personnel in detail. Even with these simplifications the development of a simulation system that would cover in detail the shop floor (including people), manufacturing planning and control and the finances is a major task. This task can be reduced by using commercial software as part of the simulation, since each package provides the necessary functionality and reporting aspects and is at the necessary level of detail. This approach also reduces the problem of validity.

Two ways of including commercial systems as part of the simulation are to:

- extend the shop floor simulation to included the commercial systems as elements with in it
- create a 'global' simulation which contains a separate shop floor simulation and the commercial systems as self contained items.

In the latter case, interactions between the shop floor simulation and the packages are limited by the shortest time that the shop floor simulation can be run. For example, if the shop floor must be run for one week, then no interaction can occur during this period, e.g. deliveries of purchase materials to the shop floor cannot occur during the week, they must occur either at the beginning or end of the week. Given the case to be simulated, running the MRP each week would be quite acceptable and realistic; but the lead time offsets of the product are such that having a bucket size of a week, which this would impose, is an unrealistic condition and so would not be acceptable. For this case, having deliveries on a daily basis is considered the maximum that is acceptable, and so this sets a requirement for the shop floor in this approach.

The former, more integrated approach requires either developing a new shop floor simulator or using an existing one, and extending it so that the MRP system, the accounting system, customers and suppliers can be integrated. Both these options have disadvantages. Developing a new shop floor simulator does allow the computing platform and software to be chosen so that the necessary integration of the packages can be achieved, but the development is not a trivial task. Extending an existing simulator requires access to the source code, hence eliminates the use of most commercial systems. The ATOMS simulator described above was developed within the Integrated Design & Manufacture Research Group at Aston University and access to the source code was possible. However, including the necessary integration would involve fundamental modifications to the existing software and hence required validation of the existing simulator logic.

Given the problems in building an integrated simulation, the 'global' simulation approach was followed. The basis of the demonstrator system is therefore a 'global' simulation system in which the shop floor simulator and commercial packages are elements within a larger simulation system. From here on the demonstrator system will be taken to mean the 'global' simulation system, the shop floor simulator and all the commercial packages.

Using a PC based system running DOS allowed an integration technology (DESQview) to be used. The demonstrator could be written in Pascal and readily available DOS based packages could be used. The ATOMS simulator is DOS based and fulfils the requirement of being able to simulate a period of one day. A commercial MRP system, UNIPLAN was available and so was used. UNIPLAN is an MRPII system but only the MRP part was to be used. A financial accounting system was not readily available and so a package, dBFLEX was bought. The overall concept of the demonstrator system can be seen in figure 8.1 where the functional areas of the business are replaced by the commercial packages namely:

- shop floor simulator - ATOMS
- manufacturing planning and control - UNIPLAN
- accounts - dBFLEX.

The demand generator of the customer was modelled using a commercial spreadsheet (SuperCalc5) and integrated in the same way as the other packages. All version numbers and suppliers of the software are given in appendix 2.

While the use of commercial packages did reduce development effort it did not make it trivial. The demonstrator system had to provide:

- the necessary integration between the commercial packages
- functions not covered by the commercial packages (e.g. forecasting)
- the ability to set and amend these additional functions
- event control (which is central to any discrete-event simulation system).

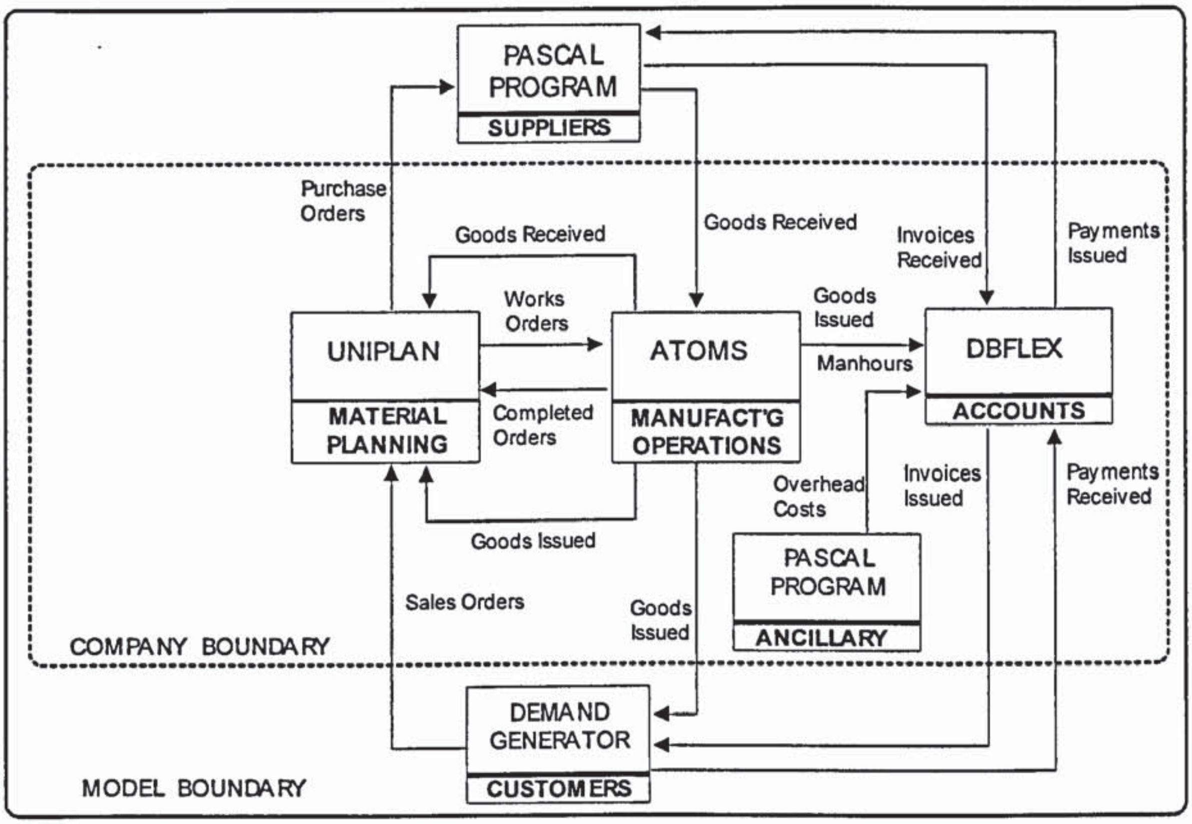


Figure 8.1 Core elements and transaction of the demonstrator

8.5.1 DESQview Integration Technology

A key feature of the demonstrator system is the ability to integrate commercial packages which were not designed to be integrated. This was achieved using DESQview, a multi-tasking environment for DOS based computers. DESQview allows a number of packages to be run concurrently by providing each package with a virtual machine. As DOS based computers are single microprocessor systems, DESQview time-slices the processor and gives each software package that is running a certain amount of the processor time. As well as multi-tasking, DESQview also provides the ability to program the launch and closure of software packages, and to interact with the peripheral devices of each virtual machine. Of relevance here is the ability to read a text mode screen (characters, foreground colour, background colour and hardware cursor position) and write to the keyboard (in effect mimicking manual typing of the keys). These functions can be accessed from a Pascal program through a DESQview API (Applications Programming Interface). This therefore gives the basis of integrating the commercial packages within a Pascal program. The program that controls a package can be thought of a driver which translates standard instructions into the specific keystrokes understood by the package and translates the output of the package back into standard responses. Figure 8.2 shows this diagrammatically.

8.5.2 Controlling Software Packages

Inputting data cannot be done reliably without visible feedback of the state of the package (try controlling a package with your eyes shut and you will appreciate the problem). To control the package it is necessary to detect when it has finished processing the previous input. Sending all the data at once is not viable because the limited keyboard buffer size results in overflow and keystrokes are lost. Using time delays is no solution either because processing times will be affected by the power of the computers used. Even using identical machines will not solve the problem because the processing time for a particular computation may be affected by the current state of the package, e.g. the time for the MRP calculation will be dependent upon the bill of materials, MPS, batching polices and the current status of the works and purchase orders. Detecting when the package has finished processing the previous input can be simple when there is only one outcome from any given position of the package but complicated when there are multiple outcomes. When there is only one outcome it can also be difficult because the state of the screen may not

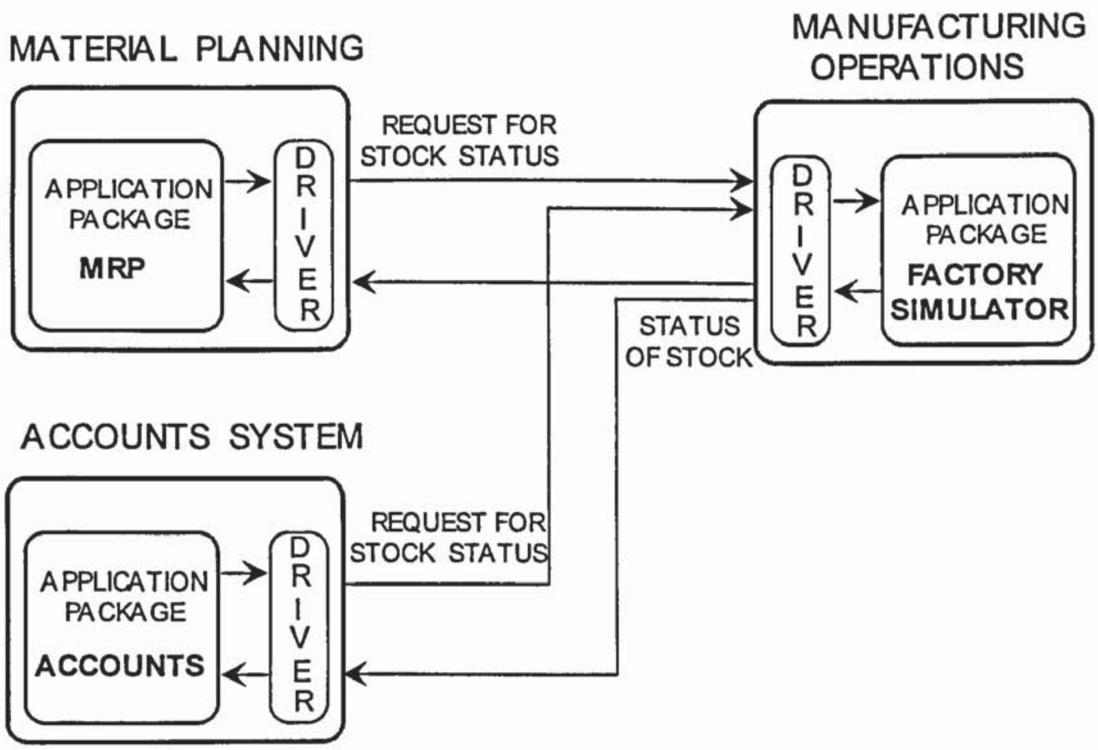


Figure 8.2 Controlling software packages

change when the package has finished processing. Writing computer code to control the packages is therefore not trivial, as each keystroke must be input and the end of processing checked.

8.5.3 Object Oriented View of the System

The demonstrator was designed using object-oriented principles (Booch, 1991) and written in Borland Pascal 7, an object-oriented language.

The view taken for the design of the demonstrator was that the main objects of the simulation were companies. The messages between these companies were also objects representing standard inter-company transactions such as purchases orders, invoices, cheques (payments), delivery notes, etc.. Products, components and raw materials were modelled using the receipt of a delivery note as a proxy for the receipt of the items themselves.

The company objects of the system are:

- manufacturing company - a company with functional departments of shop floor operations, manufacturing planning and control, and accounts
- customer - a company which only demands products (using a spreadsheet model)
- supplier - a company which only supplies components and raw materials using a delay to mimic its delivery performance
- service - a company which only supplies a service such as electricity
- postal service - a company which handles all the inter-company messages.

The functional departments of the manufacturing company object are also objects. These department objects provided the required functionality of these departments by using a combination of purposely written Pascal code and by interfacing to the commercial systems through drivers discussed above. The drivers were themselves objects within the simulation hence in this way the commercial systems appeared just like any other object within the simulation.

The basic structure is shown in figure 8.3. Detailed object structure is only shown for the material planning object of the manufacturing company.

The object-oriented principle of polymorphism (Booch, 1991, p.65) means that all the different company objects appear the same at the company level where transactions are being passed. Therefore, it would have been possible, without any reprograming, to replace the supplier object in a particular simulation run with an additional manufacturing company object, and so model the supplier in just as much detail as the company being investigated.

The system also contained two other major objects which were necessary for the operation of the simulation, an executive and a clock. The executive provides control of the execution of events in the simulation by keeping a list of the events to be actioned in chronological order. It is based on that used for the Advance Factory Simulator (Ball, 1994, pp. 106-108). This executive has no knowledge about the type of events it is controlling, only when the event is to occur and to what object it applies. The core simulation logic is contained within each object in what is known as a state transition network which triggers the object to change from one state to another. Each object has

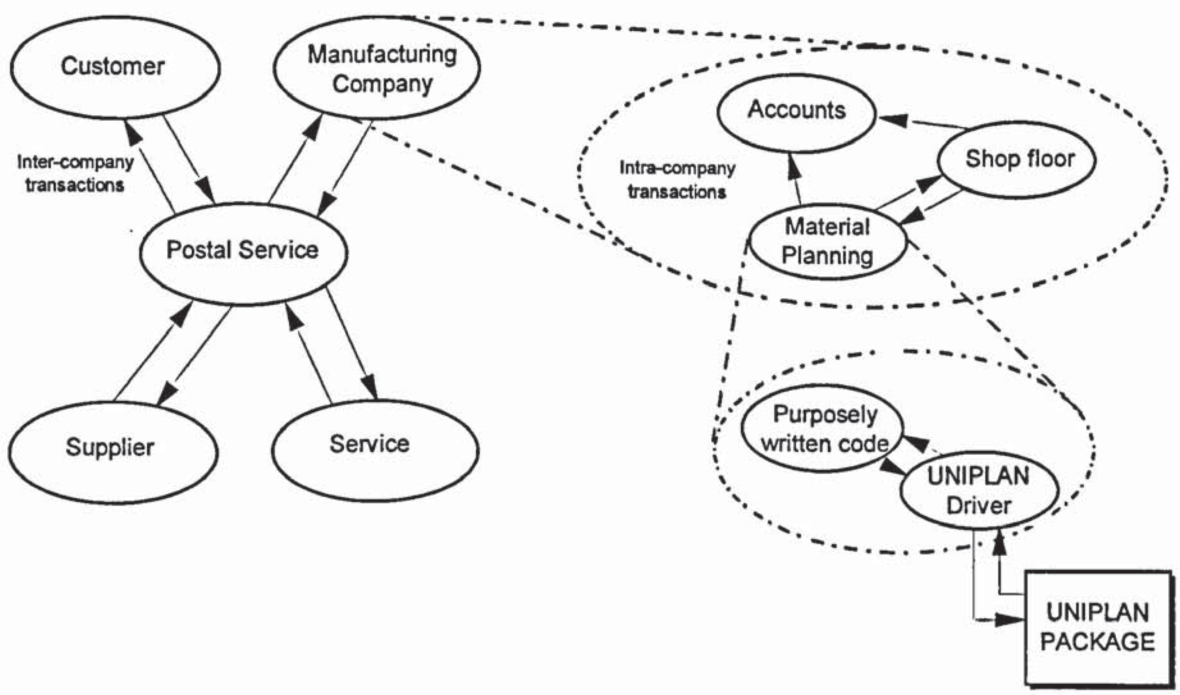


Figure 8.3 Basic object structure of the demonstrator

access to the clock and so with knowledge of its own state can schedule its next event by adding it to the executive event list.

8.5.4 Functionality

For the purposes of discussion, the functionality of the demonstrator has been split into three main aspects: states (table 8.3), parameters (table 8.4) and reports (table 8.5). The objects in the tables are in alphabetical order.

The states in this simulation equate to an action (e.g. the state RunningMRP equates to the action of running the MRP calculation). Hence the states define the range of actions that are possible in the demonstrator.

Parameters cover the value of things (e.g. processing times for components in the shop floor simulator) and the settings of decisions or options (e.g. batching or lot-for-lot in the MRP package). The parameters therefore define the data that are processed by the actions or define which option of a particular action should be processed. Reports cover the reporting that can be supported or is produced during the simulation. The table identifies whether the report is produced by a software package or by the demonstrator itself.

The description here does not cover all the functionality of each commercial system, only those aspects which were implemented or used as part of the demonstrator system. Whether a feature was provided by the software package or had to be written separately has been indicated. It should be remembered that where an action is indicated as being provided by a package it does not mean that no programming was required. The necessary keystrokes for this action will have had to be coded in the driver.

8.5.5 Logical and Physical Operation of the Demonstrator

The description in section 6.2.1 gave a general description of how the logic of the simulation would operate, more detail is provided in table 8.6. The state changes of objects generally occur at set frequencies, e.g. daily, run the factory. The objects and their states are shown in the table grouped into the time frequencies.

Simulation Object	State	Description of state	Package, program
Accounts	IssuingInvoices	raise invoices based on completed sales orders	dBFLEX
	UpDatingInvoices	enter invoices received from suppliers	dBFLEX
	IssuingPayments	based on payment dates, issue payments to suppliers	dBFLEX
	UpDatingPayments	enter payments received from customers and reconcile payments with invoices	dBFLEX & program
	UpDatingJournals	enter any journal transactions (e.g. wages, stock valuations, bank interest)	dBFLEX & program
	DepreciateAssets	calculate depreciation for assets and create journal posting	program
	PeriodEnding	period ledgers (nominal, sales, purchase)	dBFLEX
	YearEnding	year end accounts & reset period end dates	dBFLEX
Company	IssuingTimeSheets	send time sheets to accounts	program
Customer	IssuingPurchaseOrders	issue purchase orders to supplier	SuperCalc & program
	UpdatingPurchases	update for purchases received - i.e. do nothing	program
	IssuingPayments	issue payments to supplier	program
MPC	InputtingSalesOrders	enter received sales orders	UNIPLAN
	IssuingSalesOrders	send sales orders to shop floor	program
	InputtingGrossReqs	run forecast calculation and enter MPS	program
	RunningMRP	run MRP	UNIPLAN
	InputtingWorksOrders	enter suggested works orders	UNIPLAN
	InputtingPurchaseOrders	enter suggested purchase orders	UNIPLAN
	IssuingWorksOrders	send works orders to shop floor	program
	IssuingPurchaseOrders	send purchase orders to suppliers	program
	UpdatingWorks	enter works goods received notes and adjust for scrap	UNIPLAN
	UpdatingSales	enter dispatch notes	UNIPLAN
	UpdatingPurchases	enter purchase goods received notes	UNIPLAN
	StockValuing	run stock valuation option and send valuation to accounts	UNIPLAN & program
Service	SupplyingServices	calculate completed order date of sales orders based on lead time offsets	program
	IssuingInvoices	raise invoices based on completed sales orders	program
	UpDatingPayments	deal with payments received	program
Shop-floor	UpdatingPurchases	update for goods received and send purchase goods received note to MPC	ATOMS
	InputtingWorksOrders	enter works orders into factory simulation	ATOMS
	RunningFactory	run shop floor simulator and update time sheets, power consumption, etc.	ATOMS
	UpdatingWorks	create works goods received notes and send to MPC	program
	IssuingTimeSheets	send time sheets to accounts	program
	IssuingPurchaseOrders	issue purchase orders for services used (e.g. electricity)	program
	StockValuing	calculate stock valuation and send valuation to accounts	program
	IssuingFinishedGoods	dispatch customer orders if possible, send delivery note to customers, send dispatch note to MPC and send completed sales order to accounts	program
Supplier	RunningFactory	calculate completed order date of sales orders based on lead time offsets	program
	IssuingFinishedGoods	dispatch customer orders if possible, send delivery note to customers	program
	IssuingInvoices	raise invoices based on completed sales orders	program
	UpDatingPayments	deal with payments received	program

Table 8.3 States of demonstrator objects

Simulation Object	Description of parameter	Package, program	Comments
Accounts	Pay rates of each type of personnel (normal and overtime)	program	
	Sales ledger - customer name	dBFLEX	
	Sales ledger - payment days	dBFLEX	
	Purchase ledger - supplier name	dBFLEX	
	Nominal ledger - account name (whether balance sheet or Profit & Loss)	dBFLEX	
	Lookup table to specify which account name a particular transaction should be enter	program	
	Overdraft interest rate	program	Interest charged on weekly balances.
	Deposit interest rate	program	Interest charged on weekly balances.
Company	For each personnel	program	For personnel not included in shop floor simulation
	Type		
	Number		
	Hours worked		
Customers	Name of item	SuperCalc	
	Quantity	SuperCalc	A wide variety of demand patterns is a possible using a mixture of a linear equation, two sinusoidal equations and uniform randomness.
	Release date	SuperCalc	Release dates can be fixed or uniform distribution.
	Date required	SuperCalc	Required dates can be fixed or uniform distribution.
MPC	Number of weeks for moving average forecast	program	
	MPS, rolling schedule (last week of horizon or all horizon)	program	
	Number of weeks of MPS horizon	program	
	Day of week requirements are entered	program	
	Batching policy (batch or lot-for-lot)	program & UNIPLAN	In UNIPLAN the batching policy must be specified each time the MRP calculation is run. The program allows this option to be set.
	For each stock item	UNIPLAN	
	Code		
	Lead time offset		
	Selling price		
	Stock on hand		
	Reorder level		
	Reorder quantity		
	Supplier		
	Buying price		
	For each BOM	UNIPLAN	
	Code and usage of each child item		
	For each process route	UNIPLAN	
	Processing time		
	Labour rate		
	Overhead rate		
Service	Number of payment days all items	program	
	Delivery time of each item	program	Delivery time can be fixed, uniform or normal distribution.
	Price of each item	program	

Table 8.4 Parameters of demonstrator objects

Simulation Object	Description of parameter	Package, program	Comments
Shop-floor	Sales order rule (back order, sale date, sale period)	program	Back order - hold orders until enough stock to satisfy, meet orders based on due date.
			Sale date - lose any order prior to today, meet any order with date of today or later, hold on to any orders not satisfied
			Sale period - meet any order irrespective of date, lose any order not satisfied
	Power consumption rates for machines	program	
	Part value	program	An average value of all WIP (partially machined) items which is used for stock valuation.
	For each work centre	ATOMS	
	Name		
	Group Similar Waiting Batches (Y/N)		
	Select Next Batch Similar To Last Batch (Y/N)		
	Split Batches Between All Available Work Stations (Y/N)		
	Only Consider The First Queuing Batch (Y/N)		
	Sequencing Rule For Queuing Batches		
	Work Stations Included		
	For each work station	ATOMS	
	Name		
	Type		Assembly, Manual, Index
	Possible operators		
	Efficiency		
	Breakdowns/planned maintenance		For each workstation upto 4 patterns set
	For each breakdown record	ATOMS	Maximum of 20 different records
	Type		RunTime, TimeOutPut, UnitOutPut
	Breakdown interval		Fixed or distribution
	Wait Till End Of Job (Y/N)		
	Repair operator		
	Repair time		Fixed or distribution
	For each operator	ATOMS	
	Name		
	Type (skills)		
	Number		
	Efficiency		
	Shift pattern		
	Job Priority Order		Operation, Repair, Transport, Setting
	Work station priority sequence		
	Item name	ATOMS	
	For each process route	ATOMS	
	Item		
	Work centres visited		
	For each work center of a process route	ATOMS	
	Minimum setup quantity		
	Setup operator		
	Setup time		Fixed or distribution
	Process operator		
	Load quantity		
	Load time		Fixed or distribution
	Process time		Fixed or distribution
	Scrap		Fixed or distribution
	Unload time		Fixed or distribution
	Operator Freed Between Load and UnLoads (Y/N)		
	Transfer quantity		
	Transport operator		
	Transport time or (distance and speed)		Fixed or distribution
	Kitting item and quantity		
Supplier	Number of payment days all items	program	
	Delivery time of each item	program	Delivery time can be fixed, uniform or normal distribution.
	Price of each item	program	

Table 8.4 (continued) Parameters of demonstrator objects

Simulation Object	Reports	Package, program	Comments
Accounts	Balance Sheet	dBFLEX	
	Profit & Loss	dBFLEX	
	Account status	dBFLEX	e.g. current balance, year end balance, period end balances
	Payments due	dBFLEX	List of payments to suppliers which are due
	Reconciliation	dBFLEX	List of invoices and payments which have not been reconciled
Company	None		
Customer	None		
MPC	Suggested works orders	UNIPLAN	Works orders suggested by MRP
	Suggested works orders	UNIPLAN	Purchase orders suggested by MRP
Service	None		
Shop floor	WorkCentre	ATOMS	e.g. processing time, repair time, setting time, output batches, good production, scrap
	Stores	ATOMS	e.g. stock on hand, due in, issued, received
	Transport	ATOMS	e.g. number of loads, time transporting
	Operator	ATOMS	e.g. shift time, overtime, setting time, process time, material handling, repairing
	Tooling	ATOMS	e.g. utilisation
	CompletedOrders	ATOMS	e.g. date each batch completed, due date, queue time, process time, setting time, good production, scrap
	Sales dispatched	program	List of what was sold, date required, actual date, whether order complete
Supplier	None		

Table 8.5 Reports generated during the running of the demonstrator

8.5.5.2 Data Files

The data of the demonstrator simulation are stored in a number of text files while data for the commercial packages are stored in their own native format.

The state and data of permanent objects of the simulation (e.g. companies, departments, executive) are defined in a text file called a model definition file. The file is arranged into sections, each section defines a different object in the simulation including the executive and the clock. The description of each object (e.g. company, department) defines the values of parameters, when and what state changes are required, what state it is currently in and any automated report generation required. The description of the executive contains any pending events and the clock will define the current time of the simulation.

Transient objects (i.e. the transactions such as purchase orders, works orders, etc.) are saved in separate text files. These files crudely represent the in-trays and filing systems of the company and department objects. For example the MPC object will have a file for completed works orders. To identify each transaction, each one is given a unique number.

Frequency	Simulation Object	Day	Time	State	Description of state
Daily	Shop-floor	N/A	08:58	IssuingFinishedGoods	dispatch customer orders if possible, send delivery note to customers, send dispatch note to MPC and send completed sales order to accounts
	Shop-floor	N/A	09:00	RunningFactory	run shop floor simulator and update time sheets, power consumption, etc.
	Supplier	N/A	09:30	RunningFactory	calculate completed order date of sales orders based on lead time offsets
	Supplier	N/A	17:00	IssuingFinishedGoods	dispatch customer orders if possible, send delivery note to customers
	Shop-floor	N/A	17:15	UpdatingPurchases	update for goods received and send purchase goods received note to MPC
	Accounts	N/A	N/A	(Occurs automatically)	calculate overdraft/deposit interest
Weekly	Customer	Monday	08:00	IssuingPurchaseOrders	issue purchase orders to supplier
	Customer	Friday	18:00	UpdatingPurchases	update for purchases received - i.e. do nothing
	Customer	Friday	19:00	IssuingPayments	issue payments to supplier
	Shop-floor	Monday	08:59	InputtingWorksOrders	enter works orders into factory simulation
	Shop-floor	Friday	17:05	IssuingTimeSheets	send time sheets to accounts
	Shop-floor	Friday	17:10	UpdatingWorks	create works goods received notes and send to MPC
	Shop-floor	Friday	17:25	IssuingPurchaseOrders	issue purchase orders for services used (e.g. electricity)
	MPC	Monday	08:10	InputtingSalesOrders	enter received sales orders
	MPC	Monday	08:15	InputtingGrossReqs	run forecast calculation and enter MPS
	MPC	Monday	08:20	RunningMRP	run MRP
	MPC	Monday	08:35	InputtingWorksOrders	enter suggested works orders
	MPC	Monday	08:40	InputtingPurchaseOrders	enter suggested purchase orders
	MPC	Monday	08:45	IssuingWorksOrders	send works orders to shop floor
	MPC	Monday	08:50	IssuingSalesOrders	send sales orders to shop floor
	MPC	Monday	08:55	IssuingPurchaseOrders	send purchase orders to suppliers
	MPC	Friday	18:10	UpdatingWorks	enter works goods received notes and adjust for scrap
	MPC	Friday	18:15	UpdatingSales	enter dispatch notes
	MPC	Friday	18:20	UpdatingPurchases	enter purchase goods received notes
	Company	Friday	17:06	IssuingTimeSheets	send time sheets to accounts
	Accounts	Friday	18:31	IssuingInvoices	raise invoices based on completed sales orders
	Accounts	Friday	18:41	UpDatingInvoices	enter invoices received from suppliers
	Accounts	Friday	19:01	IssuingPayments	based on payment dates, issue payments to suppliers
	Accounts	Friday	19:21	UpDatingPayments	enter payments received from customers and reconcile payments with invoices
	Accounts	Friday	20:00	UpDatingJournals	enter any journal transactions (e.g. wages, stock valuations, bank interest)
	Supplier	Friday	18:32	IssuingInvoices	raise invoices based on completed sales orders
	Supplier	Friday	19:22	UpDatingPayments	deal with payments received
	Service	Friday	18:00	SupplyingServices	calculate completed order date of sales orders based on lead time offsets
	Service	Friday	18:33	IssuingInvoices	raise invoices based on completed sales orders
	Service	Friday	19:23	UpDatingPayments	deal with payments received
4 Weekly	MPC	Friday	18:25	StockValuing	run stock valuation option and send valuation to accounts
	Shop-floor	Friday	18:30	StockValuing	calculate stock valuation and send valuation to accounts
	Accounts	Friday	19:50	DepreciateAssets	calculate depreciation for assets and create journal posting
	Accounts	Monday	00:03	PeriodEnding	period ledgers (nominal, sales, purchase)
Yearly (52 weeks)	Accounts	Monday	01:30	YearEnding	year end accounts & reset period end dates

Table 8.6 Cycle of states of demonstrator objects

There are a number of other files which contain lists of fairly static information, e.g. the supplier object uses a file which contains the information on the products it supplies, delivery times and prices. The account object uses a file which defines the pay rates of personnel.

The total state of the simulation is therefore contained in numerous data files some of which are the data files of the commercial packages. If the simulation is to be valid all these different stores of data must be consistent. For example, a works order could be defined in the MRP system, the shop floor object and the shop floor simulator. In each case the information (item, quantity, date required, etc.) must agree. Hence to start the simulation in a given state (e.g. work-in-progress on the shop floor and orders at suppliers) requires that all the data, in all the systems, are consistent; this is not trivial. For this reason the simulation is always started with no work-in-progress in either the shop floor simulator or the supplier. It also means that if the simulation crashes, recovery is only achievable by going back to the previously saved version.

8.5.5.3 Physical Operation

The model definition file is read by the main Pascal program which creates the necessary objects. The objects will read any necessary data, e.g. text files of current transactions and launch the commercial packages. On the computer therefore there will be loaded the main program which controls the simulation and all of the commercial packages. The end date and time for the simulation can then be set and the simulation initiated. The time of the simulation can be set to any time, it does not have to be set to a multiple of a day as implied by the above description. Even though the simulation is usually run in multiples of weeks the ability to run to a given time is useful for debugging purposes. For example, if an error occurs part way through a simulated day it would be time consuming to have to keep running the simulation from the start of the simulated day. At the end of the run, the commercial packages are closed down (saving their data), the current transactions are saved and the current state of the objects are saved in the model definition file. The total state of the simulation therefore is a combination of the model definition file, the files of transactions and the data files of the commercial packages. The simulation can be run using a DOS batch file with switch parameters. This defines the length of a simulation run and the number of times to repeat it. Between each run, all the data files of the model are saved.

8.5.6 Memory and Data Storage Requirements

The demonstrator system has entailed writing over 78000 lines of code and produces an executable program of about 426 Kbytes. A memory requirement of 8 Mbytes is recommended to run the program, all the packages, and provide for a 2 Mbyte disk cache. A disk cache significantly reduces the run time of the simulation because the MRP and accounting packages make extensive disk access.

For the model used here, the data storage required for the model definition file, the transactions and all the commercial package data files is about 11 Mbytes for a year.

8.6 Verification and Validation

While the terms verification and validation were once used interchangeably (e.g. Naylor & Finger, 1967) they are now used to define two different activities in the simulation modelling process (e.g. Hoover & Perry, 1984; Sargent, 1994). However a valid model generally means a model which has been verified and validated.

Figure 8.4 is taken from Sargent (1994) and shows a simplified version of the modelling process. The problem entity is the real or proposed system to be modelled. The conceptual model is the abstraction of this in terms of entities and relationships. The computerised model is the implementation of the conceptual model on a computer, using for example a simulation language or simulator. Verification can therefore be seen to involve only the conceptual and computer models and is the activity of ensuring that the computer implementation is correct with respect to the conceptual model (i.e. the logic and data are as intended). Validation is not as clear cut, in broad terms it is aimed at determining if the model is fit for its intended purpose and therefore a model valid for one purpose may be invalid for another (see for example Evans et al., 1967; Herman, 1967; Forrester, 1961, p.122). From figure 8.4, it can be seen that Sargent has split this activity into three types: data validity, conceptual model validity and operational validity. These are defined by Sargent as:

Data validity

"... ensuring that the data necessary for model building, model evaluation and testing, and conducting the model experiments to solve the problem are adequate."

Conceptual model validity

"... determining that the theories and assumptions underlying the conceptual model are correct and the model representation of the problem entity is 'reasonable' for the intended purpose of the model."

Operational validity

"... determining that the model's output behavior has sufficient accuracy for its intended purpose over the domain of the model's intended applicability.".

For both verification and validation there are a number of techniques, test or approaches that can be applied, see for example Herman (1967), Naylor & Finger (1967) and Sargent (1994). No collection of techniques can deliver a valid model. Ensuring a valid model (verified and validated) is therefore a problem of the model builder convincing himself and others that it is adequate.

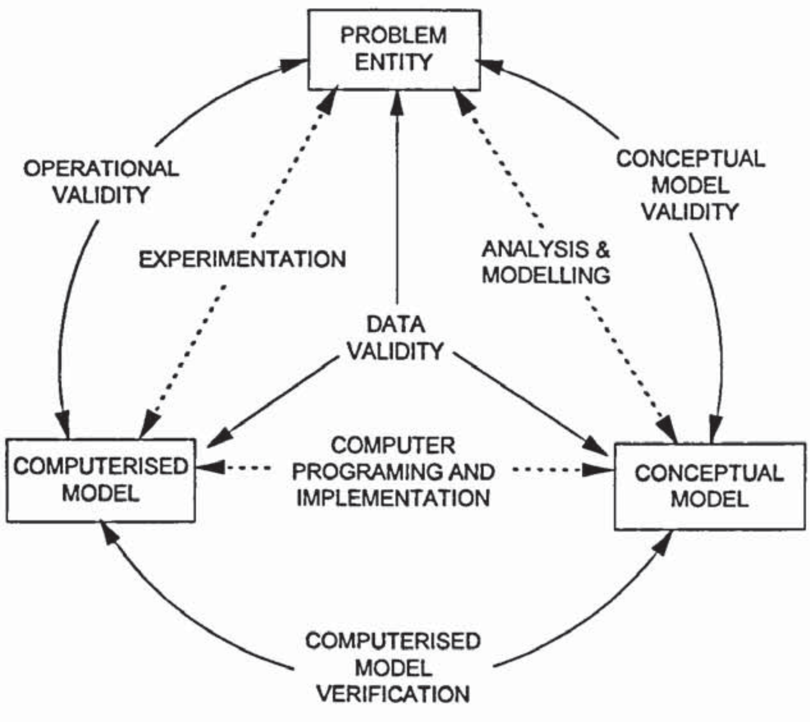


Figure 8.4 Simulation modelling process (after Sargent, 1994)

Kleindorfer & Ganeshan (1993) point out that while verification and validation appear to be the burden of builders of computer simulation models, it is something which is applicable to all model building. Therefore it should be applied to the non-simulation models to be used here, i.e. design cost model, capacity calculation, and financial model. One method of validation is to use other models as checks. As all the models here are models of the same proposed system, they can be used as checks between themselves. Verification, data validity and conceptual validity are discussed below while operational validity is covered in chapter 10 where the results of the experiment are discussed.

8.6.1 Data Validity

The basis of some of the data to be used has been discussed in chapter 7 and the basis of the rest of the data is given in appendix 1. While much of the data is a simplification of reality, the data are considered to be valid for the aims of the experiment.

8.6.2 Design Cost Model, Capacity Calculation and Financial Model

The conceptual models of the design cost model, capacity calculation and financial model are based on accepted principles for the respective models and are therefore considered valid.

The verification of these models involved manual checking of the spreadsheet formulae. Manual calculations were carried out and the differences between the two spindle assembly designs were compared to see if any trends were in the direction expected. For example, the material purchases for the 3-piece design are expected to be greater than for the 2-piece design.

8.6.3 ATOMS Shop Floor Simulator

The use of the ATOMS simulator should reduce verification and validation errors since its computer code and logic has already been verified and validated. The inputs to ATOMS are in manufacturing terms, with less translation of data and hence less chance of error. Also, any errors that do exist are more likely to be identified.

In building the ATOMS shop floor model the following procedure was used for the two designs. A basic model was built from text files using an automatic model build facility in ATOMS. This model was manually checked to see that there were no errors (e.g. work stations with no associated work centre, correct material usage). Features were then added to create a complete model. After each feature was added, a test model was run and the results inspected to check that the added feature had the expected effect.

The features were added in the following order:

- setters
- transport
- breakdowns
- repairs
- scrap.

8.6.4 Demonstrator

The demonstrator program was written in Pascal, which has strong type casting and so enables many trivial errors to be detected, both at compile time and run time. The program objects of the system, e.g. the driver for UNIPLAN, were built and tested separately to eliminate any errors specific to the object. This would sometimes involve stepping through the code with a debugger and confirming the logic and value of variables are correct. For the drivers this did not always guarantee success. When manually stepping through the code, the software packages have time to complete certain actions and the program logic can appear correct, but when running normally, the program logic might be invalid due to timing problems.

Where reasonable, checks were written into the code to detect runtime errors. Many of these were to check that the correct data were being transferred between objects. There were also a number of more specific checks. For example, in the accounts object, before carrying out the action to period end accounts, a check is made to see that the date of the simulation is after the relevant period end. After entering journal postings, the totals shown by dBFLEX are compared with the totals generated by the controlling program. In the material planning and control object, when updating works and purchase orders, the amount on the order is checked to make sure it is not greater than ordered. In the shop floor object the date used in ATOMS is checked to make sure it agrees with the global simulation date.

The program dynamically allocates memory as it runs, therefore the memory available before and after each run is checked to see it is the same. A difference does not necessarily mean a logic error, but enables detection of programing errors which may have led to problems, e.g. lists which are not cleared properly and so incorrect data may have been used.

The integration techniques used to control the packages were also used to create and check the models. Programs were written to read text files and automatically 'enter' the data. For example, the data that were used to create the ATOMS model were used as input to UNIPLAN (i.e. stock items, product structure) and so ensured consistency of data between the systems. If manual edits were carried out, programs were written to check that the data between the ATOMS model and UNIPLAN were consistent. Text files were also used to enter data into dBFLEX. Much of this data was also used by other elements of the model, e.g. raw materials in ATOMS and UNIPLAN were the same as the sale items of suppliers. In this way data inconsistency was greatly reduced.

Checks were made to see that the works orders between UNIPLAN and ATOMS agreed, that the purchase orders between UNIPLAN and the supplier agreed and that the stock position of ATOMS agreed with that of UNIPLAN. The model was run for 104 weeks and then allowed to run on with no more inputs to UNIPLAN. This was to allow the outstanding works and purchase orders to be completed and so make it easier to check. The works and purchase order positions agreed, i.e. there were no works or purchase orders outstanding in UNIPLAN, no works orders left in ATOMS and no purchase orders left in the supplier. Where the usage of items was in integer quantities (i.e. gears, spindles, spindle assemblies and tolerance rings), the stock positions agreed. Where the usage was in fractions (i.e. bars) many of the items had no difference at 2 decimal places. For some of the high usage sizes (e.g. 14 mm and 18 mm bar) the difference varied between 6 metres more in ATOMS to 3 metres more in UNIPLAN. This was considered acceptable.

The events of the demonstrator could be stepped through. This allowed the sequence of events to be easily observed and checked as acceptable.

The shop floor model used in the demonstrator was the same as that used for the shop floor on its own. Therefore the validation applied to the shop floor on it own is applicable here. The MRP model and financial accounting model are commercial software systems, therefore their conceptual validity is assumed acceptable.

9 EXPERIMENTAL RESULTS

The basis of the experiment has already been discussed but is reiterated here. Two designs of spindle assembly, a 2-piece design (spindle and gear) and a 3-piece design (spindle, gear and tolerance ring) are to be analysed using the following tools:

- design costing
- capacity calculation
- shop floor simulator
- financial model driven by shop floor simulator
- demonstrator enterprise simulation.

Each analysis is to be carried out at two levels of demand (normal and high) with a target of an average delivery performance of 95% on time.

The experiment is not only focused on the results given by each tool, but also on how the tools support the process of successful implementation of each design. Therefore the experiment will also include descriptions of how the tools were used.

For the shop floor simulator (ATOMS) the simulation procedure is:

- single replication
- run-in period of 50 weeks
- data collection period of 250 weeks, split into 5 batches of 50 weeks each
- common random numbers.

For the demonstrator the simulation procedure is:

- 5 replications
- run-in period of 52 weeks
- data collection period of 52 weeks
- common random numbers.

9.1 Design Cost Model

Rather than calculate the total product costs, a comparative calculation has been performed, i.e. the 3-piece design relative to the 2-piece design. Table 9.1 shows that at normal demand the reduction in direct labour costs of the 3-piece design are outweighed by the increase in direct material costs. The addition of overheads leads to the 3-piece design costing £14280 per year less than the 2-piece design.

At the higher demand, it is assumed that the overhead rate does not change. The only change to the calculation is in the yearly demand. At the higher demand the 3-piece design costs £14994 per year less than the 2-piece design (calculation not shown).

9.2 Capacity Calculation

From the capacity calculation the requirements for machines and operators were decided.

At normal demand both design have a relatively high maximum loads of 92% for the 2-piece design (table 9.2) and 90% for the 3-piece design (table 9.3). This was considered acceptable given that most losses have been included. For the 2-piece design the maximum utilisation occurs on the TURN1 work centre while for the 3-piece design it

	Product			
	A	B	C	D
Direct labour costs				
Standard time (mins each)	-0.1028	-0.1028	-0.1028	-0.1028
Direct labour rate (£/min)	0.0702	0.0702	0.0702	0.0702
Direct labour costs (£)	-0.0072	-0.0072	-0.0072	-0.0072
Material costs				
Material cost (due to tolerance ring) (£ each)	0.0120	0.0140	0.0160	0.0180
Scrap cost (£ each)	-0.0023	-0.0033	-0.0045	-0.0060
Material costs (£ each)	0.0097	0.0107	0.0115	0.0120
Overhead costs				
Overhead rate (£/min)	0.1298	0.1298	0.1298	0.1298
Overhead costs (£ each)	-0.0133	-0.0133	-0.0133	-0.0133
Material, Labour & Overhead (£ each)	-0.0109	-0.0099	-0.0091	-0.0085
Yearly demand	106080	517920	468000	443040
Yearly cost difference (£)	-1152	-5104	-4242	-3782
Total difference per year 3-piece cf 2-piece (£)		**-14280**		

Table 9.1 Comparative design-cost calculation at normal demand

Work Centre	Set-up Time (hr)	Process Time (hr)	Down Time (hr)	Repair Time (hr)	Waiting Time (hr)	Required Time (hr)	Available Time (hr)	Utilisation	Number of machines	Number of operators
TURN1	32.00	110.35	4.99	4.99	0.00	147.34	160.00	92%	2	?
MILL	4.00	244.82	2.65	2.65	0.00	251.47	280.00	90%	4	7
BROACH	4.00	122.57	1.33	1.33	0.00	127.89	160.00	80%	2	4
TURN2	48.00	157.64	7.13	7.13	0.00	212.77	240.00	89%	3	?
HEAT	1.00	59.13	0.64	0.64	0.00	60.77	80.00	76%	1	2
GRIND	4.00	278.87	6.40	6.40	0.00	289.26	320.00	90%	4	8
PRESS	4.00	117.96	1.88	1.88	0.00	123.84	160.00	77%	2	4
INSP	0.13	50.18	0.00	0.00	0.00	50.32	80.00	63%	0	2

Table 9.2 Summary capacity calculation for 2-piece design at normal demand

Work Centre	Set-up Time (hr)	Process Time (hr)	Down Time (hr)	Repair Time (hr)	Waiting Time (hr)	Required Time (hr)	Available Time (hr)	Utilisation	Number of machines	Number of operators
TURN1	28.80	96.46	4.53	4.53	0.00	129.79	160.00	81%	2	?
MILL	4.00	241.44	2.62	2.62	0.00	248.06	280.00	89%	4	7
BROACH	4.00	120.85	1.31	1.31	0.00	126.16	160.00	79%	2	4
TURN2	48.00	154.65	6.99	6.99	0.00	209.64	240.00	87%	3	?
HEAT	1.00	57.99	0.63	0.63	0.00	59.62	80.00	75%	1	2
GRIND	2.10	203.47	4.67	4.67	0.00	210.24	240.00	88%	3	6
PRESS	4.00	137.26	2.19	2.19	0.00	143.45	160.00	90%	2	4
INSP	0.13	49.69	0.00	0.00	0.00	49.82	80.00	62%	0	2

Table 9.3 Summary capacity calculation for 3-piece design at normal demand

occurs on the PRESS work centre. For both designs the MILL can be run with four operators on the first shift and three operators on the second shift. The biggest difference is that the 2-piece design requires four machines at the GRIND work centre compared with three for the 3-piece design. This reflects the difference in machining requirements at this work centre. The differences in the assembly time at the PRESS work centre do not quite allow the 2-piece design to run with a two and one shift pattern. The TURN1 and TURN2 work centres are auto-lathes and the number of operators required cannot be determined from the capacity spreadsheet (this is identified with a question mark). The differences in product design therefore have been reflected in differences in the production requirements to make them.

At the high demand the same work centres are still the most highly loaded, with the level now at 96% (TURN1) for the 2-piece design (table 9.4) and 94% (PRESS) for the 3-piece design (table 9.5). Although not at 100% load, the utilisation levels are high.

Work Centre	Set-up Time (hr)	Process Time (hr)	Down Time (hr)	Repair Time (hr)	Waiting Time (hr)	Required Time (hr)	Available Time (hr)	Utilisation	Number of machines	Number of operators
TURN1	32.00	115.87	5.24	5.24	0.00	153.11	160.00	96%	2	?
MILL	4.00	257.06	2.78	2.78	0.00	263.84	280.00	94%	4	7
BROACH	4.00	128.70	1.39	1.39	0.00	134.09	160.00	84%	2	4
TURN2	48.00	165.53	7.48	7.48	0.00	221.01	240.00	92%	3	?
HEAT	1.00	62.08	0.67	0.67	0.00	63.75	80.00	80%	1	2
GRIND	4.00	292.81	6.72	6.72	0.00	303.53	320.00	95%	4	8
PRESS	4.00	123.86	1.98	1.98	0.00	129.83	160.00	81%	2	4
INSP	0.13	52.69	0.00	0.00	0.00	52.83	80.00	66%	0	2

Table 9.4 Summary capacity calculation for 2-piece design at high demand

Work Centre	Set-up Time (hr)	Process Time (hr)	Down Time (hr)	Repair Time (hr)	Waiting Time (hr)	Required Time (hr)	Available Time (hr)	Utilisation	Number of machines	Number of operators
TURN1	28.80	101.29	4.75	4.75	0.00	134.84	160.00	84%	2	?
MILL	4.00	253.51	2.75	2.75	0.00	260.26	280.00	93%	4	7
BROACH	4.00	126.90	1.37	1.37	0.00	132.27	160.00	83%	2	4
TURN2	48.00	162.39	7.34	7.34	0.00	217.73	240.00	91%	3	?
HEAT	1.00	60.89	0.66	0.66	0.00	62.55	80.00	78%	1	2
GRIND	2.10	213.64	4.90	4.90	0.00	220.65	240.00	92%	3	6
PRESS	4.00	144.12	2.30	2.30	0.00	150.42	160.00	94%	2	4
INSP	0.13	52.18	0.00	0.00	0.00	52.31	80.00	65%	0	2

Table 9.5 Summary capacity calculation for 3-piece design at high demand

9.3 Shop Floor Simulation - ATOMS

As the shop floor simulator did not provide delivery performance measures, the long term trend of the WIP was used as a measure of acceptable performance. The aim was for a generally stable WIP level, indicating that there was on average enough capacity; this is to some extent a qualitative judgement.

Using the capacity spreadsheet calculations as a basis, two shop floor simulation models were built using ATOMS, one for the 2-piece design and one for the 3-piece design. The personnel not identified in the capacity spreadsheet (auto-lathe operators, craftsmen and transport operators) were each set at one per shift. These configurations gave acceptable performances.

Figures 9.1 and 9.2 show the weekly input, output and WIP for the acceptable configurations of the 2-piece and 3-piece designs respectively over the first 104 week period and is typical of the whole 300 week run. The first 104 week period has been shown to make the scale of the graphs the same as those of the demonstrator runs to be described

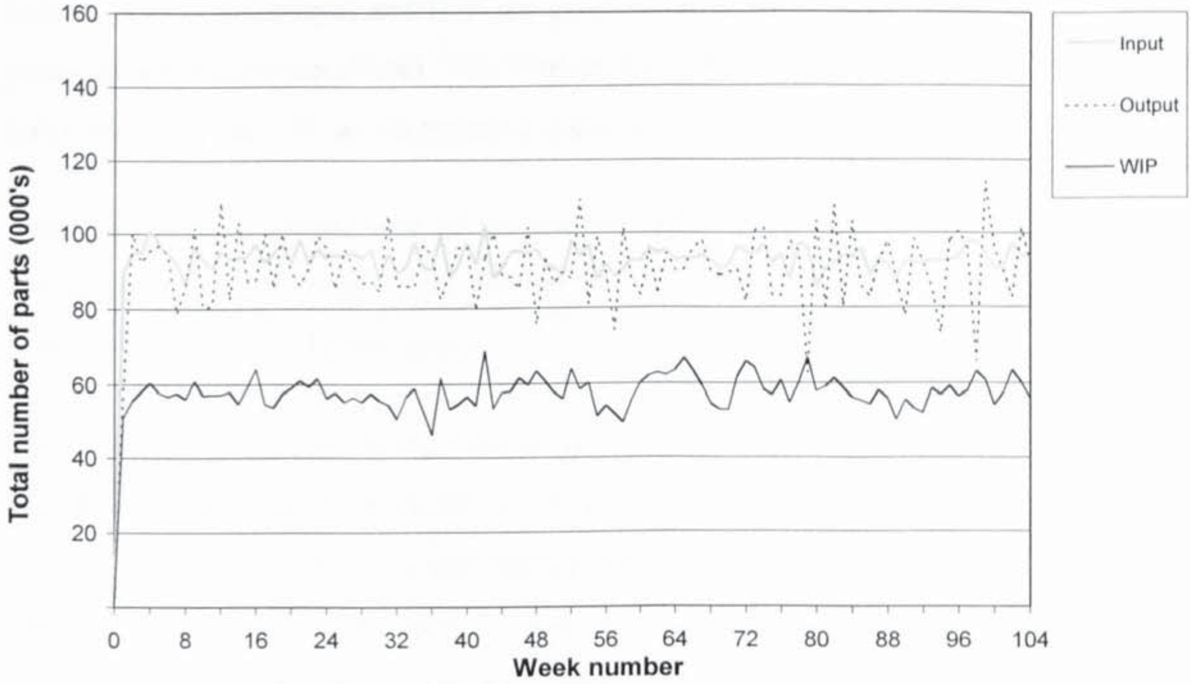


Figure 9.1 Input, output and WIP for ATOMS 2-piece design at normal demand

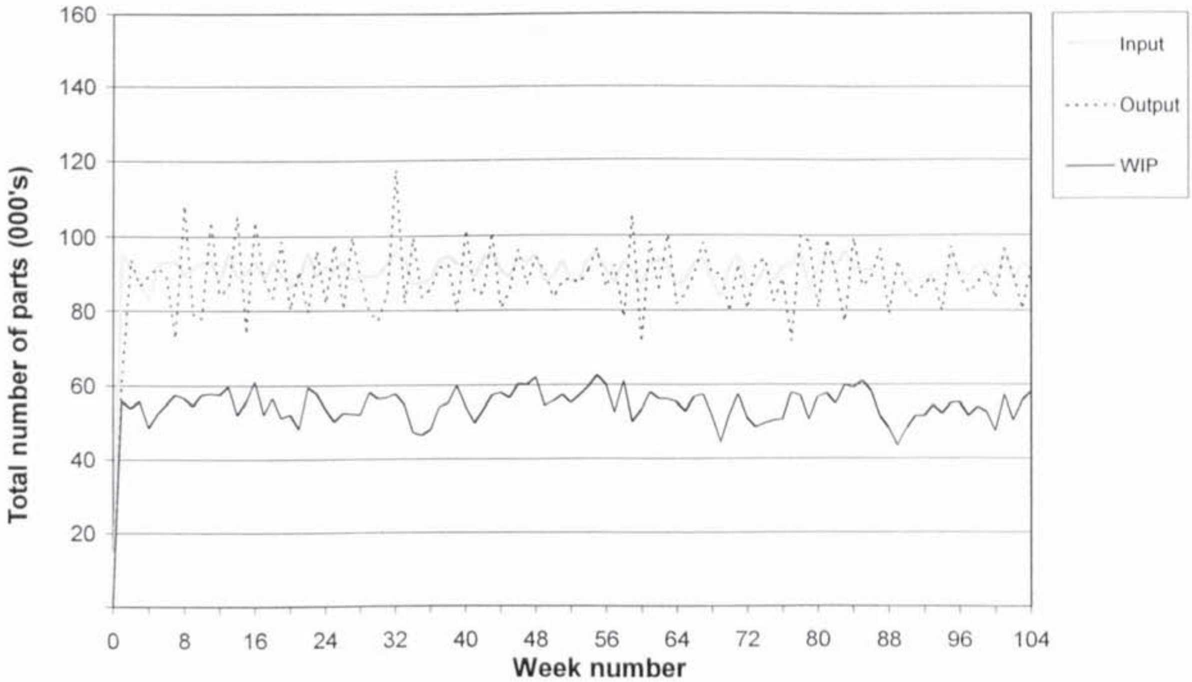


Figure 9.2 Input, output and WIP for ATOMS 3-piece design at normal demand

below. The input, output and WIP are given in terms of the total number of parts (i.e. gears, spindles and assemblies). The WIP shown in the graphs is the average level for the week based on the WIP levels reported at the end of each working day.

Table 9.6 gives a comparison of the average WIP levels (the average of the weekly averages) for each 50 week batch. The WIP levels of the two designs are similar, with the 3-piece design being slightly lower.

The values used for calculating utilisation have also been taken from the five 50 week batches and are shown in tables 9.7 and 9.8 for the 2-piece and 3-piece designs respectively. Also shown for comparison are the utilisation figures from the relevant capacity calculations. The highest loaded work centres identified by ATOMS are the same as those identified by the capacity calculation, but show higher utilisation values in ATOMS, i.e. 96% at the TURN1 for the 2-piece design, 93% at the PRESS for the 3-piece design. The utilisation values produced by the capacity calculation are different to ATOMS for a number of reasons and are generally lower, in some cases by as much as 5%. Set-up time in ATOMS is generally lower than the capacity calculation, and is most noticeable for the TURN1 and TURN2 work centres which have long set-up times. The difference may be due to the randomising of the works orders. This could lead to the last works order of one week being for the same component as the works order of the following week and so not requiring a set-up. In the capacity calculation it was assumed that there would be a set-up for each works order. Processing times reported by ATOMS are similar to the capacity calculation but repair time is slightly higher. Waiting time in ATOMS is significant at some work centres but was ignored in the capacity calculation, e.g. the waiting time at the GRIND work centre is about 4% of the available time.

These two shop floor designs were then tested at the high demand. Figures 9.3 and 9.4 show the input, output and WIP for the 2-piece and 3-piece designs respectively. Although more variable and slightly higher than at normal demand, the WIP is considered acceptable in both cases. The higher WIP levels are confirmed by table 9.9. which shows the WIP levels for each 50 week batch. In this case the average WIP for the 3-piece design is slightly higher than for the 2-piece design.

Normal demand 50 week batches	Average WIP Levels 2-Piece Design	3-Piece Design
Batch 1	58112	54034
Batch 2	56586	55251
Batch 3	55850	56731
Batch 4	57521	54067
Batch 5	56807	55455
Overall Mean	56975	55107

Table 9.6 WIP levels for ATOMS models at normal demand

Work Centre	Set-up Time (hr)	Process Time (hr)	Down Time (hr)	Repair Time (hr)	Waiting Time (hr)	Required Time (hr)	Available Time (hr)	ATOMS Utilisation	Cap. SS Utilisation	Difference
TURN1	29.82	112.16	11.01	5.73	5.29	153.00	160.00	96%	92%	4%
MILL	3.20	244.71	10.37	2.92	7.45	258.28	280.00	92%	90%	2%
BROACH	3.70	122.43	5.09	1.46	3.62	131.22	160.00	82%	80%	2%
TURN2	40.20	158.50	14.21	8.09	6.12	212.91	240.00	89%	89%	0%
HEAT	1.01	59.69	2.20	0.83	1.37	62.90	80.00	79%	76%	3%
GRIND	3.12	280.03	22.25	7.37	14.88	305.40	320.00	95%	90%	5%
PRESS	3.72	119.04	7.51	2.03	5.48	130.27	160.00	81%	77%	4%
INSP	0.15	49.75	0.00	0.00	0.00	49.90	80.00	62%	63%	-1%

Table 9.7 Work centre summary for ATOMS 2-piece design at normal demand

Work Centre	Set-up Time (hr)	Process Time (hr)	Down Time (hr)	Repair Time (hr)	Waiting Time (hr)	Required Time (hr)	Available Time (hr)	ATOMS Utilisation	Cap. SS Utilisation	Difference
TURN1	26.25	98.07	9.82	4.98	4.84	134.13	160.00	84%	81%	3%
MILL	3.21	241.45	8.96	2.95	6.01	253.63	280.00	91%	89%	2%
BROACH	3.79	120.82	4.71	1.58	3.13	129.32	160.00	81%	79%	2%
TURN2	40.61	154.48	13.27	7.85	5.42	208.35	240.00	87%	87%	0%
HEAT	1.01	58.19	1.82	0.74	1.08	61.03	80.00	76%	75%	1%
GRIND	1.78	202.52	15.09	5.25	9.84	219.39	240.00	91%	88%	3%
PRESS	3.64	137.87	7.24	2.38	4.87	148.75	160.00	93%	90%	3%
INSP	0.15	49.44	0.00	0.00	0.00	49.59	80.00	62%	62%	0%

Table 9.8 Work centre summary for ATOMS 3-piece design at normal demand

The utilisation levels for the two designs are given in tables 9.10 and 9.11. The average levels are now showing signs of reaching full capacity with levels as high as 99% at the TURN1 and GRIND work centres for the 2-piece design and 98% at the PRESS for the 3-piece design. Although these figures may be slightly higher than actual due to the reporting mechanism of ATOMS, there is no doubt that the utilisation at some of the work centres is very high. The WIP levels show that there is still enough capacity on average to deal with the high demand and so both are considered acceptable.

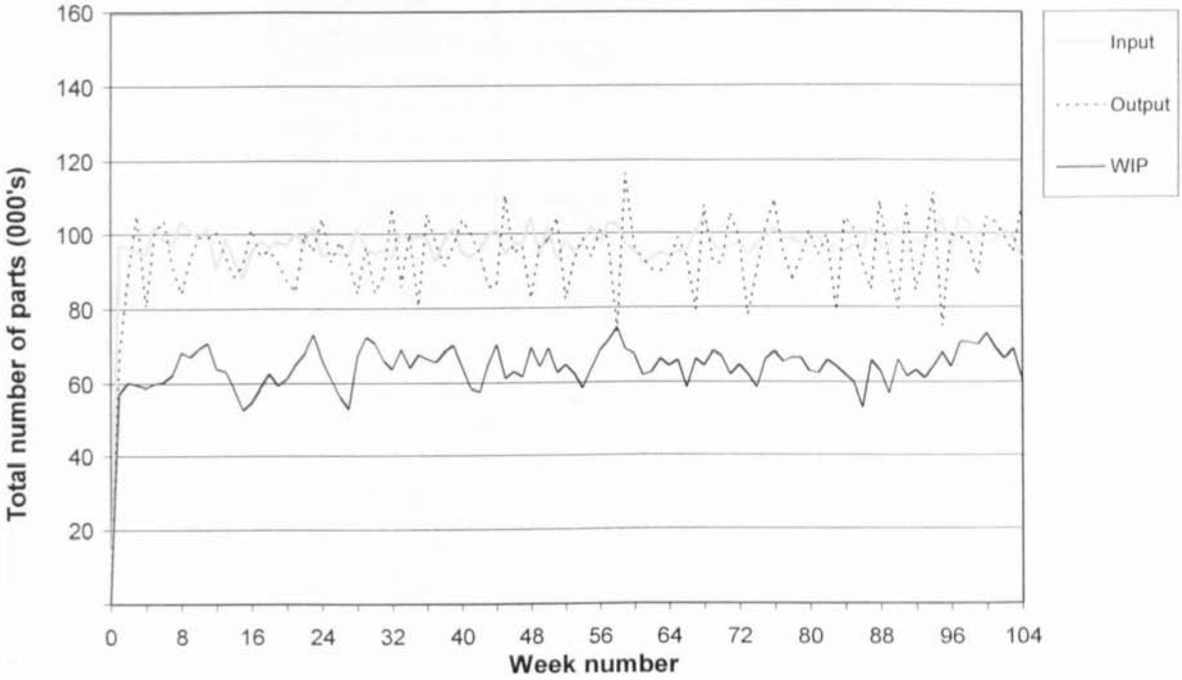


Figure 9.3 Input, output and WIP for ATOMS 2-piece design at high demand

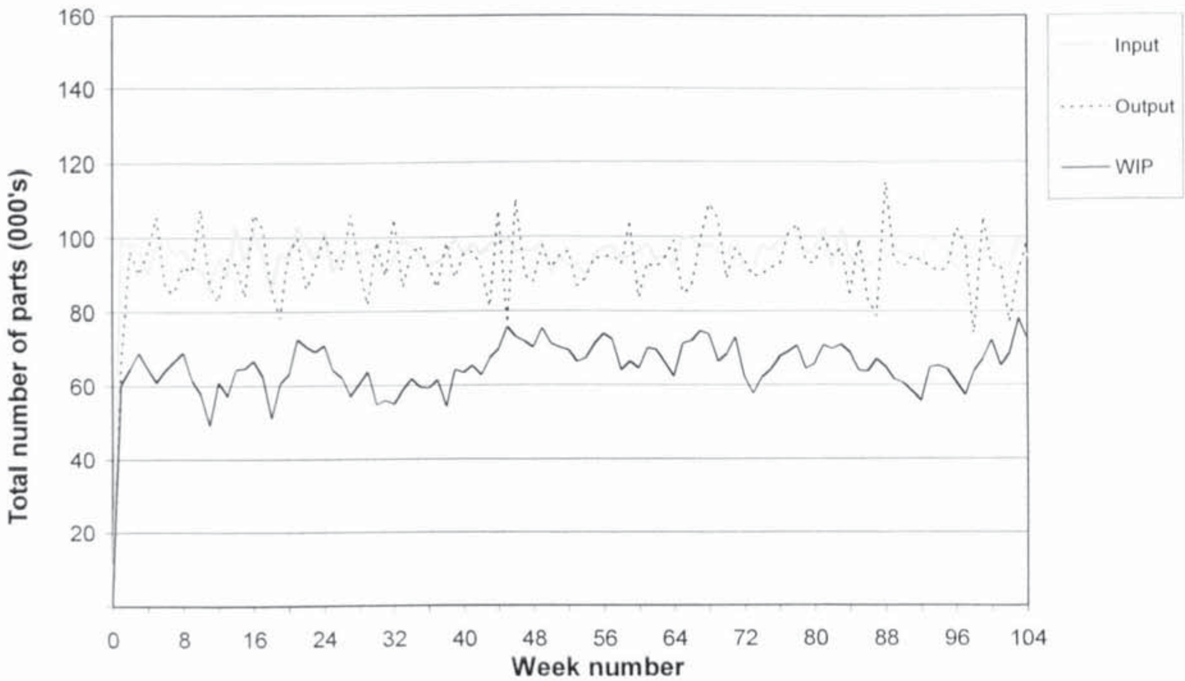


Figure 9.4 Input, output and WIP for ATOMS 3-piece design at high demand

	Average WIP Levels	
High demand 50 week batches	2-Piece Design	3-Piece Design
Batch 1	64769	66595
Batch 2	62710	68237
Batch 3	65641	72679
Batch 4	62260	63589
Batch 5	65316	63219
Overall Mean	64139	66864

Table 9.9 WIP levels for ATOMS models at high demand

Work Centre	Set-up Time (hr)	Process Time (hr)	Down Time (hr)	Repair Time (hr)	Waiting Time (hr)	Required Time (hr)	Available Time (hr)	ATOMS Utilisation	Cap. SS Utilisation	Difference
TURN1	29.52	116.88	11.33	5.84	5.50	157.73	160.00	99%	96%	3%
MILL	3.23	255.30	9.89	3.10	6.79	268.42	280.00	96%	94%	2%
BROACH	3.67	127.73	5.17	1.70	3.48	136.58	160.00	85%	84%	1%
TURN2	40.88	165.07	14.71	8.47	6.24	220.67	240.00	92%	92%	0%
HEAT	1.02	62.18	2.01	0.71	1.30	65.21	80.00	82%	80%	2%
GRIND	3.20	291.32	22.59	7.65	14.94	317.12	320.00	99%	95%	4%
PRESS	3.70	125.92	7.47	2.25	5.22	137.09	160.00	86%	81%	5%
INSP	0.15	52.62	0.00	0.00	0.00	52.77	80.00	66%	66%	0%

Table 9.10 Work centre summary for ATOMS 2-piece design at high demand

Work Centre	Set-up Time (hr)	Process Time (hr)	Down Time (hr)	Repair Time (hr)	Waiting Time (hr)	Required Time (hr)	Available Time (hr)	ATOMS Utilisation	Cap. SS Utilisation	Difference
TURN1	26.52	102.70	9.25	5.19	4.06	138.48	160.00	87%	84%	3%
MILL	3.24	253.10	9.60	3.17	6.44	265.94	280.00	95%	93%	2%
BROACH	3.71	126.63	4.35	1.48	2.87	134.69	160.00	84%	83%	1%
TURN2	40.56	163.25	14.10	8.38	5.72	217.90	240.00	91%	91%	0%
HEAT	1.06	61.50	2.43	0.83	1.60	64.99	80.00	81%	78%	3%
GRIND	1.80	214.27	15.81	5.59	10.23	231.88	240.00	97%	92%	5%
PRESS	3.81	144.70	7.86	2.51	5.35	156.38	160.00	98%	94%	4%
INSP	0.15	52.23	0.00	0.00	0.00	52.38	80.00	65%	65%	0%

Table 9.11 Work centre summary for ATOMS 3-piece design at high demand

9.4 Shop Floor Simulation Financial Model

In building the financial models, product cost models were also built. The results of these are shown in table 9.12 which gives the product costs at the normal demand for both designs. The 3-piece design costs £4518 per year less than the 2-piece design. At the high demand the trend is the same but slightly reduced to £3531 per year less for the 3-piece design (table 9.13). These are different to the design cost calculation. While they both favour the 3-piece design, the ATOMS cost difference is much lower and the trend is

	Material Cost (£)	Std. Time (min)	Lab Rate (£/hour)	Direct Lab Cost (£)	Varible Cost (£)	O/H Rate (£/hour)	O/H Cost (£)	Total (£)	Yearly Demand	Yearly Cost (£)
2-Piece Design										
SPDL_ASY_A	0.086	1.809	4.210	0.127	0.213	7.680	0.232	0.4443	106080	47136
SPDL_ASY_B	0.121	1.809	4.210	0.127	0.248	7.680	0.232	0.4798	517920	248520
SPDL_ASY_C	0.164	1.809	4.210	0.127	0.291	7.680	0.232	0.5229	468000	244701
SPDL_ASY_D	0.217	1.809	4.210	0.127	0.344	7.680	0.232	0.5751	443040	254791
									Total cost	795148
3-Piece Design										
SPDL_ASY_A	0.096	1.706	4.210	0.120	0.215	7.898	0.225	0.4398	106080	46659
SPDL_ASY_B	0.132	1.706	4.210	0.120	0.252	7.898	0.225	0.4763	517920	246710
SPDL_ASY_C	0.176	1.706	4.210	0.120	0.296	7.898	0.225	0.5202	468000	243434
SPDL_ASY_D	0.229	1.706	4.210	0.120	0.348	7.898	0.225	0.5729	443040	253827
									Total cost	790630
	Difference per year 3-piece cf 2-piece (£)									-4518

Table 9.12 Standard product costing at normal demand

	Material Cost (£)	Std. Time (min)	Lab Rate (£/hour)	Direct Lab Cost (£)	Varible Cost (£)	O/H Rate (£/hour)	O/H Cost (£)	Total (£)	Yearly Demand	Yearly Cost (£)
2-Piece Design										
SPDL_ASY_A	0.086	1.809	4.210	0.127	0.213	7.131	0.215	0.4278	111384	47648
SPDL_ASY_B	0.121	1.809	4.210	0.127	0.248	7.131	0.215	0.4633	543816	251935
SPDL_ASY_C	0.164	1.809	4.210	0.127	0.291	7.131	0.215	0.5063	491400	248793
SPDL_ASY_D	0.217	1.809	4.210	0.127	0.344	7.131	0.215	0.5585	465192	259823
									Total cost	808199
3-Piece Design										
SPDL_ASY_A	0.096	1.706	4.210	0.120	0.215	7.342	0.209	0.4240	111384	47230
SPDL_ASY_B	0.132	1.706	4.210	0.120	0.252	7.342	0.209	0.4605	543816	250444
SPDL_ASY_C	0.176	1.706	4.210	0.120	0.296	7.342	0.209	0.5043	491400	247834
SPDL_ASY_D	0.229	1.706	4.210	0.120	0.348	7.342	0.209	0.5571	465192	259160
									Total cost	804668
	Difference per year 3-piece cf 2-piece (£)									-3531

Table 9.13 Standard product costing at high demand

opposite, i.e. at high demand the difference in the ATOMS cost model has reduced whereas in the design cost model the difference has increased.

The output of the ATOMS financial model for both designs at normal demand is shown in table 9.14. This shows a profit and loss account, balance sheet and profitability measures for the second year. Interest is shown as negative due to positive cash balance at the bank. Creditors are not as high as they should since many payments are assumed to be made directly and any associated payment delays are not included.

The financial figures reflect some of the differences in the models. Creditors (suppliers) are slightly higher in the 3-piece design due the need to purchase the tolerance ring. Plant values are higher in the 2-piece design due to the greater investment in machinery for this design. The profit before tax is £4885 higher for the 3-piece. Profit should be viewed in relation to the amount of investment required to earn it. Two financial ratios are given,

Profit & Loss Account	2-Piece design	3-Piece design
Sales	£1,213,874	£1,213,874
Direct Materials	£244,781	£262,048
Direct Labour	£236,434	£218,920
Production Overhead	£313,934	£309,661
Less Stock Movement	£0	£0
Cost of Sales	£795,148	£790,630
Gross Profit	£418,726	£423,245
Sales Tech & Admin	£245,700	£245,700
Interest	-£7,442	-£7,808
Profit Before Tax	£180,468	£185,353
Tax @ 30%	£54,141	£55,606
Profit ATI (Earnings)	£126,328	£129,747
Div @ 5% of Year 1 SHF	£45,163	£44,030
Retained profits	£81,165	£85,717

Balance Sheet	2-Piece design	3-Piece design
Assets		
Buildings	£200,000	£200,000
Plant	£458,440	£436,440
Fixed Assets	£658,440	£636,440
Inventory	£29,845	£29,254
Debtors	£186,750	£186,750
Bank	£148,516	£155,545
Current Assets	£365,111	£371,550
Total Assets	£1,023,551	£1,007,990
Liabilities		
Current Liabilites		
Creditors	£39,133	£41,673
Share Holders Fund		
Ordinary Shares	£857,749	£832,414
Reserves	£45,504	£48,186
P&L account	£81,165	£85,717
Total SHF	£984,418	£966,317
Total Liabilities	£1,023,551	£1,007,990
Net Current Assets	£325,978	£329,877
(Current assets - current liabilities)		
Net Assets	£984,418	£966,317
(Fixed assets + net current assets)		

Profitability	2-Piece design	3-Piece design
ROCE	18.3%	19.2%
Return on Equity	12.8%	13.4%

Table 9.14 ATOMS financial model at normal demand

return on capital employed (ROCE) and return on equity. The former is a measure of how well the manufacturing operations are performing, while the latter is a measure relevant to the share holders because it relates to the earnings. With higher profit and lower investment, the 3-piece design has better profitability than the 2-piece design.

The financial performance at high demand is shown in table 9.15. The 3-piece design still generates more profit before tax than the 2-piece design, but the difference is reduced to £3832 per year. Both designs show a marked improvement in profitability compared with the results at normal demand.

9.5 Demonstrator

In the same way that the ATOMS models used the capacity calculations as a basis, the demonstrator models used the ATOMS shop floor models as a basis. To complete the demonstrator models required setting up the manufacturing planning and control system, financial accounts, customer and supplier aspects. For the manufacturing planning and control system this involved decisions on lead time offsets, safety stock levels, reorder quantity, forecast period and MPS planning horizon. These and other aspects are covered in appendix 1. Several versions of each model were built and these will be identified as DEM/design/version, e.g. DEM/2P/2 is the demonstrator model for the 2-piece design, second version.

9.5.1 Results at Normal Demand

Each model was run for two years and replicated 5 times. The number of orders delivered late is shown in table 9.16 for the second year. The performance for both models is unacceptable against the requirement of an average of 5% late orders (10 orders per year).

An overall idea of the system performance can seen in figures 9.5 and 9.6 which show the weekly average input, output and WIP levels for the first replication of the 2-piece and 3-piece designs respectively (the other replications were of a similar nature). The behaviour of the total system is very different to that of the shop floor simulator on its own. The batching policy seems to have led to an amplification in the variability of demand. Variations in input have subsequently led to large variations in the WIP levels. While the

Profit & Loss Account	2-Piece design	3-Piece design
Sales	£1,274,568	£1,274,568
Direct Materials	£257,020	£275,151
Direct Labour	£236,434	£218,920
Production Overhead	£314,745	£310,597
Less Stock Movement	£0	£0
Cost of Sales	£808,199	£804,668
Gross Profit	£466,369	£469,900
Sales Tech & Admin	£245,700	£245,700
Interest	-£10,460	-£10,761
Profit Before Tax	£231,129	£234,961
Tax @ 30%	£69,339	£70,488
Profit ATI (Earnings)	£161,790	£164,473
Div @ 5% of Year 1 SHF	£46,876	£45,710
Retained profits	£114,914	£118,763

Balance Sheet	2-Piece design	3-Piece design
Assets		
Buildings	£200,000	£200,000
Plant	£458,440	£436,440
Fixed Assets	£658,440	£636,440
Inventory	£29,997	£29,462
Debtors	£196,087	£196,087
Bank	£208,993	£214,729
Current Assets	£435,077	£440,279
Total Assets	£1,093,517	£1,076,719
Liabilities		
Current Liabilites		
Creditors	£41,079	£43,761
Share Holders Fund		
Ordinary Shares	£857,749	£832,414
Reserves	£79,775	£81,781
P&L account	£114,914	£118,763
Total SHF	£1,052,438	£1,032,958
Total Liabilities	£1,093,517	£1,076,719
Net Current Assets	£393,998	£396,518
(Current assets - current liabilities)		
Net Assets	£1,052,438	£1,032,958
(Fixed assets + net current assets)		

Profitability	2-Piece design	3-Piece design
ROCE	22.0%	22.7%
Return on Equity	15.4%	15.9%

Table 9.15 ATOMS financial model at high demand

Normal demand Year 2	2-Piece Design (DEM/2P/1)		3-Piece Design (DEM/3P/1)	
	No. of orders late	% of orders late	No. of orders late	% of orders late
Replication 1	29	13.9%	37	17.8%
Replication 2	69	33.2%	47	22.6%
Replication 3	36	17.3%	22	10.6%
Replication 4	19	9.1%	38	18.3%
Replication 5	40	19.2%	38	18.3%
Mean	38.6	18.6%	36.4	17.5%

Table 9.16 Delivery performance for demonstrator models DEM/2P/1 and DEM/3P/1 at normal demand

WIP is varying greatly, the general trend is reasonably level suggesting that the capacity is acceptable. Table 9.17 show the average WIP levels over the second 52 week period for the 5 replications. These figures are about one and half times that of the shop floor simulator on its own. Even though WIP level might be expected to be sensitive at high levels of utilisation this increase seems excessive, especially as utilisation, discussed below, has changed little from the shop floor simulator model.

The average utilisation of the 5 replications over the second 52 week period is given in tables 9.18 and 9.19 for the two designs. For comparison utilisation figures from the relevant ATOMS shop floor simulations are shown and there is little difference between them. For the output times shown in the work centre summaries there are minor differences which are expected due to randomness. The largest difference between the demonstrator and ATOMS is in set-up time for the TURN1 and TURN2 work centres, where it is higher in the demonstrator than in the corresponding ATOMS models, e.g. demonstrator 2-piece design, TURN2 set-up time of 42.73 hours compared with ATOMS 2-piece design, TURN2 set-up time of 40.20 hours.

A different view of system behaviour can be seen by looking at figures 9.7 and 9.8 which show the weekly average stock levels for the first replication of the 2-piece and 3-piece designs respectively. (Note, the stock levels for the raw materials have been converted into the equivalent number of components.) These show, that like the input and WIP, the material levels are very variable and much greater then expected.

While these tables and figures give an overall impression of the model performance and behaviour they do not indicate the source of poor delivery performance. An investigation of the raw materials stock levels and works order requirements showed that there was a

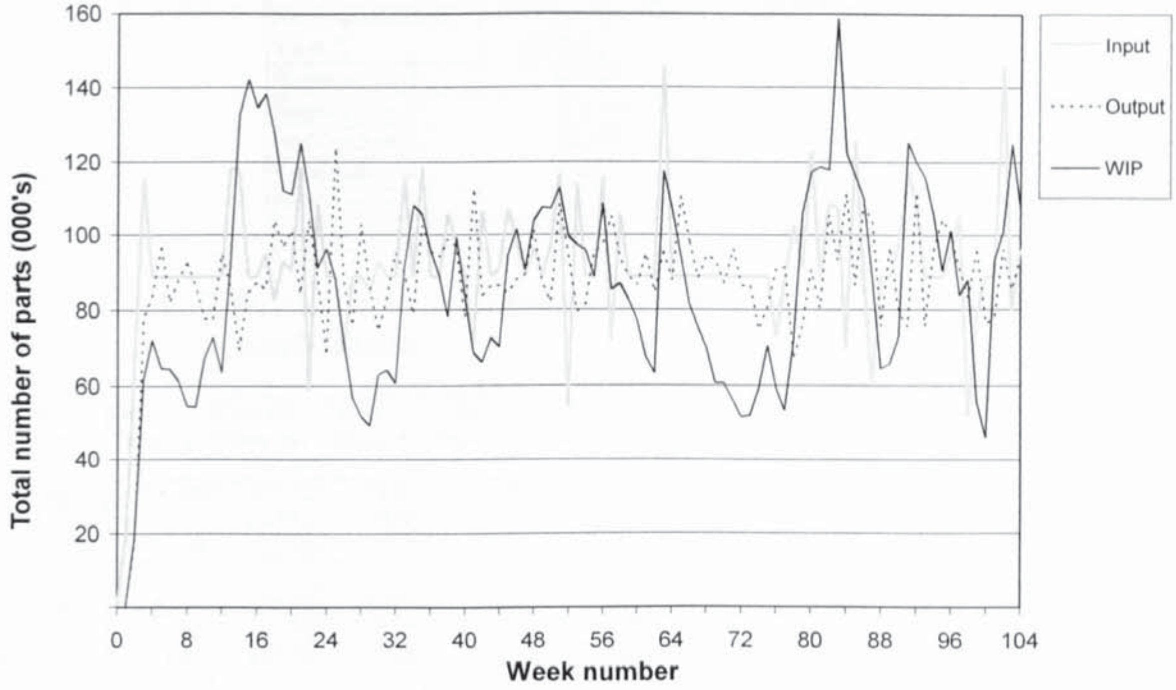


Figure 9.5 Input, output and WIP for demonstrator 2-piece design DEM/2P/1 at normal demand (1st replication)

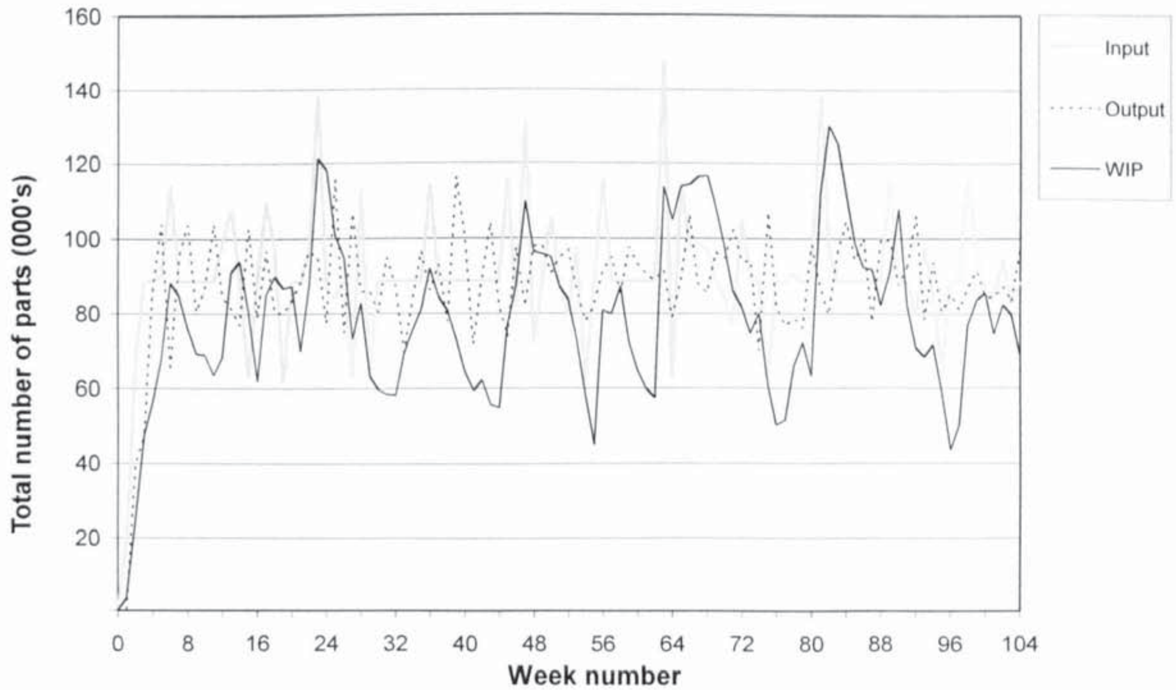


Figure 9.6 Input, output and WIP for demonstrator 3-piece design DEM/3P/1 at normal demand (1st replication)

Normal demand Year 2	Average WIP Levels 2-Piece Design (DEM/2P/1)	3-Piece Design (DEM3P/1)
Replication 1	88652	82509
Replication 2	103758	81932
Replication 3	88275	77929
Replication 4	80157	76682
Replication 5	96195	78282
Overall Mean	91407	79467

Table 9.17 WIP levels for demonstrator models DEM/2P/1 and DEM/3P/1 at normal demand

Work Centre	Set-up Time (hr)	Process Time (hr)	Down Time (hr)	Repair Time (hr)	Waiting Time (hr)	Required Time (hr)	Available Time (hr)	Demo Utilisation	ATOMS Utilisation	Difference
TURN1	31.02	111.75	11.43	5.75	5.68	154.21	160.00	96%	96%	0%
MILL	3.34	243.89	9.68	3.00	6.68	256.91	280.00	92%	92%	0%
BROACH	3.91	122.02	4.75	1.57	3.18	130.68	160.00	82%	82%	0%
TURN2	42.73	159.28	14.64	8.32	6.32	216.65	240.00	90%	89%	1%
HEAT	1.09	60.05	2.75	0.79	1.95	63.88	80.00	80%	79%	1%
GRIND	3.40	281.31	22.86	7.71	15.14	307.56	320.00	96%	95%	1%
PRESS	3.78	119.54	6.92	2.06	4.87	130.25	160.00	81%	81%	0%
INSP	0.15	49.82	0.00	0.00	0.00	49.97	80.00	62%	62%	0%

Table 9.18 Work centre summary for demonstrator 2-piece design DEM/2P/1 at normal demand

Work Centre	Set-up Time (hr)	Process Time (hr)	Down Time (hr)	Repair Time (hr)	Waiting Time (hr)	Required Time (hr)	Available Time (hr)	Demo Utilisation	ATOMS Utilisation	Difference
TURN1	27.11	97.44	9.56	5.21	4.36	134.11	160.00	84%	84%	0%
MILL	3.37	241.03	8.48	3.00	5.47	252.87	280.00	90%	91%	-1%
BROACH	3.86	120.59	4.13	1.47	2.67	128.58	160.00	80%	81%	-1%
TURN2	41.56	154.79	13.02	7.69	5.33	209.37	240.00	87%	87%	0%
HEAT	1.05	58.35	2.15	0.76	1.39	61.55	80.00	77%	76%	1%
GRIND	1.87	203.37	13.71	5.40	8.31	218.95	240.00	91%	91%	0%
PRESS	3.79	137.44	6.22	2.45	3.77	147.45	160.00	92%	93%	-1%
INSP	0.15	49.25	0.00	0.00	0.00	49.40	80.00	62%	62%	0%

Table 9.19 Work centre summary for demonstrator 3-piece design DEM/3P/1 at normal demand

stock out occurring almost every week, for each item. The variability in demand for raw materials is more than was assumed when the safety stock levels were set. While this would be expected to affect customer delivery performance, its effect is increased due to the shop floor policy of only releasing works orders when all the material is available. This policy therefore will hold up an order even if there is only a small amount of material short. The safety stock level for raw materials and purchased parts were therefore increased to the average demand plus 20% so that generally there would be enough raw

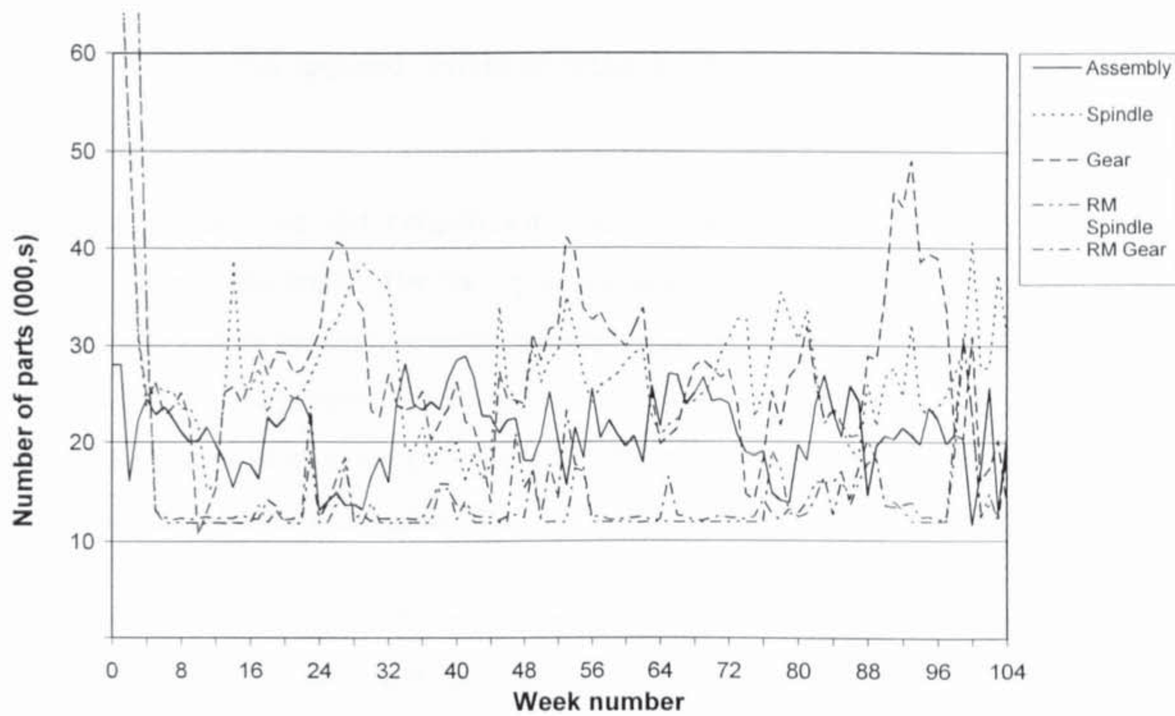


Figure 9.7 Material stock levels for demonstrator 2-piece design DEM/2P/1 at normal demand (1st replication)

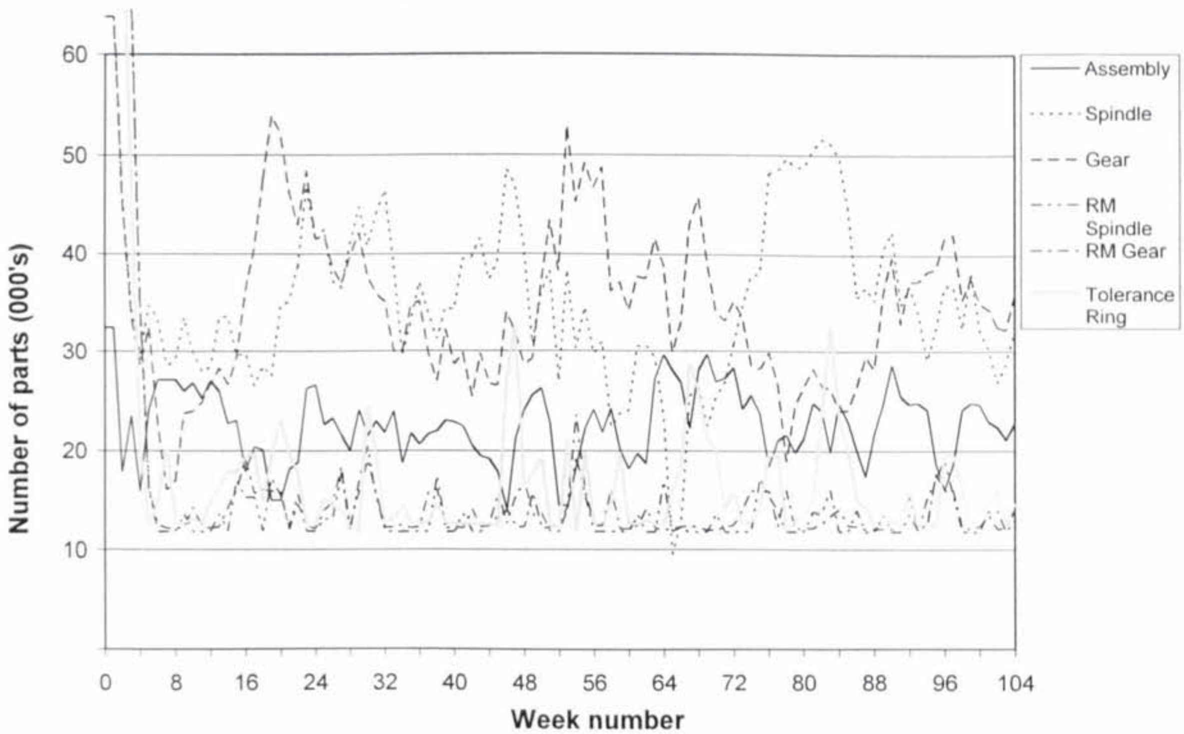


Figure 9.8 Material stock levels for demonstrator 3-piece design DEM/3P/1 at normal demand (1st replication)

material stock when required (details of actual levels are given in appendix 3, section A3.1).

This change was tested and it significantly reduced the number of stock outs but it did not eliminate them completely. For the 2-piece design there was an average of about 8 stock outs per year and for the 3-piece design an average of about 4 stock outs per year. Delivery performance was improved. The 3-piece design was acceptable at average of 3.7% late orders while the 2-piece design was unacceptable at 7.7% late orders. These models were designated DEM/2P/2 and DEM/3P/2.

The policy of zero safety stock for finished goods was reconsidered because of the large variability in load. It was decided to set some finished goods safety stock as a way of improving the delivery performance. As a first estimate the standard stock control equation was used and this gave a safety stock level of about 15% of the average demand (details are given in appendix 3, section A3.2).

Although the 3-piece design was acceptable the finished goods safety stock was also increased in this model. These two models were designated DEM/2P/3 and DEM/3P/3. The overall improvement in delivery performance can be seen in table 9.20. The 2-piece design is acceptable against the requirement of 5% late orders. Interestingly the 3-piece design has improved but by not as much as the 2-piece design. These configurations were therefore considered acceptable.

Figures 9.9 and 9.10 show the WIP levels for the first replication. While the delivery performance is now acceptable overall behaviour is still very variable. Table 9.21 shows the average WIP levels; they are lower than the initial configurations but still above those

Normal demand Year 2	2-Piece Design (DEM/2P/3)		3-Piece Design (DEM/3P/3)	
	No. of orders late	% of orders late	No. of orders late	% of orders late
Replication 1	4	1.9%	2	1.0%
Replication 2	5	2.4%	19	9.1%
Replication 3	4	1.9%	2	1.0%
Replication 4	1	0.5%	4	1.9%
Replication 5	2	1.0%	0	0.0%
Mean	3.2	1.5%	5.4	2.6%

Table 9.20 Delivery performance for demonstrator models DEM/2P/3 and DEM/3P/3 at normal demand

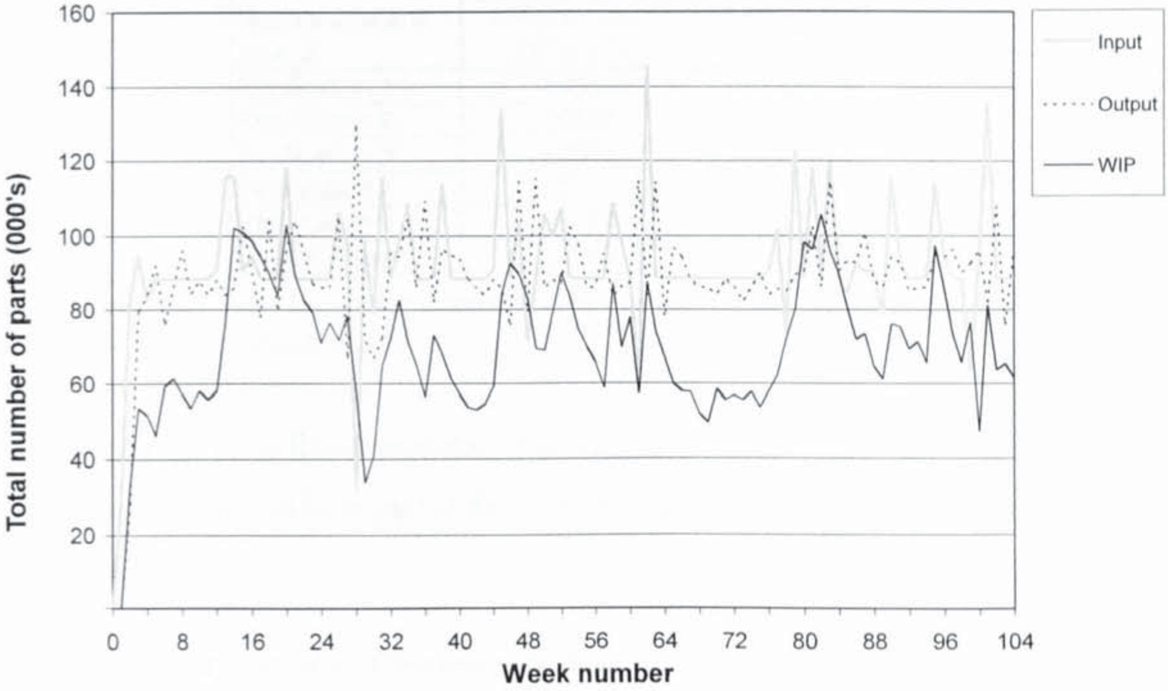


Figure 9.9 Input, output and WIP for demonstrator 2-piece design DEM/2P/3 at normal demand (1st replication)

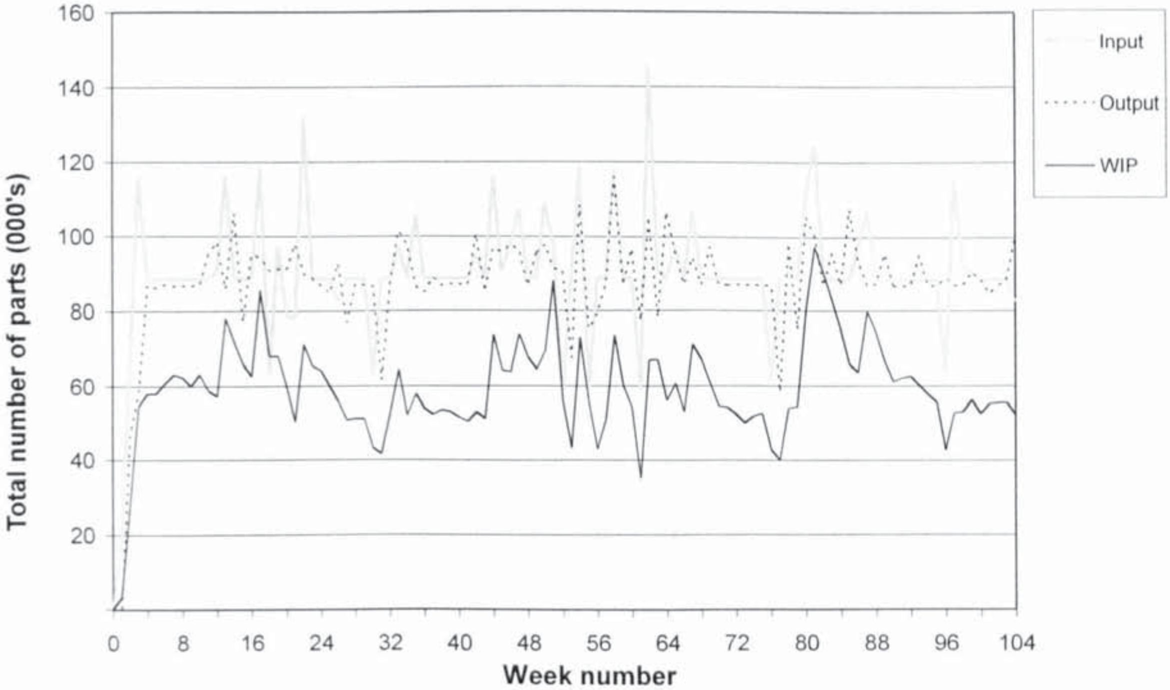


Figure 9.10 Input, output and WIP for demonstrator 3-piece design DEM/3P/3 at normal demand (1st replication)

Normal demand Year 2	Average WIP Levels 2-Piece Design (DEM/2P/3)	3-Piece Design (DEM3P/3)
Replication 1	70669	59775
Replication 2	70828	71000
Replication 3	72805	61217
Replication 4	65732	56391
Replication 5	69294	57789
Overall Mean	69866	61234

Table 9.21 WIP levels for demonstrator models DEM/2P/3 and DEM/3P/3 at normal demand

predicted by the shop floor simulator. Material stock levels were still very variable and had increased as would be expected due to the increase in finished goods and raw material safety stock levels.

The financial performance of the two models in their acceptable configurations is shown in table 9.22. Finances are for the second year of operation and are the average of the 5 replications. The sales value is different to that of the ATOMS financial model and is different between the 2-piece and 3-piece designs because the demonstrator sales values are based on invoiced sales. The total invoiced for the year can vary between replications depending how the invoices occur at the beginning and end of the financial year.

The timing of invoices at the year ends (first and second year) will have the same effect on purchases. There will also be differences in material purchases due to effect the of scrap being handled properly in the demonstrator compare with the ATOMS financial model.

The profit before tax is higher for the 2-piece design by £1054 which is the reverse of the ATOMS financial model. However profitability is slightly better for the 3-piece design due to the lower investment required.

9.5.2 Results at High Demand

As with the shop floor simulator the acceptable configurations were tested at high demand without any changes. This led to a large reduction in performance. The 2-piece design had an average delivery performance of 20.9% late orders while the 3-piece design had an average 29.3% late orders. This gives an indication as to what might happen if no changes were made to the business. If demand was higher than expected then it is reasonable to

Profit & Loss Account	2-Piece design	3-Piece design
Sales	£1,213,567	£1,215,206
Direct Materials	£238,212	£257,096
Direct Labour	£236,434	£218,920
Production Overhead	£314,038	£309,627
Less Stock Movement	£868	-£5,031
Cost of Sales	£787,816	£790,673
Gross Profit	£425,752	£424,533
Sales Tech & Admin	£245,700	£245,700
Interest	-£8,065	-£8,229
Profit Before Tax	£188,116	£187,062
Tax @ 30%	£56,435	£56,119
Profit ATI (Earnings)	£131,681	£130,944
Div @ 5% of Year 1 SHF	£46,574	£45,659
Retained profits	£85,108	£85,285

Balance Sheet	2-Piece design	3-Piece design
Assets		
Buildings	£200,000	£200,000
Plant	£458,440	£436,440
Fixed Assets	£658,440	£636,440
Inventory	£51,362	£49,168
Debtors	£185,131	£189,290
Bank	£158,410	£162,861
Current Assets	£394,902	£401,318
Total Assets	£1,053,342	£1,037,758
Liabilities		
Current Liabilites		
Creditors	£36,758	£39,291
Share Holders Fund		
Ordinary Shares	£857,749	£832,414
Reserves	£73,728	£80,769
P&L account	£85,108	£85,285
Total SHF	£1,016,585	£998,468
Total Liabilities	£1,053,342	£1,037,758
Net Current Assets	£358,145	£362,028
(Current assets - current liabilities)		
Net Assets	£1,016,585	£998,468
(Fixed assets + net current assets)		

Profitability	2-Piece design	3-Piece design
ROCE	18.5%	18.7%
Return on Equity	13.0%	13.1%

Table 9.22 Demonstrator (DEM/2P/3 & DEM/3P/3) financial accounts, acceptable configuration at normal demand

High demand Year 2	2-Piece Design (DEM/2P/4)		3-Piece Design (DEM/3P/4)	
	No. of orders late	% of orders late	No. of orders late	% of orders late
Replication 1	7	3.4%	7	3.4%
Replication 2	64	30.8%	200	96.2%
Replication 3	5	2.4%	3	1.4%
Replication 4	11	5.3%	11	5.3%
Replication 5	25	12.0%	19	9.1%
Mean	22.4	10.8%	48	23.1%

Table 9.23 Delivery performance for demonstrator models DEM/2P/4 and DEM/3P/4 at normal demand

assume that the manufacturing planning and control policy decisions that were set for normal demand would be amended in line with the higher demand. This was done, requiring changes to the safety stock levels and lead time offsets (details are given in appendix 3, section A3.3). The main change was to increase the lead time offset of the spindle for the 2-piece design and the spindle assembly for the 3-piece design, both by 1 day. These configurations are designated DEM/2P/4 and DEM/3P/4. The delivery performance improved and is shown in table 9.23. In both cases the overall delivery performance was unacceptable (i.e. above 5% late orders).

As was hinted in the shop floor simulation models the limit on capacity is probably being reached and this is certainly the case for the second replications where the WIP is seen to increase greatly, figures 9.11 and 9.12. Tables of the utilisation (tables 9.24 and 9.25) show that many work centres, especially for the 2-piece design, are running at a very high utilisation. The figures of utilisation greater than 100% are due to the method of reporting down time. Compared with the shop floor simulator, the utilisation levels of the 3-piece design are a few percent higher. Much of this is due to increases in the set-up time of the TURN1 and TURN2 work centres. The 2-piece design shows slightly greater differences. Some of this difference is due to the processing times being slightly higher in the demonstrator than ATOMS. This is considered to be due to the demand pattern used in ATOMS being about 0.4% lower on average compared with that used for the demonstrator. Due to the limits of capacity being reached it was decided to add machines as a way of achieving a satisfactory performance. Shop floor configurations were therefore derived and tested using ATOMS on its own. To reduce the time required to achieve an acceptable configuration in the demonstrator, the maximum utilisation allowed during the ATOMS runs was 90%.

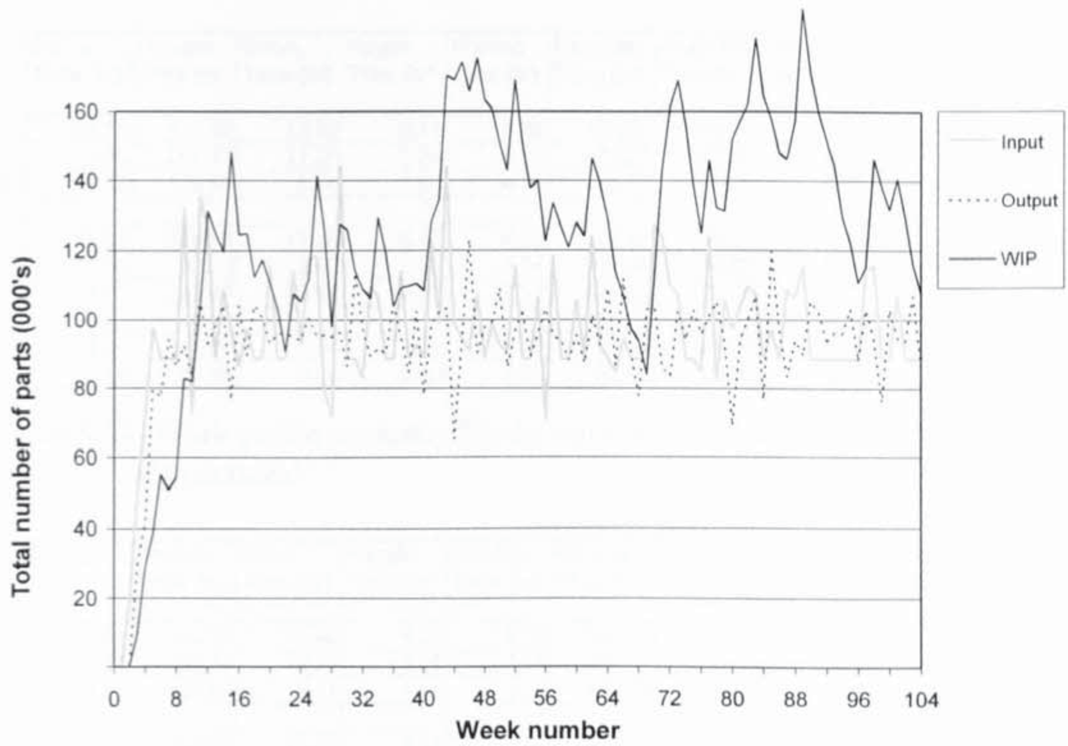


Figure 9.11 Input, output and WIP for demonstrator 2-piece design DEM/2P/4 at high demand (2nd replication)

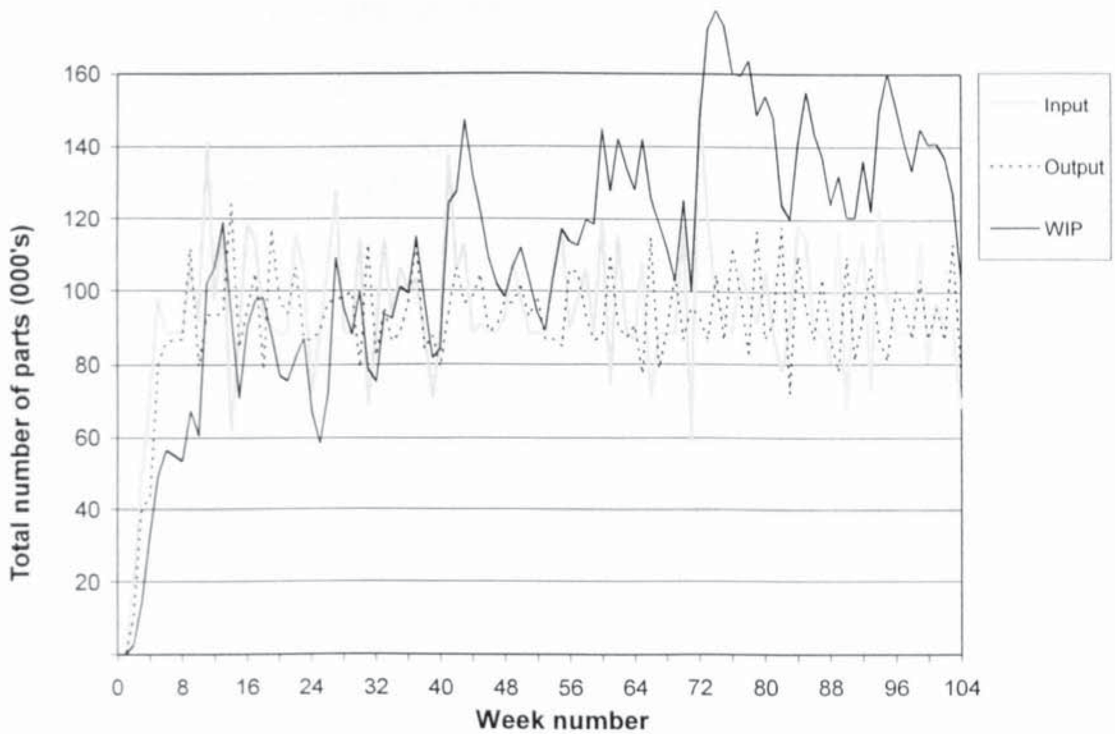


Figure 9.12 Input, output and WIP for demonstrator 3-piece design DEM/3P/4 at high demand (2nd replication)

Work Centre	Set-up Time (hr)	Process Time (hr)	Down Time (hr)	Repair Time (hr)	Waiting Time (hr)	Required Time (hr)	Available Time (hr)	Demo Utilisation	ATOMS Utilisation	Difference
TURN1	32.63	117.92	12.03	6.21	5.82	162.58	160.00	102%	99%	3%
MILL	3.58	257.37	11.26	3.26	8.00	272.21	280.00	97%	96%	1%
BROACH	4.17	128.81	5.74	1.60	4.14	138.72	160.00	87%	85%	2%
TURN2	45.25	166.42	15.29	8.47	6.83	226.97	240.00	95%	92%	3%
HEAT	1.16	62.70	2.63	0.79	1.84	66.49	80.00	83%	82%	1%
GRIND	3.61	293.97	25.87	7.90	17.97	323.45	320.00	101%	99%	2%
PRESS	4.01	125.99	7.54	2.25	5.29	137.54	160.00	86%	86%	0%
INSP	0.16	52.48	0.00	0.00	0.00	52.64	80.00	66%	66%	0%

Table 9.24 Work centre summary for demonstrator 2-piece design DEM/2P/4 at high demand

Work Centre	Set-up Time (hr)	Process Time (hr)	Down Time (hr)	Repair Time (hr)	Waiting Time (hr)	Required Time (hr)	Available Time (hr)	Demo Utilisation	ATOMS Utilisation	Difference
TURN1	28.91	102.73	10.48	5.38	5.10	142.13	160.00	89%	87%	2%
MILL	3.57	253.37	10.24	3.07	7.17	267.17	280.00	95%	95%	0%
BROACH	4.00	126.83	5.77	1.62	4.15	136.59	160.00	85%	84%	1%
TURN2	45.23	163.89	15.08	8.54	6.54	224.19	240.00	93%	91%	2%
HEAT	1.12	61.86	2.40	0.81	1.60	65.38	80.00	82%	81%	1%
GRIND	1.99	215.23	17.09	5.77	11.32	234.31	240.00	98%	97%	1%
PRESS	3.90	144.25	8.63	2.52	6.11	156.77	160.00	98%	98%	0%
INSP	0.15	51.71	0.00	0.00	0.00	51.86	80.00	65%	65%	0%

Table 9.25 Work centre summary for demonstrator 3-piece design DEM/3P/4 at high demand

To achieve this for the 2-piece design required:

- an extra lathe in the TURN1 work centre
- an extra operator on the second shift for the MILL work centre so that both machines are operated on the second shift
- an extra grinding machine in the GRIND work centre and 2 operators, one for each shift
- an extra lathe in the TURN2 work centre.

For the 3-piece design this required:

- an extra operator on the second shift for the MILL work centre so that both machines are operated on the second shift
- an extra grinding machine in the GRIND work centre and 1 operator, for the first shift
- an extra lathe in the TURN2 work centre
- an extra press for the PRESS work centre and 1 operator, for the first shift
- 1 extra craftsmen on the first shift.

These changes gave maximum utilisation levels of 90% for the 2-piece design at the PRESS work centre and 87% for the 3-piece design at the TURN1 work centre in the ATOMS model.

The demonstrator was run with these configurations (designated DEM/2P/5 and DEM/3P/5) while all the other policy decisions were left unchanged. The results are given in table 9.26 and show that the 3-piece design missed virtually no sales orders but the performance of the 2-piece design has become worse.

An additional craftsman was added to the 2-piece design but the performance was still just unacceptable at 5.7% (designated DEM/2P/6). With two additional craftsmen (one per shift) an acceptable performance of 2.6% was achieved (designated DEM/2P/7)

Financial performance for the acceptable configurations are given in table 9.27. This shows that the average profit before tax is now higher for the 3-piece design by £17694. This has been achieved with less investment and this is reflected in the profitability where the 3-piece design is a few percent higher than the 2-piece design. Interestingly the profitability of both designs at the high demand is lower than that at the normal demand.

This completes the experimental procedure. Part of the experiment was implicitly the building and running of the models and these aspects are discussed below.

High demand Year 2	2-Piece Design (DEM/2P/5)		3-Piece Design (DEM/3P/5)	
	No. of orders late	% of orders late	No. of orders late	% of orders late
Replication 1	22	10.6%	0	0.0%
Replication 2	48	23.1%	0	0.0%
Replication 3	29	13.9%	1	0.5%
Replication 4	15	7.2%	0	0.0%
Replication 5	35	16.8%	0	0.0%
Mean	29.8	14.3%	0.2	0.1%

Table 9.26 Demonstrator (DEM/2P/5 & DEM/3P/5) delivery performance at high demand

Profit & Loss Account	2-Piece design	3-Piece design
Sales	£1,279,916	£1,281,073
Direct Materials	£249,605	£272,354
Direct Labour	£262,704	£245,190
Production Overhead	£345,827	£328,804
Less Stock Movement	-£5,280	-£1,616
Cost of Sales	£863,415	£847,964
Gross Profit	£416,501	£433,108
Sales Tech & Admin	£245,700	£245,700
Interest	-£8,227	-£9,312
Profit Before Tax	£179,027	£196,721
Tax @ 30%	£53,708	£59,016
Profit ATI (Earnings)	£125,319	£137,705
Div @ 5% of Year 1 SHF	£52,098	£50,000
Retained profits	£73,221	£87,704

Balance Sheet	2-Piece design	3-Piece design
Assets		
Buildings	£200,000	£200,000
Plant	£542,440	£499,640
Fixed Assets	£742,440	£699,640
Inventory	£52,272	£49,694
Debtors	£195,844	£195,898
Bank	£164,288	£185,691
Current Assets	£412,404	£431,283
Total Assets	£1,154,844	£1,130,923
Liabilities		
Current Liabilites		
Creditors	£39,671	£43,211
Share Holders Fund		
Ordinary Shares	£993,496	£938,016
Reserves	£48,456	£61,993
P&L account	£73,221	£87,704
Total SHF	£1,115,173	£1,087,713
Total Liabilities	£1,154,844	£1,130,923
Net Current Assets	£372,733	£388,073
(Current assets - current liabilities)		
Net Assets	£1,115,173	£1,087,713
(Fixed assets + net current assets)		

Profitability	2-Piece design	3-Piece design
ROCE	16.1%	18.1%
Return on Equity	11.2%	12.7%

Table 9.27 Demonstrator (DEM/2P/7 & DEM/3P/5) financial accounts, acceptable configuration at high demand

9.6 Build Time and Run Time

The time to build a model is not just dependent upon the intrinsic difficulty of the problem but on the familiarity and expertise of the builder. Where aspects of the model building are tedious and time consuming, there is an incentive to develop techniques to reduce the effort. For example, ATOMS provides an ability to upload manufacturing data (e.g. BOM, routing data) to create a basic simulation model. In building the demonstrator models it has been explained that programs were written using the DESQview integration technology in order to input data into UNIPLAN and dBFLEX rather than typing it in manually. Creating models automatically from existing data not only reduces build time but also verification time, as much checking of manually typed data is eliminated. This, combined with the learning curve effect, meant that the time needed to build a demonstrator model was considerably less at the end of the experimental procedure than during the development of the demonstrator system. The actual time to build a model is further complicated by the fact that the models used in the experiments were modifications of earlier models used for development purposes.

No controlled experiment was carried out to measure the exact time to build the various models. However, assuming that the data were available and the modelling systems existed, it is estimated that the build and verify times for a model of the spindle assembly are of the order of:

• design cost model	1/2 hr
• capacity spreadsheet	1 hr
• ATOMS shop floor simulation	8 hrs
• ATOMS financial model (excluding ATOMS)	4 hrs
• demonstrator	20 hrs.

Therefore, notwithstanding the above qualifications, the models can be ranked with reasonable confidence in increasing build time as design cost model, capacity spreadsheet, shop floor simulator and demonstrator.

The run time of the models is easier to quantify. The cost models, capacity model and shop floor simulator cost model were built in a spreadsheet package and had negligible computation times. For the ATOMS shop floor simulator and demonstrator, the run times are dependent upon the computer used. The times given below are for the faster computer that the models were run on, i.e. a Pentium 166 MHz with 24 MBytes of memory. To run a 50 week period of the ATOMS takes 3 minutes while a 52 week period of the demonstrator takes 3 hours.

10 DISCUSSION

The experimental procedure described in the previous chapter was primarily aimed at comparing enterprise simulation with existing tools and so demonstrating the benefit of enterprise simulation. Implicit in this was the building and use of an enterprise simulation model to provide support for the feasibility of the technique. Before discussing these aspects, the validity of the results will be established because if the results are considered invalid it would undermine any conclusions drawn from them.

10.1 Validity of the Results

Support for the validity of the results has already been provided by the arguments made previously for the validity of the tools themselves. This section will look at providing further support for the validity of the results of the demonstrator by examining the reasons for differences in the predicted performance and behaviour of the models. If these differences can be explained, and the reasons are valid, then this will provide support for the validity of the results. As the shop floor simulator is the most valid of the existing tools used, the discussion will concentrate on a comparison of this tool and the demonstrator. The shop floor simulator did not provide a measure of delivery performance therefore other measures of performance such as WIP and utilisation will be compared.

The WIP of the demonstrator was generally higher and more variable than that predicted by the shop floor simulator. It was mentioned that this might be due to the orders generated by the MRP system of the demonstrator, being very different to those used for the ATOMS simulation. To test this proposition, the 2-piece design ATOMS model was run with works orders generated by the first replication of the demonstrator model (DEM/2P/1) which is the original configuration. To ensure as close a comparison as possible, the starting seed used in the demonstrator run was also used in the ATOMS model. Figure 10.1 shows the WIP of the ATOMS model with that of the demonstrator. It can be seen that the pattern is very similar but the ATOMS model WIP is generally lower than the demonstrator. This is considered to be due to there being no material constraints in the ATOMS shop floor simulation model. This is supported by figure 10.2 which is a comparison of same ATOMS model but with the ordering pattern from the first replication of the demonstrator model (DEM/2P/3). This is the acceptable configuration of the 2-

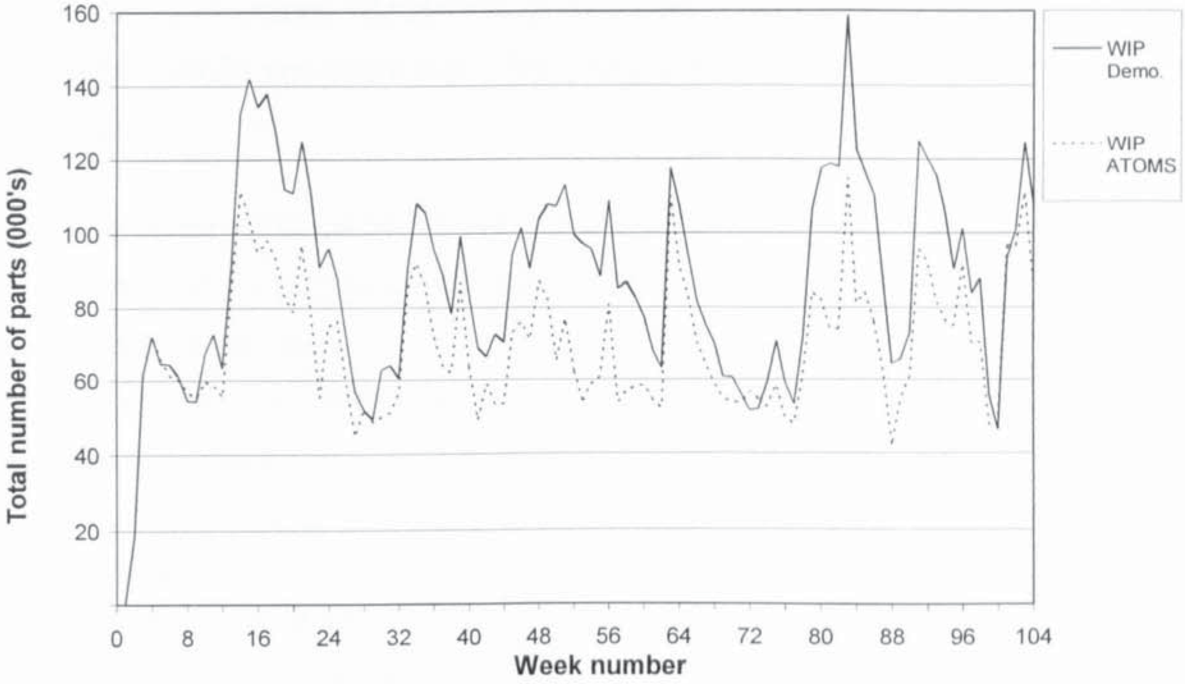


Figure 10.1 WIP of ATOMS model 2-piece design with demonstrator (DEM/2P/1) works orders, 1st replication

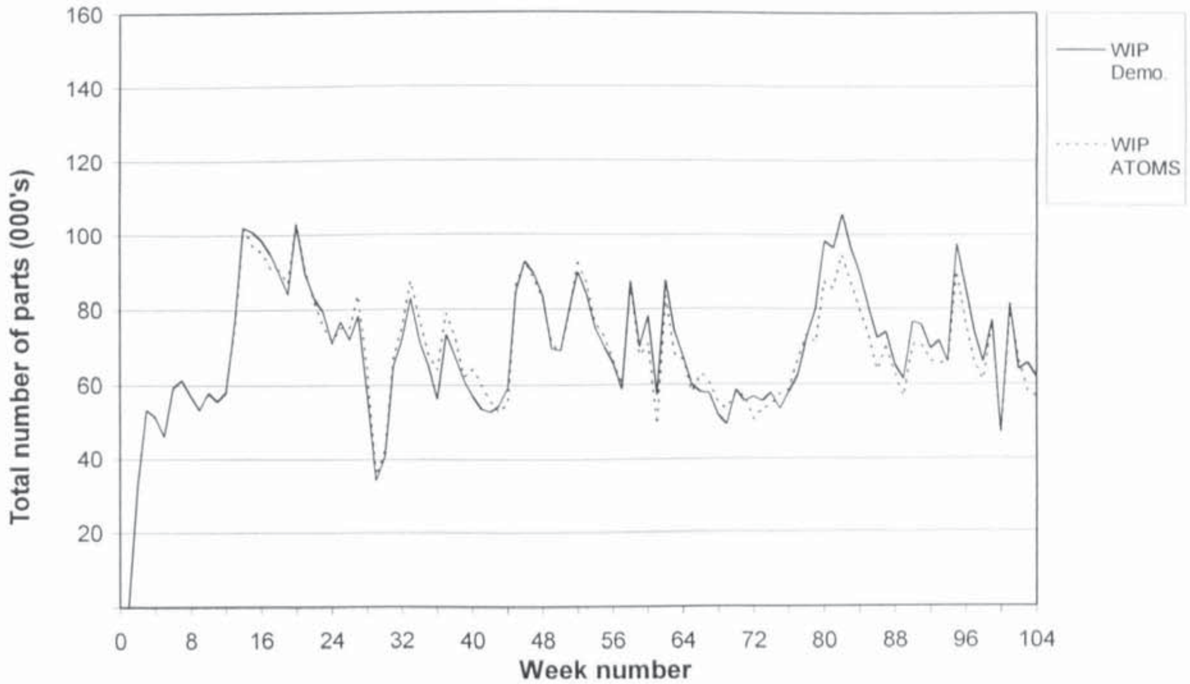


Figure 10.2 WIP of ATOMS model 2-piece design with demonstrator (DEM/2P/3) works orders, 1st replication

piece design at normal demand which had much lower level of material shortages compared with the previous model. The correspondence between the two models is now very close.

The WIP levels displayed by the demonstrator are therefore considered to be due to the works order pattern generated by the MRP system and not due to some inherent flaw in the model itself. As the demonstrator used a real MRP system to generate the works orders it is concluded that the WIP is more valid in the demonstrator than in the shop floor simulation on its own.

The average utilisation levels were generally similar between ATOMS and the demonstrator. The major difference between ATOMS and the demonstrator was in the set-up times where the demonstrator was generally higher. The greatest difference was evident for the TURN1 and TURN2 work centres which have relatively long set-up times.

Visual inspection of the works orders generated by the MRP system showed that there was a certain amount of sequencing. This may reduce the number of set-ups compared with the fully randomised works orders used for the ATOMS model. This explanation is supported by table 10.1 which shows the set-up times from the ATOMS model 2-piece design, the first replication of the demonstrator model (DEM/2P/3) and the ATOMS model 2-piece design with the ordering pattern from the first replication of the demonstrator model (DEM/2P/3) discussed above. Although not identical, the latter run is closer to the demonstrator than the original ATOMS run. A certain amount of sequencing of works

	ATOMS (2-piece design) average values	Demonstrator (DEM/2P/3) first replication.	ATOMS (2-piece design) with works order pattern of demonstrator (DEM/2P/3) first replication
	Weekly set-up times (hrs)		
TURN1	29.82	32.34	32.25
MILL	3.20	3.57	3.54
BROACH	3.70	4.02	4.09
TURN2	40.20	46.91	45.55
HEAT	1.01	1.16	1.23
GRIND	3.12	3.59	3.66
PRESS	3.72	4.05	4.04
INSP	0.15	0.16	0.17

Table 10.1 Set-up time comparisons

orders in the MRP is due to suggested works orders being produced in alpha-numeric order when there were orders on the same day. While the effect in the demonstrator might be slightly exaggerated due to the small number of components, it is not unreasonable, as such effects will could occur in real life.

To remedy the poor delivery performance of the demonstrator models at high demand, extra machine capacity was added to both. This action had quite differing effects. For the 2-piece design the performance became worse, while for the 3-piece design it gave almost zero late orders. It was only after the inclusion of two extra craftsmen that the performance of the 2-piece design became acceptable. This situation obviously requires some explanation.

It had been expected that the addition of machine capacity would reduce the throughput time of the components therefore the lead time offset settings in the MRP system were not changed. It was assumed that any reduction in the actual lead times would act in a similar way to safety stock and so improve the delivery performance.

As was stated in section 9.5.2, these shop floor configurations were run using ATOMS on its own and the maximum utilisation allowed during these runs was 90%. These runs can be compared to the ATOMS 2-piece and 3-piece design at high demand. In the case of the 3-piece design, WIP reduced by 21% from an average of 66864 (table 9.9) to 52568; for the 2-piece design WIP levels increased slightly by 2.6% from 64139 (table 9.9) to 65800.

As the demand is constant, the increase in WIP will have increased the throughput times in line with the formula for steady state queuing processes (Little, 1963):

$$L=\lambda.W$$

Where:

- L = expected number of units in the system
- W = expected time spent by a unit in the system
- $1/\lambda$ = expected time between two consecutive arrivals to the system.

The WIP is equivalent to L, throughput time is equivalent to W and the demand is equivalent to $1/\lambda$.

Even though the increase in WIP will have increased the throughput times, it is puzzling that such a small increase in WIP could be responsible for the very large down turn in performance for the 2-piece design. A closer inspection of all the work centres showed that for 3-piece design, the utilisation of each work centre of the demonstrator shop floor configuration were lower or about the same as the ATOMS 3-piece model. For the 2-piece design some work centre utilisations of the demonstrator shop floor configuration had increased compared to the ATOMS 2-piece design. For example, the BROACH had increased from 85% (table 9.10) to 88% and the PRESS had increased from 86% (table 9.10) to 90%. The increases in utilisation were mainly due to down time. Therefore, while the average level of WIP had changed little, its distribution amongst the various work centres, inferred from the utilisation levels, had changed a lot. This is supported by the lead times measured in ATOMS, where the spindle and gear lead times were virtually unchanged but the lead time for the spindle assembly had increased by 2 days. This therefore gives an explanation for the poor performance of the 2-piece design. The addition of the craftsmen reduced the down time and brought the lead times for the spindle assembly into line with the setting in the MRP system. The difference in performance therefore has a logical and valid explanation.

It might be claimed that the change in performance of the 2-piece design could have been predicted had the lead times been looked at. However, at the time, what was done was considered sensible and it was not considered necessary to check the lead times. Only in retrospect did it become clear that the lead times should have been considered further. With a different design of product and shop floor some other aspect might be critical and need investigation, but it would be difficult to predict which are the critical aspects of any given situation. More importantly, it is only because the demonstrator highlighted the poor performance that this problem was discovered. In real life situations, the poor performance would only have come to light after the changes had been implemented.

As well as operational differences there are also financial differences. Table 10.2 shows the better design and the yearly financial advantage associated with it. For example, the

	Demand	
	Normal	High
Design cost model	3-piece	3-piece
	£14,280	£14,994
ATOMS cost model	3-piece	3-piece
	£4,518	£3,531
ATOMS finance model	3-piece	3-piece
(Profit Before Tax)	£4,885	£3,832
Demonstrator finance	2-piece	3-piece
(Profit Before Tax)	£1,054	£17,694

Table 10.2 Cost and financial comparisons

design cost model shows that at both normal and high demand, the 3-piece design has a financial advantage over the 2-piece design; at normal demand it is £14280 and at high demand it is £14994

The design cost model is based upon the average overhead rate, of the 2-piece and 3-piece designs, derived from the ATOMS financial models at normal demand. It is this that leads to a difference with the ATOMS product cost model. If the respective overhead rates are used then the answers match.

The ATOMS financial model is based upon financial accounting principles and therefore should be close to the demonstrator accounts. At normal demand there is disagreement in ranking, while at the high demand the results agree in ranking but the values are very different. The differences at the normal demand can be explained by the assumptions and simplifications of the ATOMS financial model, e.g. sales volume was based on the theoretical demand and not what was invoiced (similarly for purchases), scrap is estimated, interest payments are based on average bank balances. At the high demand these aspects will also apply but this does not explain all of the difference. The majority of the difference is due to the ATOMS financial model being based upon the configurations considered acceptable in ATOMS. These configurations were entirely different to those which were considered acceptable in the demonstrator, which required extra machines and personnel. It is accepted that the decision to have a maximum utilisation of 90% may have resulted in more machines and labour being required beyond the minimum required to achieve an acceptable performance. Some additional capacity was required, so there would have been some additional machines and labour which were not suggested by the

ATOMS model. Using the ATOMS financial model with the configuration of the demonstrator gives the 3-piece design as being £17896 more profitable than the 2-piece design. This answer is now of the right order of magnitude. The remaining differences can then be explained by the simplifications and assumptions in the ATOMS financial model.

The differences in the financial figures can therefore be explained by either differences in the models or by acceptable differences in the data used in them and are therefore considered to be valid.

10.2 The Benefits of Enterprise Simulation

10.2.1 Inputs and Feedback

It has been argued that the enterprise simulation should support a product development team better because it will allow them to implement the range of decisions that would have to be taken to bring about the manufacture of the product. Feedback (local and global) would also be provided to enable the goodness of the decisions to be judged and to allow investigation of problems.

From the experiment it can be seen that the demonstrator did provide a wide range of inputs across many areas of the business such as the shop floor, manufacturing planning and control, purchasing and finance. This represents an improvement on existing tools, which lack many inputs such as forecasting method, supplier performance and MRP policies. In the case of the design cost model there was no input to handle the change in demand. This and many other factors had to be handled by the overhead rate. In the shop floor simulator many decisions could not be implemented directly. Assumptions were therefore made about such things as the availability of raw materials and the demand variability of works orders.

Feedback was also better in the demonstrator. The main requirement of the scenario was customer delivery performance but this measure was not provided by any of the existing tools. In using the existing tools, reliance was placed on other measures of performance (e.g. utilisation and WIP) to judge the suitability of the decisions. The shop floor simulator was the most sophisticated of the existing tools used but even this proved to be inadequate in judging what was a suitable shop floor design. While the outputs of the ATOMS financial model were similar to the financial accounts of the demonstrator, the demonstrator is superior because it allows detail investigation of financial transactions.

When problems were found in the delivery performance, the demonstrator's ability to interrogate the relevant business area allowed problems to be identified. The wide range of inputs then allowed possible solutions to be tried. For example, by looking at the MRP works order requirements and comparing this with the raw materials stocks, stock outs were seen to be higher than expected. By implementing a change in the safety stock levels the number of stock outs was reduced and the delivery performance improved. Note, it is not being claimed that this was the best solution but it was one way of resolving the problem. Other options might have been to look at the forecasting method, batching policy, lead time offsets or supplier performance as a means of reducing the stock outs. Similarly, if there had been financial problems the individual accounts in the financial accounting system could have been investigated. These are all facilities which were available in the demonstrator but not in the other tools.

It can be seen therefore that the demonstrator has identified problems that the other tools could not. Having done so it has enabled a possible solution to be derived and implemented. Even if these problems were suspected, the existing tools would have been very limited in their modelling capability to resolve them.

10.2.2 Differences in the Results

The results given by the various tools can be viewed in terms of how they ranked the two designs and in terms of the quantitative differences. At the high demand the shop floor configuration used in the demonstrator was different to that used in the other tools. Therefore in comparing the results there are differences in the tools themselves and also differences in the data used.

Work-in-progress levels can only be compared between the ATOMS and demonstrator models. Table 10.3 gives the average WIP levels for the ATOMS models and for corresponding configurations of the demonstrator models. Also given is whether the WIP

	Normal Demand		High Demand	
	2-Piece Design	3-Piece Design	2-Piece Design	3-Piece Design
ATOMS	(not significant)		(not significant)	
	56975	55107	64139	**66864**
Demonstrator (initial)	DEM/2P/1	DEM/3P/1	DEM/2P/4	DEM/23P/4
	(significant)		(significant)	
	91407	79467	**100540**	89851
Demonstrator (final)	DEM/2P/3	DEM/3P/3	DEM/2P/7	DEM/2P/5
	(significant)		(significant)	
	69866	61234	**59804**	54697

Table 10.3 WIP comparisons

levels between the 2-piece and 3-piece designs are statistically significant at the 95% level using a paired t-test (Law & Kelton, 1991, p. 587). It can be seen that the ATOMS model and the demonstrator model agree in their rankings at normal demand, while at the high demand they are different for the initial and final configuration. As some of the differences are not statistically significant the agreement in some of the ranking may just be due to chance.

Generally the demonstrator WIP levels were much higher and more variable than those of the corresponding ATOMS models. This under estimation by ATOMS, of the level and variability of WIP, is likely to lead to flawed decisions which are based on the WIP levels, e.g. the numbers of containers to transport components or the amount of floor area for buffers. Had these aspects been modelled it may have led to an even greater difference in the financial figures.

	Normal Demand		High Demand	
	2-Piece Design	3-Piece Design	2-Piece Design	3-Piece Design
Capacity S/S	TURN1 92%	PRESS 90%	TURN1 96%	PRESS 94%
ATOMS	TURN1 96%	PRESS 93%	TURN1 & GRIND 99%	PRESS 98%
Demonstrator (initial)	DEM/2P/1	DEM/2P/1	DEM/2P/4	DEM/3P/4
	TURN1 & GRIND 96%	PRESS 92%	TURN1 102%	GRIND & PRESS 98%
Demonstrator (final)	DEM/2P/3	DEM/3P/3	DEM/2P/7	DEM/3P/5
	TURN1 98%	GRIND & PRESS 93%	PRESS 85%	TURN1 89%

Table 10.4 Utilisation comparisons

Average utilisation was an area where there was closer agreement between the tools. Table 10.4 gives a summary of results showing the highest loaded work centres and the level of utilisation. It is only in the final configuration at high demand that there are major differences. This difference is due to the shop floor configuration of the demonstrator being different to that of the ATOMS model. While the capacity spreadsheet generally over estimated set-up times, this was more than offset by the waiting times which were ignored. The overall effect is an under estimate compared with ATOMS and the demonstrator. The ATOMS and the demonstrator were generally fairly close, the main differences were due to set-up times being greater in the demonstrator. The figures in the table are for the long term average utilisation and not the transient values. It might be expected that the greater weekly variability in WIP level would lead to a greater variability in utilisation levels. Therefore, if transient utilisation was important, the use of a shop floor simulator on its own is likely to under estimate the effect.

Unlike the demonstrator, none of the existing tools provided information on the levels of raw materials and finished goods. As was seen from the demonstrator runs these levels varied quite dramatically. Using estimates to determine the number of storage devices and space requirements is therefore likely to lead to problems. Again, had these aspects been included in the analysis, it may have led to greater differences.

While differences in operational measures are of concern it is how they impact on the finances which will be important, as the financial results will generally be a major factor in the decision making process of which design to choose. A summary of the financial results has already been given in table 10.2 and showed that there was not a consistent ranking of the designs across the tools used. Accepting the greater validity of the demonstrator one might question the quality of financial results from existing tools. In the case of the design cost model, the data which would be used in practice are likely to be less reliable than those used in the experiment and so cast further doubt on the quality of the answers. For the ATOMS financial model, it has been pointed out that the difference in the answers at the high demand was largely due to the input data generated by the ATOMS model rather than a flawed financial model. But arriving at a set of valid configuration data to be used in a model is an important aspect of the analysis.

When viewed in terms of the total sales value, the differences between the financial performance of the 2-piece and 3-piece designs may appear trivial; what is important is how the differences relate to profits. Taking the differences as a percent of earnings (i.e. operating profit after tax and interest) gives values in the range of 0.6% for the demonstrator at normal demand and 10% at high demand. While 0.6% may be small, 10% would make a significant impact on the profits of the business.

The results of the demonstrator are therefore considered to be better for two reasons. Firstly, the basis of the model itself is such that where the inputs between the models are comparable the results are of greater validity. Secondly, and more importantly, is the fact that the demonstrator has enabled an acceptable set of implementation actions to be derived. Using a valid model with invalid data is just as flawed as using an invalid model with valid data. What is required is validity in both the modelling process and the data used in it, and the demonstrator fulfils both these criteria.

10.3 The Feasibility of Enterprise Simulation

The extent to which the feasibility of enterprise simulation is supported by the experiment is determined by the scope, detail and size of the model, and how it was used. These aspects are discussed below.

10.3.1 Use of the Demonstrator

The experiment imitated in a simple way how enterprise simulation might be used in practice by using the demonstrator to analyse two designs. Decisions were implemented in the various areas of the modelled business that would be required to manufacture the product. Problems were found, but after investigation of the business systems, these problems were resolved by amending some of the original decisions. Although a multi-functional team did not do the experiment, there was nothing about the experiment that could not be done by such a team. The decisions taken were those that a team would be expected to make as part of their job. Similarly, all the data required to complete the demonstrator (e.g. supplier lead times, interest rates) were within the expertise of a team.

10.3.2 Scope, Detail and Size

The scope and detail of the demonstrator is good and covers the major elements internal and external to a business. This is due in part to the use of real software systems as models of major elements of a manufacturing business. The main aspect which was omitted was a model of the activities of the support department personnel. There was also simplification of certain aspects as there is in any model. The limited ranges of end products, components and raw materials was probably the major simplification, as even a small business is likely to have many more products than was modelled here. This simplification was made to render the experiment tractable and not because the demonstrator is incapable of handling a large product range. While there is nothing in principle against modelling a large product range, it is an aspect which affects build time and run time, both of which are discussed below.

With the previous qualification about product range, the size of model built was not trivial in that it was representative of a small to medium sized business.

10.3.3 Build Time and Run Time

As has been discussed in the previous chapter the time to create the demonstrator models was greater than that to create the ATOMS or other models but was comparable with the build time of ATOMS shop floor simulator plus financial model. Build time would obviously increase with an increased product range as it would for the other techniques. With the use of the automated building methods it would be quite feasible to build a model of a business which had a reasonable product range.

The run time of the demonstrator was relatively long but not extreme. It was an order of magnitude greater than the comparable ATOMS simulator but this difference needs some qualification. The demonstrator was an experimental vehicle and not built primarily for speed while ATOMS is a purpose built shop floor simulator intended for commercial use. The techniques used in the demonstrator to integrate the software systems are not particularly efficient. The DESQview screen reading and keystroke input routines are relatively slow. To enable the updating of works orders and recording of results, the ATOMS model and results files had to be saved at the end of each simulated day which increased the run time of the demonstrator. The proportion of time spent inputting and updating varies with the model and the computer used, but is in the region of 65% to 85% of the total run time of the demonstrator. With purposely designed integration techniques such as OLE and Active X (Chappell, 1996) it would be expected that a WBS system would have run times which are much more comparable with conventional simulation than was implied by the experiment.

While the computers used for running the models were relatively powerful DOS based machines, they are by no means the most powerful computers available. Computer work stations used in CAD and CAE are generally much more powerful. In addition, the trend for computing power to increase over time will continue to reduce the problem of run time.

It is considered therefore that the building of the demonstrator and running of the experiment provide good initial support for the feasibility of enterprise simulation. Further support is provided by the use of the demonstrator to model a large business. It was used for research into Manufacturing Systems Design methodology. The model and its use are described in detail in Lewis (1994, chp. 8). The model used actual company data, an idea of its size can be gained from some summary statistics:

- £22.4 million turnover
- 200 direct operators
- 80 indirect operators
- 96 work centres
- 220 work stations
- 11 end items
- 2416 stock records
- 50 raw materials.

The run time of this model on a 66MHz, 486 computer, was between 4 to 8 hours per 2 weeks, when at steady state; a year would take about 4 to 8 days. On present day computers, run times would be much less, at about 1 day for one year.

10.3.4 Future Possibilities

It is realised that the experiment is quite some way from actual use, but for a proper system it is envisaged that other techniques would be employed to make it a practical proposition.

That a completely detailed enterprise simulation model would be built anew, each time a product design is to be analysed, is probably not realistic. It can be envisaged that there would be a permanent model which reflected the present structure of the business. To analyse a design, the current state of the business systems could then be uploaded into this model and the design analysed. Systems are being developed which provide this sort of capability for manufacturing simulations of the shop floor (e.g. Fabre & Leblanc, 1993; Thompson, 1994) but they would need to be extended to include the other areas of the business. Another possibility is to extend computer integrated manufacturing (CIM) so that the business systems themselves become part of an enterprise simulation model in a similar way to how the real software systems were used in the demonstrator (Love & Barton, 1996). While these techniques will aid in the building of comprehensive and detailed models, the need for such detail in all areas is obviously not required in every situation. The idea of multi-level modelling discussed in chapter 4 offers a number of benefits. A comprehensive but abstract model can be built and used to investigate a large number of alternatives since these simplified models will have relatively small build and run times. As the alternatives are reduced, greater detail can be added to increase the confidence in making decisions between the remaining alternatives. For specific problems, the area of interest can be modelled in detail and other areas modelled at an abstract level. In this way the specific problem is captured to the relevant level of detail without sacrificing the important interactions of the other areas of the business.

Even with automatic data uploading and multi-level techniques, enterprise simulation might still require a large amount of data which does not exist and so involve a large amount of time and effort to generate it. This would apply especially to much of the manufacturing data for new components such as process routes and times. It has been argued that a number of existing techniques could be used to generate estimates (Barton & Love, 1995). The product design analysis techniques such as functional costing could be used to provide costs for many purchased parts while DFA/DFM techniques could provide process times. Since the existing DFM techniques for machined parts assume that all the processing is carried out on a single machine there is a problem where manufactured parts require more than one type of machining operation. Given that much design is variant or adaptive (Pahl & Beitz, 1988, p. 4; Court et al., 1993, p. 7) it is likely that parts already exist in the company's current product range which are similar to or comparable with the new design. Such parts, once identified, by a technique such as coding and classification (Holmes & Love, 1992), could provide routing data of acceptable accuracy. Also, as generative computer aided process planning is developed it will provide another source of data. With such techniques therefore, data could be generated to populate an enterprise simulator.

The above techniques therefore provide a number of avenues to a practical application of enterprise simulation. In addition, as many of these techniques could be applied early in the design process it opens up the possibility of applying enterprise simulation at a stage in the design process that might not otherwise have seemed possible.

10.4 Is Enterprise Simulation Worthwhile?

It has been argued above that the aims of the experiment have been met in that enterprise simulation does support the design team better than existing tools and has provided good support for the feasibility of the technique. What remains to be discussed is whether these benefits are worth the extra effort that would obviously be involved in employing enterprise simulation? From the experiment this question cannot be answered conclusively, therefore a number of arguments will be put forward which contend that it is worthwhile.

The experiment was a simplified, but representative, example of what might be done in practice, but even so it was not straightforward to produce an acceptable set of downstream actions even with the aid of tools. In a more realistic situation, with a more complicated product it is likely that it would be even more difficult to do it right first time. Lewis (1994, chp. 5) gives a number of examples in the area of manufacturing systems design where serious problems have emerged after implementation, even though systematic methods and tools were employed.

Resolving problems after implementation leads to two further points. It has been assumed that these problems can be resolved after implementation and that the cost of doing so is negligible. While the symptoms of problems, e.g. material shortages, high levels of WIP, will be obvious, their resolution may not be so simple. What is the real cause of the problem may not be self evident and may be due to a combination of factors in a number of different business functions and therefore may require a coordinated set of actions. Tackling the problem where the symptoms are visible may lead to problems in other areas. While some corrective actions (assuming they are known), such as amending stock records, may cost little to implement, others actions such as new machines or extra personnel could be expensive. As well as the cost of rectification, there may be transient costs cause by the problem itself and these could be significant. In a competitive situation, delays to delivery while problems are resolved are likely to lead to more than just delays in sales and subsequent payments, but to a permanent loss of sales.

This discussion of transient effects, leads to a final point. The experiment has just looked at the steady state condition of the business but the introduction of new products is likely to lead to a significant transient. Managing this transient is therefore important if major problems are to be avoided with the subsequent impact on costs. Product life-cycles are generally considered to be shortening but there are some who question that it is as extensive as claimed (Murphy & Braund, 1990). Whatever the actual position, problems during the transient period will be even more significant where life-cycles are short and hence time available to generate income is limited.

In summary therefore it is considered that the experiments support the proposition that enterprise simulation can provide a better analysis than existing tools, and that this analysis brings with it potential benefits that are worth the additional effort that would be required to implement enterprise simulation.

11 CONCLUSIONS AND FURTHER WORK

11.1 Conclusions

The idea of decision chains has been used to derive requirements for the valid analysis of the operational and financial impact of product design decisions. The key requirements are:

- inputs which match, in scope and detail, the downstream decisions required to implement a product design
- a dynamic modelling capability which can model the operational, control and financial aspects of a manufacturing business
- provision of operational and financial measures of performance which match the user's view of the business
- outputs at a level of detail that enable the investigation and resolution of poor business performance.

A form of enterprise simulation, Whole Business Simulation, has been shown to match the above requirements and hence should provide a valid analysis of product design decisions. However, Whole Business Simulation systems (or other enterprise simulation systems which match the above requirements) do not exist. Consequently, an experimental whole business simulation system was built and used to investigate the benefits and feasibility of the approach.

This experimental system is a combination of specialist simulation elements and standard operational applications software packages. Together they provide a model that incorporates all the key elements of a manufacturing business, including its customers and suppliers. Combining simulation elements and real software systems is not new, but the experimental system is novel in that its scope and detail of modelling is beyond that seen before.

A case study was developed which, while relatively simple, incorporated many aspects which are typical of actual products and manufacturing companies. This case was used to compare the capability of the experimental system with a representative range of existing analysis tools (DFX, capacity calculation, shop floor simulation, and business planner driven by a shop floor simulator).

The results of the experiments support the proposition that enterprise simulation can provide a better analysis compared with existing tools. This is considered to be due to the superiority of enterprise simulation in terms of:

- the validity of the operational and financial modelling
- the capability to implement the necessary scope and detail of design and operational decisions
- the provision of feedback to confirm the goodness of the decisions and to assist in the resolution of poor decisions.

The experiments also confirmed the feasibility of building and running an enterprise simulation model for the analysis of design decisions. Additional support for the feasibility of the approach has been provided; the experimental system has been used to model a large business as part of research into Manufacturing Systems Design methodology. With the experimental system it is possible, with present day personal computers, to simulate in detail one years operation of a medium sized business in a few hours.

Enterprise simulation requires additional effort compared with existing analysis tools but it has been argued that the potential benefits of enterprise simulation are worthwhile.

11.2 Further Work

This thesis has argued for the use of enterprise simulation to analyse design decisions. To support this argument, an experiment has been performed which has demonstrated the benefits and feasibility of the approach. The size and complexity of the model used in the experiment was appropriate for this initial work. Future work should involve larger models that include aspects such as greater product range, more levels in the bills of materials and commonality of sub-assemblies, components and raw materials. Such models would be expected to exhibit a greater complexity and subtlety of interactions in the decision chains not apparent in the model used here. This would enable further potential of the enterprise simulation approach to be investigated and demonstrated. Larger models would also provide greater confidence in the feasibility of the technique. Initial work in this area could be readily achieved by repeating the experiment with the complete Mandrill model.

It is not always necessary to model all the areas of the business at the finest level of detail. Consequently the concept of multi-level modelling has been suggested as an approach which offers a number of benefits, for example earlier application of the analysis, efficient utilisation of effort and resources, quicker build and run times. Before multi-level modelling can be successfully applied, answers to a number of questions are required:

- which areas of a model can be abstract and which should be at a detail level?
- what modelling abstractions are appropriate and what are not?
- what are the trade-offs between speed of execution and validity of results?

For each stage in the product development process, what level of detail is required to achieve valid results?

Although there is an argument for the modelling of support department functions in an enterprise simulation, this feature was omitted from the experiment. This aspect should be included in the investigation into multi-level modelling. It would need to address a similar set of questions: when, to what extent and in what detail do support departments need to be modelled to ensure valid analysis.

The use of an enterprise simulation like WBS has been argued to support a product development team. How teams would interact with such a system and how they should be organised for best effect were not features of the experiment. These are aspects which require researching as they are likely to have an impact on the adoption of the technique and the overall benefit derived from it.

The whole business simulator is not a trivial system and hence a methodology for its use as a design analysis tool is required. The knowledge gained from the above investigations will provide essential information for the development of a methodology, e.g. when and where it should be used, what must be included in a model and how teams should be organised.

Finally, the application of WBS in industry is required to ultimately confirm the potential benefits and feasibility of the technique.

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APPENDIX 1 DETAILS OF CASE DATA

A1.1 Shop Floor Data

A1.1.1 Process Routing

In the Mandrill case data, each type of component (gear, spindle and spindle assembly) has the same processing requirements, which is for simplification of the case. While in reality this might be so for the heat treatment, press and inspection operations, it is unlikely to be so for the machining operations due to the differences in size. The simplification was not considered to affect the experiment, therefore the times were not changed to reflect the size differences.

Table A1.1. shows for the 2-piece, the set-up times, processing times and where applicable load and unload quantities and times. The same information is shown in table A1.2 for the 3-piece design.

For the TURN1 and TURN2 work centres, the machines are automatic and so the operator is not tied to a machine but is engaged in loading the machines with the bars of raw material.

Part	Work Centre	Set-up time (mins.)			Load Qty	Processing time (mins.)			Load time (mins.)			Unload time (mins.)		
		Distri-bution	Mean	Std. Dev.		Distr-bution	Mean	Std. Dev.	Distr-bution	Mean	Std. Dev.	Distr-bution	Mean	Std. Dev.
GEAR	TURN1	Normal	240	60	250	Fixed	51	0	Normal	2	0.5	Not applicable		
	MILL	Normal	15	5	1	Fixed	0.473	0	Not applicable			Not applicable		
	BROACH	Normal	30	10	1	Fixed	0.24	0	Not applicable			Not applicable		
SPINDLE	TURN2	Normal	240	60	50	Fixed	13.2	0	Normal	2	0.5	Not applicable		
	HEAT	Normal	15	5	50	Fixed	5.75	0	Not applicable			Not applicable		
	GRIND	Normal	15	5	10	Fixed	4.85	0	Normal	0.2	0.1	Normal	0.4	0.1
SPINDLE	PRESS	Normal	30	10	1	Normal	0.233	0.1	Not applicable			Not applicable		
ASSY.	INSP	Normal	2	0.5	1	Normal	0.1	0.03	Not applicable			Not applicable		

Table A1.1 Process times for 2-piece design

Part	Work Centre	Set-up time (mins.)			Load Qty	Processing time (mins.)			Load time (mins.)			Unload time (mins.)		
		Distri-bution	Mean	Std. Dev.		Distri-bution	Mean	Std. Dev.	Distri-bution	Distr-bution	Std. Dev.	Distri-bution	Mean	Std. Dev.
GEAR	TURN1	Normal	216	60	250	Fixed	45	0	Normal	2	0.5	Not applicable		
	MILL	Normal	15	5	1	Fixed	0.473	0	Not applicable			Not applicable		
	BROACH	Normal	30	10	1	Fixed	0.24	0	Not applicable			Not applicable		
SPINDLE	TURN2	Normal	240	60	50	Fixed	13.2	0	Normal	2	0.5	Not applicable		
	HEAT	Normal	15	5	50	Fixed	5.75	0	Not applicable			Not applicable		
	GRIND	Normal	10.5	5	10	Fixed	3.45	0	Normal	0.2	0.1	Normal	0.4	0.1
SPINDLE	PRESS	Normal	30	10	1	Normal	0.275	0.1	Not applicable			Not applicable		
ASSY.	INSP	Normal	2	0.5	1	Normal	0.1	0.03	Not applicable			Not applicable		

Table A1.2 Process times for 3-piece design

The changes to the 2-piece design are assumed to have had the following impact on set-up and processing times. The need not to ream the bore of the gear has reduced TURN1 set-up time and processing time by about 10%. At the GRIND work centre, the need to grind the diameter for the interference fit is eliminated and so the set-up time and processing times have been reduced. As this was a significant part of the grinding required (based on surface area) it has reduced the processing time by about 30%. At the PRESS work centre the processing time has increased by about 2.5 seconds, the approximate time required to reach and fit a tolerance ring.

A1.1.2 Scrap Rates

The machining tolerance is assumed to have been allocated more to the reaming operation than the grinding operation because the cost of achieving a given tolerance is generally greater for an internal bore than for an external bore. This is indicated by relative cost tables as given in Parker (1984, tables 2.19 and 2.20). Therefore the reduction in scrap rates is assumed to have been more significant at the GRIND work centre (about 50%) than the TURN1 work centre (about 10%). At the assembly operation and inspection it also assumed that there are also significant reductions of about 50%. The values of scrap rates for the two designs are given in table A1.3.

A1.1.3 Stoppages

Work stations have two type of stoppages. Planned stoppages due to minor resets of the machine while unplanned stoppages are due to breakdowns. The mean time between (MTB) stoppages is based on the processing time of the machine. Table A1.4 show the distributions, means and standard deviations used for the MTB stoppages and for service times to reset or repair the machines. These values have been used for both designs of spindle assemblies.

A1.1.4 Machine Power Consumption

To account for the electrical power consumption of the machines, the values shown table A1.5 were used and are the rated power of similar machines given in manufacturers brochures of machine tools. The actual power consumption will vary with the work being done but for the purposes of the experiment using a constant value was considered acceptable. The power consumed is then the processing time multiplied by the consumption rate.

A1.1.5 Transport

The time to transport batches between work centres is common, taking a mean of 30 seconds with a normal distribution of 9 seconds. There is a fixed delay of 4 minutes for the transport operator to respond to a request for transport.

Part	Work station	2-piece design			3-piece design		
		Distribution	Mean	Std. Dev.	Distribution	Mean	Std. Dev.
GEAR	Auto-Lathe	Normal	0.60	0.20	Normal	0.54	0.20
	Milling m/c	Normal	1.40	0.50	Normal	1.40	0.50
	Broach	Normal	0.90	0.30	Normal	0.90	0.30
SPINDLE	Auto-Lathe	Normal	0.90	0.30	Normal	0.90	0.30
	Heat treat	Normal	0.50	0.20	Normal	0.50	0.20
	Grinding m/c	Normal	1.10	0.30	Normal	0.55	0.30
SPINDLE	Press	Normal	0.90	0.30	Normal	0.45	0.15
ASSEMBLY	Inspection	Normal	2.00	0.70	Normal	1.00	0.35

Table A1.3 Scrap levels for 2-piece and 3-piece designs

MINOR RESETS						
Work station	MTB stoppages (processing hours)			Service Time (minutes)		
	Distribution	Mean	Std. Dev.	Distribution	Mean	Std. Dev.
Auto-Lathe	Normal	16	5	Normal	5	1.5
Milling m/c	Normal	20	6	Normal	5	1.5
Broach	Normal	20	6	Normal	5	1.5
Heat treat	Normal	20	6	Normal	5	1.5
Grinding m/c	Normal	12	4	Normal	5	1.5
Press	Normal	16	5	Normal	5	1.5

BREAKDOWNS						
Work station	MTB stoppages (processing hours)			Service Time (minutes)		
	Distribution	Mean	Std. Dev.	Distribution	Mean	Std. Dev.
Auto-Lathe	Normal	200	50	Normal	480	60
Milling m/c	Normal	300	100	Normal	120	40
Broach	Normal	300	100	Normal	120	40
Heat treat	Normal	300	100	Normal	120	40
Grinding m/c	Normal	500	15	Normal	480	160
Press	Normal	200	50	Normal	120	40

Table A1.4 Stoppages for 2-piece and 3-piece designs

Machine	Power rating (kw)
Auto-lathe	10
Heat treatment	20
Grinding m/c	5
Milling m/c	5
Broach	5
Press	2

Table A1.5 Machine power consumption rates

A1.1.6 Shop Floor Policies

The following shop floor policies apply:

- batches are split into transfer quantities of 1500
- at work centres, similar waiting batches are grouped together
- batches are split amongst all the workstations in the work centre
- sequencing rule for waiting batches is first-in-first-out.

A1.1.7 Operator Priorities

Craftsmen have first priority to set-up machines and second priority to repair machines. Inspector have first priority to inspect and second priority to do set-ups.

A1.2 Manufacturing Planning and Control Data

A1.2.1 Reorder Quantity (batch size)

The reorder quantity was set equal to the average weekly demand for each type of component. For raw materials and purchase parts the reorder quantity was set to what were considered to be the minimum purchase quantities. For the raw material this was a 3 metre bar of material and for the tolerance ring this was a box of 500 items.

A1.2.2 Lead Time Offset

In industry the lead time offset might be based on similar existing components, a rule of thumb (e.g. as half a week per operation) or calculation. From a limited survey of 13 companies, Wemmerlov (1979) reported that half used experience and the other half used some form of calculation, although the type of calculation used was not reported. The use of rules of thumb may be acceptable for particular companies or classes of industry but their use here is not considered justifiable. The values given in the Mandrill case are a possible source but as they do not form part of the systems dynamics model their validity is questionable. It was therefore decided to derive lead time offsets from the ATOMS shop floor simulation.

The latter 250 weeks of results were used to determine how long each order took to complete. The results were collected in 5 blocks of 50 weeks each. Although there are 50 orders released in a 50 week block, the works orders in the final week will not necessarily be completed. Therefore the orders in the last week were excluded, giving 49 results per item, per block. The lead time was taken from the day the order was released to the day it was completed, this therefore included waiting time for the orders at the first operation. The lead times will vary because of such things as variability in batch size, processing, breakdowns and the randomness in the sequence that orders are released. Using the maximum value might lead to extreme lead times so it was decided that a value of lead time offset that encompassed the majority of orders would be used, a figure of 95% was chosen. The differences in batch size could be expected to affect lead time but when the results were examined the lead time of each type of component were reasonably similar so

	Lead time offsets (days)			
	2-Piece Design		3-Piece Design	
	Derived from ATOMS	Set in UNIPLAN	Derived from ATOMS	Set in UNIPLAN
Spindle Assembly	5	7	6	8
Spindle	7	9	7	9
Gear	7	9	7	9

Table A1.6 Lead time offsets set in MRP system at normal demand

it was decided to use the same lead time across a given type of component i.e. gears, spindles and spindle assemblies. The values of lead time derived from ATOMS were in working days, therefore the values used in UNIPLAN have had an extra two days added to cover the weekend. The results of this analysis are shown in table A1.6. The lead time offset for the spindle assembly of the 3-piece design is thought to be greater than the 2-piece design because of the extra processing time and higher utilisation at the PRESS work centre.

For the purchase parts the lead time offset was set at the supplier average (14 days). The variability in lead time was to be covered using safety stock (reorder level in UNIPLAN) which is discussed below.

A1.2.3 Safety Stock Levels

For finished goods and components, safety stock levels were set to zero as it was expected that the batching in the MRP system would cover any differences between customer demand and forecast demand; it would also account for the small amount of scrap that would occur. For raw materials and purchase parts a safety stock level was set based on conventional stock control calculations to cover variability in delivery and the variability in demand. The equation for safety stock given below is based on Lewis (1981, p. 50) equation 3.3.

$$S = k\sqrt{\left(\overline{L}\sigma_d^2 + \overline{D}^2\sigma_l^2\right)}$$

Where

- S = safety stock level
- k = standard variate
- $\overline{L}$ = average lead time
- σ_d = standard deviation of demand
- $\overline{D}$ = average demand
- σ_l = standard deviation of lead time

This equation is strictly only applicable if the lead time and demand are normally distributed and independent. While the demand for raw materials and purchased parts

Steel Bars (Diameter)	Safety Stock Level (metres)	Tolerance ring	Safety Stock Level	Spindles	Safety Stock Level	Gears	Safety Stock Level	Finished Goods	Safety Stock Level
12 mm	53	A	814	A	0	A	0	A	0
14 mm	263	B	3972	B	0	B	0	B	0
16 mm	242	C	3589	C	0	C	0	C	0
18 mm	234	D	3398	D	0	D	0	D	0
40 mm	8								
45 mm	45								
50 mm	45								
55 mm	47								

Table A1.7 Safety stock levels

does not probably meet this requirement, it was considered acceptable to use it as a first estimate. The value of *k* determines the level of service and a value of 2.33 was used which gives a theoretical probability of stock out of 1%. Assuming an average of one order per week this means that about one stock out should occur over a two year period. Average lead time is 2 weeks with standard deviation of 1 day (see section A1.4.2 below). The standard deviation of demand was based on the +/- 20% demand variation. This range was assumed to be equivalent to 6 standard deviations. The safety stock levels are shown in table A1.7.

A1.2.4 Bucket Size

A bucket size of one day was used which might be considered small but given that the lead times are relatively short (of the order of 9 days, see below) this was considered necessary. A day bucket size is not uncommon, in a survey of UK manufacturing by New & Myers (1986, pg. 37) it was found that 23% of those surveyed used a bucket size of one day, with a shift by others to a smaller bucket size. New & Myers also claim that irrespective of the lead time used, a bucket size of more than one week is too crude for effective planning in any manufacturing system.

A1.2.5 Forecast Method and Forecast Period

As the average demand is level with randomness, a moving average forecasting method used was used (Lewis, 1981, p. 15). A decision is required on the number of periods to use for the moving average. The intention of the experiment was not to investigate what the best forecast period would be, but to set a period so that the effect of forecasting would be reasonably captured in the model. A very short period would produce a very erratic forecast and transmit every movement on to the shop floor. A very long period would produce a level forecast tending to the longer term average demand and so miss out the short term movement that would occur. A length of 4 weeks moving average period was considered reasonable. A two week moving average tended to follow the peaks and valleys to closely while a 6 week moving average was providing too much smoothing.

A1.2.6 MPS Horizon

The MPS horizon was set so that it covered the longest cumulative lead time offset. The cumulative lead time offset is 30 days (7+9+14) for the 2-piece design and 31 days

(8+9+14) for the 3-piece design. Therefore for both designs a horizon of five weeks was set

A1.3 Financial Data

A1.3.1 Accounting Periods

To simplify the simulation there were 13 accounting period of 4 weeks each, rather than 12 periods based on calendar months.

A1.3.2 Depreciation Method and Rates

The depreciation method and rate were taken from the Mandrill case, namely straight-line machinery at 10% and no depreciation for building. From Gordon & Gray (1994, chp. 7) this is an acceptable method and value to use.

A1.3.3 Stock Valuation

For financial accounting purpose stocks can be valued using only direct costs (material and labour) or they can include indirect production costs (production overhead) (Gordon & Gray, 1994, p. 117). As the latter is done in Mandrill it was also done here. The value of overhead used in the Mandrill case was not considered applicable though as it is for a much larger size of business and would not reflect differences that might occur due to the two designs of spindle assembly. A value was therefore derived from the business planning model.

A1.3.4 Interest Rates

The Mandrill case only has an interest rate for overdrafts. For this experiment it was considered biased if there were only a cost for an overdraft and no reward for excess bank balances. It was considered that cash balances would be put to use, either earning interest or being reinvested in the business, therefore interest is to be paid for cash balances. A reasonable spread between loans and savings is considered to be about 4% (Pringle, 1973, pp. 13-14), therefore a saving interest rate of 4% less than the overdraft rate was to be used. The Mandrill overdraft rate used is 13.25% but a slightly more modest rate of 10% was used which is considered typical Reynolds (1992, p. 112) and hence gives a saving rate of 6% per year.

A1.3.5 Taxation

The amount of corporation tax payable is not straight forward. There are many rules covering what is considered as profit for taxable purposes, what can be offset against tax, what the corporation tax rate is and when it must be paid (Gordon & Gray, 1994, chp. 3). The intention here was not to include all the nuances but include some effect. Therefore for the purposes of this experiment it was assumed that tax was payable on operating profit and interest (i.e. profit before tax), it was paid at the end of each accounting year, and was at a single fixed rate.

The rate of corporation is not fixed. For example there are two levels of corporation tax rate dependent upon the profits earned (full rate and small companies rate). In the financial year 1993/4 the full rate was paid when profits exceeded £1,250,000 and the small companies rate when profits are below £250,000. Between the two levels there is a varying tax rate. In the financial year 1982/3 the rates were 52% and 38% and in 1993/94 were 33% and 25%. A single of figure of 30% was therefore considered reasonable.

Valued added tax was not included in the experiment.

A1.3.6 Dividend

The return to the shareholders of a company can considered in two parts, dividend payments and the growth of the business. Based on the shareholders fund (initial investment plus any reserves), rates of 5% for dividend and 10% for growth are considered to be realistic figures for engineering companies (Reynolds, 1992, p. 112). The figure of 5% for dividend was therefore used here. The dividend was assumed to be paid at the end of the accounting year.

A1.3.7 Payment Terms

The payment terms in the Mandrill model was used, this was 56 calendar days for sales.

A1.3.8 Selling Prices

Obviously the Mandrill model did not have sales prices for the spindle assembly. As mentioned above the growth of the business can be viewed as part of the interest for investing in the business. The prices were therefore set so that the retained profits would be around 10% of the share holders funds. The prices for each type of spindle was in proportion to its standard cost. As with the derivation of the overhead rate, these value were derived using the business planning model and are shown in table A1.8. The same prices were used at the high demand.

A1.3.9 Machine and Building Values

The values of the machines were taken from the Mandrill model and are shown in table A1.9. The value of the building was taken as a proportion of the Mandrill model based on

Spindle Assembly	Sales price (each)
A	£0.57
B	£0.71
C	£0.79
D	£0.94

Table A1.8 Sales prices of spindle assemblies

Machine	Value
Auto-lathe	£38,750
Heat treatment	£24,000
Grinding m/c	£27,500
Milling m/c	£31,400
Broach	£47,100
Press	£12,750

Table A1.9 Machine values

the approximate floor area and equated to £200,000. The same value was used for both designs.

A1.3.10 Labour Rates

The labour pay rates were taken from the Mandrill case and reflect rates of a few years ago. The rates are shown in table A1.10.

A1.3.11 Production and Administrative Overheads

A number of overheads were treated as fixed costs. These overheads were factored from the Mandrill case data to give reasonable values. The weekly values used are given in table A1.11. These values do not include the overheads of depreciation and machine power consumptions described elsewhere.

A1.4 Supplier Data

A1.4.1 Purchased Prices

The prices for raw material bar were derived as follows. Parker (1984, figure 2.6) gives material prices for ferrous and non-ferrous bars for the year 1980 (which is contemporary

Grade	£/hr
Operator	4.21
Transport	4.08
Craftsmen	4.92
Inspector	4.08

Table A1.10 *Hourly pay rates of shop floor personnel*

Production Overheads		Administrative	
Tooling & Consumables	£492.27	Sales, Technical & Admin.	£4,725.00
Heating	£700.00		
Rent & Rates	£379.94		
Repairs & Maintenance	£1,160.64		
Total	£2,732.85		

Table A1.11 Weekly production and administrative overheads

Diameter	Price per 3m bar	Tolerance ring	Price each
12 mm	£0.45	A	0.012 p
14 mm	£0.61	B	0.014 p
16 mm	£0.80	C	0.016 p
18 mm	£1.01	D	0.018 p
40 mm	£4.98		
45 mm	£6.31		
50 mm	£7.79		
55 mm	£9.42		

Table A1.12 Prices of raw materials and tolerance rings

with the Mandrill case). Prices for steel bar, covers a range from 0.36 £/kg for black mild steel to 0.81 £/kg for 55 tonne carbon steel. A figure of 0.51 £/kg was used as this is considered to be represent of the material used for the spindle and gears. The length of bar used is 3 metres and with the diameter of bar as given above the prices can be calculated based on the volume of the bar and assuming a density for steel of 7.81 gm/cm^3. The prices of tolerance rings were not based on actual prices but chosen to give an alternative design which was comparable to the standard interference fit design. The prices for the raw materials and tolerance rings are given in table A1.12.

For the price of electricity was taken as £0.05 per kW/hour, this is the approximate price per unit of UK electricity in 1993 (Electricity Association, 1993).

A1.4.2 Delivery Terms

The value in Mandrill for the bar material was specified as 2 weeks. This figure was used for both raw materials and the tolerance ring. A small amount of variability added to include the effect of delivery problems, namely, a normal distribution with 1 day standard deviation.

A1.4.3 Payment Terms

The payment terms in the Mandrill model was 56 calendar days for purchases, the same as for sales. This was used for the raw materials and tolerance rings. For the electricity 28 days was used.

APPENDIX 2 SOFTWARE SYSTEMS AND SUPPLIERS

ATOMS Version 5.01j
Aston University
Birmingham
West Midlands
B4 7ET
UK

Borland Pascal, Version 7.0
Borland International, Inc.
1800 Green Hills Road
P.O. Box 660001
Scotts Valley
California 95067-0001
USA

dBFLEX Version 4.0
Dataflow (UK) Limited
Dataflow House
Mill Mead
Staines
Middlesex
TW18 4UQ
UK

DESQview Version 2.61 & DESQview Pascal API Version 2.313
Quarterdeck Office Systems
150 Pico Boulevard
Santa Monica
California 90405
USA

SuperCalc5, Revision C
Computer Associates International, Inc.
1240 McKay Drive
San Jose
California 951312
USA

UNIPLAN
PPL-Sheffield Micro Limited
Rutland House
Rutland Park
Sheffield
South Yorkshire
S10 2PB
UK

APPENDIX 3 REVISED CASE DATA

A3.1 Raw Material Safety Stock Levels for Demonstrator Models DEM/2P/2 and DEM/3P/2

The safety stock level for raw materials and purchased parts were set to the average demand plus 20% and are shown in table A3.1.

Diameter	Safety Stock Level (metres)	Tolerance ring	Safety Stock Level
12 mm	159	A	2448
14 mm	792	B	11952
16 mm	729	C	10800
18 mm	703	D	10224
40 mm	24		
45 mm	135		
50 mm	135		
55 mm	141		

Table A3.1 Raw material safety stock levels for demonstrator models DEM/2P/2 and DEM/3P/2

A3.2 Finished Goods Safety Stock Levels for Demonstrator Models DEM/2P/3 and DEM/3P/3

There is no variability in customer demand, therefore the standard stock control equation given in appendix 1, section A1.2.3 was used with σ_l set to zero. As the customer demand is not a normal distribution the standard deviation of demand was assumed to be a sixth of the range. The value of k was set to 2.33. Average lead time is 7 days for the 2-piece spindle assembly and 8 days for the 3-piece spindle assembly. The standard deviation of demand was based on the +/- 20% demand variation. This range was assumed to be equivalent to 6 standard deviations. The safety stock levels are shown in table A3.2

Finished Goods	Safety Stock Level 2-piece	Safety Stock Level 3-piece
A	317	339
B	1547	1654
C	1398	1495
D	1323	1415

Table A3.2 Finished goods safety stock levels for demonstrator models DEM/2P/3 and DEM/3P/3

A3.3 Lead Time Offsets and Safety Stock Levels at High Demand

The lead time offsets were based on the shop floor models at the high demand. This gave the lead time offsets as shown in table A3.3 which show that the only change was to increase the spindle to 10 days for the 2-piece design and spindle assembly to 9 days for the 3-piece design.

Based on the high demand and the increased 3-piece spindle assemble lead time, gives the safety stock levels as shown in table A3.4.

	Lead time offsets (days)			
	2-Piece Design		3-Piece Design	
	Derived from ATOMS	Set in UNIPLAN	Derived from ATOMS	Set in UNIPLAN
Spindle Assembly	5	7	7	9
Spindle	8	10	7	9
Gear	7	9	7	9

Table A3.3 Lead time offsets in MRP system at high demand

Steel Bars (Diameter)	Safety Stock Level (metres)	Tolerance ring	Safety Stock Level	Spindles	Safety Stock Level	Gears	Safety Stock Level	Finished Goods	Safety Stock Level 2-piece	Safety Stock Level 3-piece
12 mm	167	A	2570	A	0	A	0	A	333	377
14 mm	832	B	12550	B	0	B	0	B	1624	1842
16 mm	765	C	11340	C	0	C	0	C	1468	1664
18 mm	739	D	10735	D	0	D	0	D	1390	1576
40 mm	26									
45 mm	142									
50 mm	142									
55 mm	148									

Table A3.4 Safety stock levels at high demand